EFFECTS OF IRRIGATION AND NITROGEN FERTILIZER LEVELS ON WATER AND NITROGEN USE EFFICIENCY AND YIELD OF DROUGHT TOLERANT HYBRID MAIZE (*Zea mays* L.) IN EMBU COUNTY, KENYA

CHARLES ANDREW NYAMBANE ONYARI

A Thesis Submitted to Graduate School in Fulfillment for the Requirements of Doctor of Philosophy Degree in Agronomy of Egerton University

EGERTON UNIVERSITY

AUGUST 2018

DECLARATION AND RECOMMENDATION

Declaration

This is to certify that this thesis is my original work and has not been presented to any other University for any degree or diploma.

Signature: ……………………………………… Date: ……………/…………../2018

Charles Andrew Nyambane Onyari
KD12/0305/11

Recommendation

This thesis has been submitted with our approval as University supervisors.

Signature: ……………………….. Date: ……………/…………./2018

Prof. Antony Mwangi Kibe
Egerton University
Department of Crops, Horticulture and Soils

Signature: ……………………….. Date: ……………/…………./2018

Prof. Samuel Mwonga
Egerton University
Department of Crops, Horticulture and Soils

DEDICATION

This work is dedicated to my late parents, Mr. Samson Onyari Nyakundi and Mrs. Neliah Moraa Onyari, who always encouraged and taught me hard work, determination and focused persistence for success in life.

ACKNOWLEDGEMENT

First, I humbly thank the Almighty God for giving me good health and patience throughout my doctoral studies. My special gratitude also go to my wife, Elizabeth Bosibori and children, Neliah Moraa, Daniel Nyakundi, Faith Kerubo and Zeinabu Mong'ina, for their patience and encouragement during this long journey. I cannot forget to thank the Ministry of Agriculture for allowing me to pursue the graduate degree while working at Embu Agricultural Staff Training (EAST) College and later the Kenya School of Government in Nyeri County. The unsolicited support from the Management of the University of Embu (formerly Embu University College, Constituent College of the University of Nairobi) cannot pass without mention. The institution provided the study site where my research work was conducted in a span of two years. The constant reminder by senior management that I needed to complete the PhD degree the soonest possible was a worthwhile challenge that I took positively since it re-energized my effort towards meeting this noble goal.

It's with great pleasure and appreciation to acknowledge my supervisors, Professor Antony Mwangi Kibe and Professor Samuel M. Mwonga for their untiring sacrifice, support and patience as they guided me through my research work and final preparation thesis. Their corrections made the realization of this dream come true. Thank you very much and may the Almighty God continue blessing you as you endeavor to mentor other researchers into greater heights of career development in matters academics.

I would also like to thank the Post Graduate School of the Egerton University for facilitating my studies in matters of quality reporting, consistence and timeliness. It was a great pleasure studying in my University of Choice: three degrees from the same institution is a sign of trust and love.

Many people, friends, relatives and colleagues gave me a helping hand whenever I was down due to the overwhelming challenges associated with doctoral studies. Some helped in literature search by directing my focus areas, others encouraged me while others felt the work was too much and unnecessary. To you all, I say thank you because all the comments, utterances, actions and thoughts went a long way to shape my personality in studies. Whatever type and level of faith you had in me, it was worth the push that I needed to complete my studies.

To all, once again, God the Creator of the Heavens and the Earth, bless you abundantly.

LIST OF ABBREVIATIONS AND ACRONYMS

AE_{BN}	Agronomic Efficiency of Nitrogen, Biomass Basis
AE_{GN}	Agronomic Efficiency of Nitrogen, Grain Basis
AEZ	Agro-Ecological Zone
ANOVA	Analysis of Variance
FAO	Food and Agriculture Organization of the Unite Nations
GDD	Growth Degree Days, (^oC)
FAO	Food and Agriculture Organization of the United Nations
HI	Harvest Index
HU	Heat Units, (^oC)
IWUE	Irrigation Wter Use Efficiency
NUE	Nitrogen Use Efficiency
PFP	Partial Factor Productivity
PUE	Precipitation Use Efficiency
WAS	Weeks After Sowing
WUE_b	Water Use Efficiency, Biomass basis
WUE_g	Water Use Efficiency, Grain basis

ABSTRACT

Food grain shortage in Kenya is attributed to low rainfall and poor distribution in maize growing areas particularly as well as low soil fertility associated mainly with nitrogen deficiency. Use of irrigation water and nitrogen fertilizer is likely to solve this food security challenge. This study was conducted over two seasons covering 2012 and 2013 with the aim of establishing optimal irrigation and nitrogen fertilizer rates for drought tolerant hybrid maize (*Zea mays* L.), DK8031, grown in furrows to optimize rainfall capture with the objective of simultaneously achieving high water and nitrogen use efficiencies and yields. Four irrigation levels allocated as main plots were given: I_{119} - only once at sowing with 119 mm; I_2 = 238 mm - at sowing and two weeks after sowing (WAS); I_{357} – at sowing followed by applying at two and six WAS; I_{476} - at sowing, followed by applying at two, six and ten WAS. These totaled to 119.05, 230.10, 357.15 and 476.2 mm of applied irrigation water, respectively, exclusive of the 542.4 and 780.0 mm seasonal rainfall received in 2012 and 2013. Nitrogen was allocated to the subplots incrementally at $N_0 = 0$, $N_{30} = 30$, $N_{60} = 60$, $N_{90} = 90$ and $N_{120} = 120$ kg-N/ha application rates. It was observed that application of irrigation water and nitrogen positively and significantly affected biomass and grain yields as well as the yield components of the DK8031 maize variety. The highest dry matter and grain yields of 13,200 and 4,000 kg/ha were obtained with 476.6 mm applied irrigation water and 120 kg/ha nitrogen rate. The aboveground biomass and grain yields varied from 11.8 to 16.3 and 3.7 to 4.0 t/ha. The highest number of cobs per ha (47,500 to 62,778 cobs/ha), cob length (17.5 to 19.9 cm) and lines per cob (12.9 to 13.4) were achieved at $I_{476}N_{120}$ treatment combination in both season and increased with additional inputs, implying higher production potential at higher values of irrigation levels and fertilizer rates. The biomass and grain based water use efficiencies decreased with increase in irrigation but increased with increasing nitrogen rates and ranged from 8.2 to 12.8 kg-DM/ha-mm and 4.3 to 4.4 kg-grain/ha-mm in Season I and II, respectively. Linear and quadratic production functions developed predicted yields with high certainties (R^2) ranging between 0.60 and 1.00. Optimal yield was obtained with 357 mm supplemental irrigation water and 90 kg-N/ha of application nitrogen. Farmers in Embu can grow the DK8031 maize with at least 238 mm and 357 mm depth of supplemental irrigation at nitrogen rates of 90 and 100 kg/ha to promote productivity of the crop in the October to March and April to September seasons, respectively.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background Information

The need to be food secure worldwide receives critical priority as this determines the health and wealth of a country in the face of global warming that leads to prolonged drought and unpredictable weather patterns. Declining soil fertility, ever increasing human population and limited natural resource base add to this, resulting in reduced crop yields. Cereal grains such as maize (*Zea mays* L.) are known to provide a staple source of food for many communities in the world (Namara *et al.,* 2010).

The UN Task Force on hunger reports that 854 million people worldwide, constituting 14% are chronically or acutely malnourished, mostly in Asia but in sub-Saharan Africa the hunger prevalence is above 30% with absolute number of those malnourished on the rise (Sanchez and Swaminathan, 2006). About 380 million women, children and men in sub-Saharan Africa live on less than $ 1.25 a day (James, 2014), of which many are malnourished or hungry. With some 80 million small farmers in the region producing 80% of agricultural goods, smallholder farmers have a key role to play in resolving the financial and food crises and unleashing Africa's potential to feed itself.

Agriculture, predominantly on a small scale, accounts for about 30 percent of the sub-Saharan Africa's GDP and at least 40 percent of export value. In a number of countries, the sector plays an even greater role, representing 80 percent or more of export earnings. The potential of these numbers will remain untapped unless African countries put the right policies in place.

To increase agricultural production so as to achieve economic development and attain food security in sub-Saharan Africa, there is need to expand irrigation so as to realize full potential of water resources and irrigated agriculture (Hanjra *et al.,* 2000; Munir *et al*., 2009). This is in line with the meeting on the Millennium Development Goals of eradicating poverty and extreme hunger without compromising on environmental sustainability (UN 2000). The report notes that less than 4% of renewable water resources in Africa are currently withdrawn for agriculture. Barriers include the lack of financial and human resources to build irrigation and related rural infrastructure and acquire agricultural technology, and inadequate access to markets. Since water causes changes in the soil to the full depth to which it penetrates, then regulated irrigation can be a means of modifying soil properties for production of crops such as maize (Widtose, 2010).

Agriculture is very important in Kenya as 75% of its population depends on it for food and income generation. The sector contributes 26% of the Gross Domestic Product and 60% to foreign exchange earnings (Karanja 2006; GoK, 2005). Eighty three percent (83%) of the land in Kenya is classified as arid and semi-arid, with the rest having a medium to high productive potential (Onyari *et al*., 2010). The mean annual rainfall ranges from less than 250 mm in semi-arid and arid areas to more than 2000 mm in high potential areas (Perret, 2006). Maize, mostly rainfed, the staple food for most Kenyans, fell from 27.3 million bags in 1998 to 25.0 million bags in 2008 resulting in 73.3 thousand tons had to be imported (CEEPA, 2006). In view of the potential further decrease in yields due to climate change, such trends are of great concern to food security management.

Drought is a major constraint for plant productivity worldwide and different mechanisms of drought-tolerance have been reported for several plant species including maize (Kanashiro *et al.,* 2010). Drought is economically and ecologically disruptive and in severe conditions profoundly impacts on agriculture, water resources, tourism, ecosystems and basic human welfare (FEMA, 1995). Climate data models indicate drought will be more frequent in future and that the likelihood of heat waves may progressively increase in intensity and frequency over the next several decades, strengthening the environmental conditions for drought and wildfire events (CEEPA, 2006). The report recommends intensification and increased productivity of production factors, including land and water, in the context of good arable land in Kenya and the underdeveloped irrigation.

It has been shown that arid and humid regions can look to irrigation as one of the chief weapons by which to conquer drought and to make the land yield richly (Widtose, 2010). The author further noted that the benefits of irrigation include dependable crop yields from year to year, controlling water application that regulates crop yields and quality of the crop and makes life worthwhile in areas demanding irrigation under given soil and climatic conditions. It also enhances social interaction between people sharing the same canal that binds them together. The author emphasizes on the significance of soil temperature in irrigated farming as this influences both seed germination and subsequent growth phases, thereby determining the rate of growth and length of the growing season for crops such as maize.

Work done in India shows that most of the improved varieties of maize require 100-120 days to mature with early vegetative stage (20-40 DAS) and tasselling and silking (45-60

DAS) being critical in demand for water (Michael, 1983). The author also notes that maize is very sensitive to excess water and hence advisable to plant it on ridges or make ridges in the field after its establishment. Submergence in the soil for 3 – 5 days during seedling or flowering period reduces the yield considerably.

Nitrogen fertilizers are developed to supply nitrogen (N) as the major nutrient which is a major constituent of all cells of plant and animal origin (Mugendi *et al*., 2006). The authors indicate that inadequate supplies of N supplies leads to stunted growth, reduced yield, reduced water use efficiency and impairment of crop quality. The nutrient is absorbed as nitrate (NO_3^-) and ammonium (NH_4^+) ions and its excessive supply in relation to phosphorus, potassium and sulphur can delay crop maturity.

The nitrogen fertilizers are valued according to their N-content, the N-forms and side effects such as acidification of the soil. Nitrate (NO_3^-) is quick acting because it is immediately available. Plants take up N mainly in NO_3^- form but it is most leachable. Nitrogen use efficiency can be enhanced through matching crop need with nutrient availability; application of the right N-fertilizer for specific crops and soils; correct rates of application that are zone and crop specific; correct mode and method of application for particular tillage system; proper timing of fertilizer application to the target yields; availability of other nutrients in adequate amounts and balanced proportions; and proper control of soil fertility (Mugendi *et al*., 2006). Nitrogen fertilizers are available in three main forms: ammonium, amide and ammonium nitrate forms. They are usually applied as top dressing when plants are actively growing and the soils are moist.

This study proposes to provide information to manage soil and water resources through efficient irrigation and nutrient nitrogen utilization as one way of addressing the food challenges facing Kenya in form of cereal maize production. Planning for future drought events and their impacts on society is a responsibility that must be jointly coordinated at the local, county and national levels.

1.2 Statement of the Problem

Food deficits related to the grain cereals are commonly reported in Kenya as a majority of her population relies heavily on maize as a staple food. The potential for opening up land in marginal areas for crop production, especially maize, is enormous in the country but has not been fully utilized given that only less than 6% of the land is under irrigation in Kenya. Maize in the country's marginal areas is mainly grown on rain-fed agriculture despite the fact that than 83% of the country land is under arid and semi-arid conditions. Prolonged droughts make water a key limiting factor in crop production in such areas, leading to famine and abject poverty besides loss of human lives and livestock. The production, processing and consumption of the maize provide critical points of consideration if the supply of this food commodity is to be ascertained lest the country will continue relying on external supplies whose prices are not only prohibitive but also availability is limited at critical areas and times. The scarce availability of literature on the maize production for marginal areas in Kenya, and particularly Embu, means little or no work has been done to assess the potential use of irrigated agriculture and nitrogen fertilizer use to enhance maize production.

1.3 Objectives

1.3.1 General Objective

The broad objective of this study was to enhance maize productvity through improved use of irrigation water and nitrogen fertilizer by farmers in Embu.

1.3.2 Specific Objectives

The specific objectives were:

(a) To determine the effects of irrigation on the yield, water use efficiency and nitrogen use efficiency of drought tolerant hybrid maize

(b) To determine the effects of nitrogen rates on the yield, water use efficiency and nitrogen use efficiency of drought tolerant hybrid maize

(c) To determine the interaction effects between irrigation levels and nitrogen rates on the yield, water use efficiency and nitrogen use efficiency of drought tolerant hybrid maize.

(d) To develop production function models for predicting grain yields of drought tolerant maize under varying irrigation and nitrogen levels.

1.4 Research Hypotheses

(a) Varying irrigation levels have no significant effects on the yield, water use and nutrient nitrogen use efficiency of drought tolerant hybrid maize

(b) Varying nitrogen rates have no significant effects on the yield, water use and nutrient nitrogen use efficiency on drought tolerant hybrid maize

(c) There are no interaction effects between irrigation and nitrogen rates for the yield, water use and nutrient nitrogen use efficiency on drought tolerant hybrid maize

(d) Production functions cannot be developed for predicting yield of drought tolerant maize under varying irrigation levels and nitrogen rates.

1.5 Justification

Maize is an important economic food resource whose limited supply signals hunger and suffering among many people in the Horn of Africa in general and Kenya in particular. The most affected sections of the population are children, women and elderly as has been witnessed in the recent past due to prolonged drought in the region. The national average precipitation for Kenya is 400 mm of annual rainfall with only 17% of its land being considered high potential for arable use. Over use of the arable land for crop production purposes, declining soil fertility and limited utilization of available precipitation result in low crop yields such as maize. With ever increasing population, now standing at over 40 million, declining soil fertility levels and a surging demand for food in form of grain cereals and their products, it is incumbent that available resources for agriculture be utilized prudently so as to alleviate these challenges. Food deficits have been reported in the country by the Ministries of Agriculture and Special Programmes and with prolonged drought in northern Kenya and other marginal areas. This resulted in acute hunger and loss of human and livestock lives, prompting the Government of Kenya to declare a national disaster and appealing for donor aid. The global warming seems to be having a toll on food production as the weather has become unpredictable with low rains which are poorly distributed even in areas once regarded as humid. Off-season periods can be utilized through controlled irrigation and fertilizer management as an initiative towards addressing food security. This work proposes examine the effects of irrigation levels and nutrient nitrogen application rates on the performance of maize in a marginal humid area in a bid to contribute towards food sufficiency in Embu County.

1.6 Beneficiaries

The work aimed to provide information on prudent use of nitrogen fertilizer and appropriate irrigation management for maize production in Embu, Kenya. The findings of the project are envisaged to provide a basis for policy formulation by the government and stakeholders on sustainable resource management with regard to nutrient nitrogen for irrigated agriculture in the country. Findings resulting from this work will provide the basis for further research on the subject area besides availing knowledge for training.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

Low agricultural production leads to low incomes, poor nutrition, vulnerability to risk and threat and lack of empowerment. Land degradation and soil fertility depletion are considered the major threats to food security and natural resource conservation in sub-Saharan Africa. Investments in technology, policy and institutional reforms are needed to increase agricultural productivity, to ensure food security and sustained national economies (Bationo *et al*., 2007). Production of maize which is the staple food for over 90% of Kenya's population and mostly produced under rainfed agricultural systems has been declining at an alarming rate leading to food insecurity (Ketiem *et al*., 2008).

Kenya's blueprint development plan identifies agriculture as the mainstay of the country's economy that currently represents 24% of the gross domestic product (GDP) and accounting for 65% of Kenya's exports and 18% of the total formal employment (Vision 2030). The current Constitution of Kenya mandates the National Government to be in charge of policy development and the County Governments to implement the agricultural policies (Kenya, 2010). The first Medium Term Plan (MTP) identifies arid and semi-arid (ASAL) development projects as of the key flagship projects to be achieved through irrigation (Kenya, 2008). The MTP envisions that agricultural research and development will be enhanced through collaboration and linkages with emphasis laid on irrigation among other agricultural developments meant to improve on national food security. The developed technologies are to be relayed to farmers and other stakeholders through holistic approach in extension service provision.

Widtose (2010) defines irrigation as the artificial application of water to lands for the purpose of producing large and steady crop yields whenever the rainfall is insufficient to meet the full water requirements of crops. The author notes that about 25% of the earth's surface receives 250 mm or less of rainfall annually and can only be reclaimed using irrigation, while intensive crop production for areas receiving between 250 and 500 mm annual rainfall require irrigation and dry-farming.

The government of Kenya through the Ministry of Agriculture recognizes that irrigation projects are constrained with high costs of pumping water and maintenance of canals in the schemes managed by the National Irrigation Board (SAR, 2004). The policy document proposes to revitalize irrigation agriculture supported by the public and private sectors through a raft of recommendations that include enhanced stakeholder involvement, use of gravity-fed water systems, introduction of water saving technologies and reviewing and implementing irrigation and Drainage Policy among others. The development of canals and water harvesting through dams and pans is seen to facilitate farmer-led irrigation programmes and recovering the costs through water fees. It is estimated that intensified irrigation can increase agricultural productivity fourfold, depending on the crop, and incomes can be multiplied ten times (ASDS, 2010).

The National Soil and water Conservation Project (NS&WCP) of the Ministry of Agriculture intends to enhance land management and promote soil and water conservation through irrigation schemes, soil and water conservation projects, reclamation of dry and marsh lands, forest protection and riverbank protection (GoK, 2015). The Plan notes that irrigated agriculture in Kenya is carried out mainly in irrigation schemes and in large-scale irrigation of crops such as rice and coffee. Individual farmers have developed their own systems of irrigation especially for export crops such as coffee and horticulture. Large commercial farms account for 40% of the irrigated land, smallholder farmers 42% and the Government-managed schemes 18% (ASDS, 2010). This sector policy document reports that with a national average of 400 mm rainfall, the country should harvest and store adequate water for agriculture and other uses. Ground water resources to be exploited for agriculture need to be tested and quantified and that more land can be reclaimed for crop production by developing infrastructure in the ASALs.

2.2 Crop Evapotranspiration

The FAO Penman-Monteith equation (Allen *et al.,* 1998) was used to estimate reference evapotranspiration (ETo) for the experimental site thus:

$$ET_o = \{0.408\Delta (Rn - G) + \gamma\}\underline{\ 900\ }u_2(e_s - e_a)\underline{(\ T + 273)}.$$

$$+ \gamma(1 + 0.34u_2)$$

where:

ETo = reference evapotranspiration (mm day^{-1})
Rn = net radiation at the crop surface (MJ m^{-2} day^{-1})
G = soil heat flux density (MJ m^{-2} day^{-1})
T = mean daily air temperature at 2 m height (^{o}C)
u_2 = wind speed at 2 m height (m s^{-1})
e_s = saturation vapour pressure (kPa)

e_a = actual vapour pressure (kPa)

$e_s - e_a$ = saturation vapor pressure deficit

Δ = slope vapor pressure curve (kPa $^oC^{-1}$)

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

The FAO Penman-Monteith is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. It uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed (FAO, #56).

The other parameters were computed thus:

$$G = c_s \frac{T_i + T_{i-1}}{\Delta t} \Delta z$$

where:

G = soil heat flux (MJ m^{-2} day^{-1})
c_s = soil heat capacity (MJ m^{-3} $^oC^{-1}$)
T_i = air temperature at time I (^oC)
T_{i-1} =air temperature at time T_{i-1} (^oC)
Δz = length of time interval (day)
Δt = effective soil depth (m)

When assuming a constant soil heat capacity of 2.1 MJ m^{-3} $^oC^{-1}$ and an appropriate soil depth, the equation above was used to derive G for monthly periods thus:

$$G_{month,i} = 0.07(T_{month,i+1} - T_{month,\ i-1})$$

Or if $T_{month,i+1}$ is unknown,

$$G_{month,i} = 0.14(T_{month,i} - T_{month,\ i-1})$$

where:

$T_{month,i}$ = mean air temperature of month I (^oC)

$T_{month,i+1}$ = mean air temperature of next month (^oC)
$T_{month,\ i-1}$=mean air temperature of previous month (^oC)

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)}.$$

where:

u_2 =wind speed at 2m above ground surface (m s^{-1})
u_z =measured wind speed at z m above ground surface (m s^{-1})
z = height of measurement above ground surface (m)

The psychometric constant is given by

$$\gamma = \frac{c_p P}{\epsilon\lambda} = 0.665 \times 10^{-3}P$$

where:

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

c_p = specific heat at constant pressure, 1.013×10^{-3} (MJ kg^{-1} $^oC^{-1}$)
P = atmospheric pressure (kPa)
ϵ =ratio molecular weight of vapor/dry air 0.622
λ=latent heat of vaporization, 2.45 (MJ kg^{-1})

The mean daily air temperature (T_{mean}) was employed in the FAO Penman-Monteith equation to calculate the slope of the saturation vapor pressure curves (Δ) and the impact of mean air density (Pa) as the effect of temperature variations on the value of the climatic parameter is small in these cases. For standardization T_{mean} for 24-hour periods is defined as the mean of the daily maximum (T_{max}) and minimum (T_{min}) temperatures rather than as the average of the hourly temperature measurements.

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

The temperature is given in degree Celsius (^oC) or Fahrenheit (^oF)

The saturation vapor pressure values as a function of air temperature are non-linear and were expressed by:

$$e_o(T) = 0.6108 \exp\left(\frac{17.27T}{T + 273.3}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..11$$

where:

$e_o(T)$ = saturation vapor pressure at the air temperature (T)

T = air temperature (^oC)

exp(…) =2.7183(base natural logarithm) raised to the power (…)

Due to the non-linearity of the last equation, the mean saturation pressure was computed thus:

$$e_s = \frac{e_o(T_{max}) + e_o(T_{min}).}{2}$$

The slope of the relationship between the saturation vapour pressure and temperature were required to calculate the evapotranspiration thus:

$$\Delta=4098\ \ 0.6108\exp\ \ 17.27\ T\left(\frac{.T+237.3\ \ .}{(T + 237.3)^2}\right)$$

where:

Δ=slope of saturation vapor pressure curve at air temperature T (kPa $^oC^{-1}$)

T= air temperature (^oC)

exp[…] = 2.7183 (base natural logarithm) raised to the power […]

In the FAO Penman-Monteith equation, where Δ occurs in the numerator and denominator, the slope of the vapor pressure curve is calculated using the mean air temperature (Equation 10). As the dew-point temperature is the temperature to which the air needs to be cooled to make the air saturated, the actual vapor pressure (e_a) is the saturation vapor pressure at the dew-point temperature (T_{dew}), [^oC], or:

$$e_a = e_o(T_{dew}) = 0.6108 \exp\left(\frac{17.27T_{dew}}{T_{dew} + 237.3}\right)$$

2.3 Effects of irrigation application on yield and water and nitrogen use efficiencies

Limited irrigation results when water supplies are restricted and full crop water requirements or evapotranspiration (ET) cannot be met and changes in irrigation management practices can improve net returns under limited water supplies (Shanahan and Groeteke, 2011). The researchers add that the vegetative stage of corn is the least sensitive to water stress, and judiciously delaying the first irrigation may offer an opportunity to conserve water and maintain profitability. Growers may therefore delay the first irrigation as late as tasseling in years of lower evaporative demand provided soil water reserves are ample at planting and irrigation systems have the capacity to rapidly correct soil water deficits.

When irrigation water is applied, the soil mass expands, only to contract gradually as the water is lost through evaporation or transpiration and upward leaching results when water moves up to replace that removed by the roots, carrying with it some of the minerals dissolved from the lower soil layers (Widtose, 2010). The author adds that cultivation loosens the top soil permitting free exchange of atmospheric gases and the soil air which enables various physical, chemical and biological changes to occur. Since water causes changes in the soil to the depth to which it penetrates, then regulated irrigation can be a means of modifying soil properties for crop growth such as maize.

Irrigation efficiency is influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. It is important to properly design production practices to minimize the effects of low precipitation and high temperatures that characterize regions such as the Sudan savanna zone of West Africa (Kamara *et al*., 2009). Research by Xiying *et al*. (2005) indicated that water use efficiency of corn cultivars in China has improved over the years by about 30% due to crop improvement and agronomic management. The number of kernels per spike of maize, for instance, has increased from 350 in the 1980s to 450 currently while the water use efficiency was reported to be significantly higher for maize under mulch.

Jordan *et al*. (1990) defined water use efficiency (WUE) as a ratio of biomass accumulation, expressed as carbon dioxide assimilation (A), total crop biomass (B), or crop grain yield (G) to water consumed expressed as transpiration (T), evapotranspiration (ET), or total water input system. The time scale for defining water use can be instantaneous (i), daily (d), or seasonal (s) and expressed in the form WUE (G, ET, s) or WUE (A,T,i). The most commonly used definition of water use efficiency was given by Viets (1962) as the ratio of the weight produced (Y) to the evapotranspiration rate (ET). WUE = Y (kg ha^{-1})/ET (mm). Quite often the yield (Y) or dry matter produced is referred mainly to grain. Stanhill (1966) gave a more meaningful hydrological definition of WUE as the ratio between the volumes of water productively used to the volume of water potentially available for the process. Potential availability naturally includes the whole rainwater and the water already stored in the soil before sowing of the crop (Hedge, 1995). Agronomic practices for reducing evaporation from the soil surface and those for increasing water supply to plants are said to improve WUE (Gregory, 1988). For areas where potential evapotranspiration exceeds precipitation for the growing season crops depend heavily on stored soil moisture for their water requirements (Ash *et al.,* 1992).

Working on three hybrids (Babe, Pioneer 30P45 and Syngenta 6621) in Pakistan, Inamullah *et al.* (2011) found out that 1000 grain weight of 280.56 and 303.68g and a grain yield of 3281.3 and 3696 kg/ha, and a biological yield of 10889 and 11830 kg/ha and harvest indices of 30.1 and 31.42% were obtainable from higher levels of 240 and 300 kg-N ha^{-1}, respectively. These reviews indicate that effects of irrigation on water use efficiency and yield of drought tolerant maize is yet to be documented under Kenya semi-arid regions.

2.3 Effects of nitrogen fertilizer rates on yield and water use and nitrogen use efficiencies

Nitrogen use efficiency (NUE) is defined based on two components: recovery nitrogen, either in grain (RE_{NG}) or in total aboveground biomass (RE_{NT}) in the current crop or a part of the applied nitrogen N that is left behind (immobilized) in the soil and becomes available to subsequent crops (Ladha *et al.*, 2005). Several other derivatives based on economic, agronomic or physiological principles of NUE are used. Accurate NUE estimates are used to devise new management practices and to accurately estimate projected amounts of N needed to meet increasing global food demand. To measure or quantify NUE, the output is taken as the numerator and the input the denominator of the economic or biological yield. The biological yield can include either the total aboveground plant dry matter or total plant N whereas the economic yield includes either grain yield or total grain N.

The ratio of yield to N supply is commonly referred to as the agronomic efficiency of N (AE_N) computed thus (Ladha *et al*., 2005; Sharma *et al*., 2012):

$$AE_N = (Y_T - Y_0)/F_N = \Delta Y/\Delta N$$

where Y_T = grain yield (kg ha^{-1}) in treatments with total N (soil and fertilizer) or in fertilizer N plot (FN, kg ha^{-1}); Y_0 = crop yield (kg ha^{-1}) measured in a control treatment with no fertilizer rate of N application or with only a supply of soil N.

The ration of plant N to N supply is referred to as recovery efficiency of N, calculated thus:

$$RE_N = (U_T - U_0) = \Delta U/\Delta N, \text{ in kg kg}^{-1}$$

where U_T = plant N uptake measured in aboveground biomass (kg) in a plot that received N at the rate of F_N (kg ha^{-1}); U_0 = total N uptake without fertilizer N addition and with only supply of soil N (S_N).

The ration of yield to plant N is referred to as the physiological or internal efficiency of N (PEN), computed thus:

$$PE_N = (Y_T - Y_0)/(U_T - U_0) = \Delta Y/\Delta U$$

$$= [\text{kg grain increase } \{Y_F\} \text{ kg}^{-1} \text{ additional N taken up } \{U_F\}]$$

The AE_N is an integrated index of RE_N and PE_N. This is also referred to in economic terms as partial factor productivity (PFP_N) inputs relative to the use of all N sources (T_N), indicating soil N (S_N) and applied fertilizer F_N.

PFPN = Y_T/F_N, (kg product kg-1 N applied.

where Y_T – total grain yield (kg ha^{-1}) at a certain level of fertilizer N applied (F_N, kg ha-1).

Nitrogen recovery efficiency (RE_N) considers the capacity of the plant to acquire N, whereas physiological N-use efficiency (PE_N) considers the efficiency with which the plant uses acquired N to produce grain or total plant matter (Ladha *et al*., 2005). The authors reported that the average AE_N varies over a small range of 18 to 24 kg grain increase per kg applied N and is smallest in maize and largest in rice compared to wheat. In the same research, the PFP_N differed markedly among these three cereals though maize and rice had similar values of 62 to 70 compared to wheat with 44 kg grain kg^{-1} applied N. These large differences in PF_N indicate that maize and rice produced larger economic outputs compared to wheat in terms of the use of all N (soil and fertilizer) probably due to the differences in inherent N concentrations in these crops.

Nitrogen use efficiency (NUE) and/or fertilizer recovery in production systems can be calculated using many methods (Moll *et al*., 1982). The authors report that for fertilizer application rates ranging between 0 and 150 kg ha^{-1} for maize, the grain yield, N-content and N-uptake vary from 1000 to 2000 kg ha^{-1}, 2.0 to 2.3% and 20 to 46 kg ha^{-1}, respectively. In the same work, they reported that fertilizer recovery increased from 14.6 to 17.0%. To accurately compute the crop N content at particular growth stages when sampling is made at other time points requires two destructive plant harvests are done within the main growth period (Weih, 2014).

$$\mathrm{NUE} = N_y/N_p = U_N.E_{NY}.C_{NY}$$

The following has been proposed to compute N% derived by the plant (Davis *et al.*, 2003):

$$\text{\% plant N derived from the fertilizer} = [N_u - N_t]/[N_u - (N_f/n)]$$

where N_u = atom % ^{15}N in unfertilized plants; N_t = atom % ^{15}N in fertilized plots; Nf = atom % 15N in the fertilizer (e.g. 0.006%) and n = plant discrimination factor between ^{14}N and ^{15}N. if it is assumed that there is no discrimination between ^{14}N and ^{15}N, then $n = 1$.

Other methods of computing fertilizer N recovery have been suggested by various researchers as illustrated in the following formulae:

Difference method (Varvel *et al.*, 1997; Varvel and Peterson, 1990):

$$\mathrm{PFR} = [N_F - N_0]/R$$

where N_F is the total N uptake in corn from fertilized plots; N_0 the total N uptake from unfertilized plots; R the rate on N fertilizer applied and PFR the percent nitrogen recovery.

Isotopic Method (Depleted material, Sanchez *et al.*, 1987)

$$\mathrm{PFR} = [\mathrm{NF} \times (C - B)/D]/R$$

where N_F the total N uptake in corn from N fertilized plots; B the atom % ^{15}N of plat tissue from N fertilized plots; C the atom % ^{15}N of plant tissue from unfertilized N plots (0.366); D the depleted %^{15}N in applied N fertilizer and R the rate of applied ^{15}N-labeled fertilizer.

Isotopic Method (Enriched Material, Sanchez *et al.*, 1987)

$$F = (A_s - A_r)/(A_f - A_r)$$

where F = fraction of total N uptake derived from ^{15}N enriched fertilizer; A_s = atom % ^{15}N measured in harvested plant sample; A_f = atom % ^{15}N in enriched fertilizer; A_r = atom % 15N of the reference harvested plant material from non ^{15}N enriched fertilizer treatments.

Shearer and Legg (1975)

$$\Delta^{15}N = \frac{[\text{atom \% } ^{15}N \text{ (sample)} - \text{atom \% } ^{15}N \text{ (standard)}] \times 100}{\text{atom \% 15N (standard)}}$$

Hauck and Bremmer (1976)

$$\text{Percent nitrogen recovered} = \frac{100P(c - b)}{f(a - b)}$$

where P = total N in the plant part or soil in kg ha^{-1}; f = rate of ^{15}N fertilizer applied; a = atom percent ^{15}N in the labeled fertilizer; b = atom percent ^{15}N in the plant or soil receiving no ^{15}N; c = atom percent 15N in the plant part or soil that did receive ^{15}N.

Unlabeled N uptake = (total N uptake in grain and straw) – N rate (% recovery of ^{15}N in grain and straw).

Benincasa *et al*. (2006) noted that NUE of crops takes into account both plant N uptake efficiency which focuses on the recovery of fertilizer-N and the utilization efficiency of the absorbed N. They noted further that the fertilizer-N rate is the main factor affecting crop NUE for a given irrigation management and rainfall regime. Wood *et al*. (2004) estimated that 50 to 70% more cereal grain would be required by 2050 to feed 9.3 billion people. This would require increasing N fertilizer by the same (50 to 70%) magnitude. They observed that the projected requirements may even double since NUE generally declines with increased fertilizer use. Avoiding over-fertilization is the first and primary means to match a high use efficiency and economic return of fertilizer-N with limited environmental risks from nitrate leaching. Thus, the form and method of application of fertilizer-N also affects the nitrogen use efficiency particularly in the case of limited or abundant supply of N. However, the two recovery factors are required because soil-N and fertilizer-N may be differently available in space and time (Ladha *et al*., 2005).

In cultivated crops, the NUE is mainly based on the sole marketable dry weight (DW) yield or marketable fresh weight yield (MFWY) per kg of absorbed N (Thorup-Kristensen *et al*, 2003; Guohua *et al*., 2007). The problem is even more complex in vegetables for which the potential yield can be much different from the actual marketable yield (MY) because only part of the yield is of sufficient quality to be commercialized (Van Eerd, 2007). Sometimes the NUE is reported in terms of harvest index on DW basis and N (Schenk, 2006).

The global N consumption has increased much faster than that of phosphorus (P) and potassium (K) due to relatively low cost per unit of nutrient input, widespread availability, quick yield response of new crop cultivars, less dependence of legume-based rotations and elevation of nutrient status, particularly of P, because of more use in the last thirty years (Dobermann and Cessman, 2004; Ladha *et al*., 2005). At least half of the applied nitrogen fertilizer is removed by the harvested crops. Synthetic nitrogen fertilizer supplies approximately 45% of the total N input for global food production, the rest coming from biological nitrogen fixation (BNF), recycling of N from crop residues, animal manure, atmospheric deposition and irrigation through fertigation (Cessman *et al*., 2002; IFA, 2002). The report informs that half of the available N remains in the soil via crop residues or other parts of the environment (leaching, runoff and erosion), ammonia volatilization, denitrification and gaseous oxide emissions.

Work done in Zimbabwe and South Africa indicates that resource poor farmers often grow maize under poor soil fertility conditions that lead to unstable crop production, low incomes and food insecurity (Suzette and Toit, 2001). However, this would be reversed as shown by research done at the Research Farm of Islamic Azad University that revealed that varying nitrogen levels for maize can improve the performance of various crop attributes (Raouf and Reza, 2009). In this study, the maximum grain yield (7.76 ton ha^{-1}) was obtained in the plots with N 240 kg ha^{-1} and SC-404 cultivar while the minimum yield (5.12 ton ha^{-1}) was obtained in the plots with 0 kg N ha^{-1} and SC-301 cultivar. But in seasons with poor or medium water supplies, moderate fertilizer rates are known to be more effective than higher rates in years with better water supplies (Mikova *et al.*, 2013).

It was apparent there that work on nitrogen nutrient use efficiency and yield of drought tolerant maize in transitional environments needed to be done as was intended and done in this study. There was need to document research work on the effects of irrigation rates on drought tolerant maize on nutrient use efficiency and yield.

2.4. Interaction effects of irrigation and nitrogen fertilizer

It has been observed that the interaction of nitrogen fertilizer application with maize hybrids significantly affects the grain yield, biological yield and the harvest index (Inamullah *et al.*, 2011). The authors noted that yield can be increased to a greater extent provided high yielding hybrids are identified and planted at optimum sowing dates. For instance, sowing on 1st and 16th July gave significantly higher but at par grains ear^{-1} (562 and 556), 1000 grains weight (445 and 421 g), grain yield (9004 and 7813 kg ha-1) and biological yield (25055 and 23240 kg ha^{-1}) respectively. Hybrids sown on 16th July produced taller plant height (232 cm). Delayed sowing as on 30th July decreased grains ear^{-1} to 460, 1000 grains weight to 391 g, grain yield to 6060 kg ha^{-1}, biological yield to 15972 kg ha^{-1} and plant height to 185 cm.

While studying the on corn yield and nitrogen use efficiency, Gholamohoseini *et al.* (2013), found out that that the enhancement of applied N (0–450 kg N ha^{-1}) increased corn grain yield by 63% with high frequency irrigation and by 25% with low frequency irrigation when averaged over the two years of the trials. The authors found out that for the mean comparisons of N use efficiency in the N_{150} treatment, each kilogram of applied N led to the production of 19 and 14 kg grain ha^{-1} with high and low frequency irrigation, respectively. In contrast, in the N_{450} treatment, each kilogram of applied N resulted in the production of 8 and

5 kg grain ha^{-1} in the high and low frequency irrigation regimes, respectively. Finally, results showed that it is necessary to achieve equilibrium between applied water and N, especially in sandy soils, which will lead to a reduction in the indiscriminate application of nitrogen fertilizer that does not effectively increase the corn yield whereas it severely increases nitrate leaching loss.

Markovic *et al*. (2017) reported that grain yield of maize is mostly affected by amount of available water and nitrogen and correlated to yield components. The influence of all tested factors was significant ($P<0.05$) in both years of study. Specific study results were obtained in extremely wet year 2010 when irrigation water reduced grain yield and yield components (9.9; 8.8; 7.8 t ha^{-1}). Correlation analysis showed strong positive correlation between yield and cob weight ($r = 0.77$ (2010); $r = 0.84$ (2013)) as was confirmed with direct and indirect path analysis test for the study. This shows that nitrogen and water application had significant effects on the yield and yield components on the maize crop.

The interaction of nitrogen and irrigation is reported to have significant effects on grain and biomass yield of corn (Wang and Xing, 2017). The greatest yield-increasing potential in this study was obtained in MF treatment. At the same irrigation level, the grain yield increased and had a most significant correlation relation with the harvest index. The population physiological indices of maize were increased with irrigation amount and fertilizer level, except the harvest index, and the incentive of population physiological indices in irrigation was higher than nitrogen fertilization.

Productivity and resource-use efficiency in corn (*Zea mays* L.) are crucial issues in sustainable agriculture, especially in high-demand resource crops such as corn (Elvio and Rinaldi, 2007). The results of this study indicated a large yearly variability, mainly due to a rainfall event at the silking stage in the first year; a significant irrigation effect was observed for all the variables under study, except for plant population. Nitrogen rates affected grain yield $plant^{-1}$ and ear^{-1}, grain and biomass yield, HI, WUE, IWUE and NUE, with significant differences between non-fertilized and the two fertilized treatments (15 and 30 g (N) m^{-2}). Furthermore, deficit irrigation (50% of ETc) was to a large degree equal to 100% of the ETc irrigation regime. The authors reported that a significant interaction “N × I” was observed for grain yield and WUE and that the effect of nitrogen availability was amplified at the maximum irrigation water regime.

2.5 Production models with irrigation application and nitrogen fertilizer rates

Crop models can be important tools for predicting the production of maize in semi-arid Kenya (Ogola *et al.,* 2006). Scientists spend a great deal of time building, testing, comparing and revising models, and much journal space is dedicated in introducing, applying and interpreting these valuable tools: this makes models one of the principal instruments of modern science (Heuvelink *et al*., 2007). The application of techniques of simulation of cooling processes, for instance, has become an important and practical tool as it allows predicting with great approximation the response of the horticultural crops to the cooling process (Gary *et al*., 1998).

Understanding processes of maize growth and production of grain in high-yielding, irrigated conditions offers hope to understand yield potential in many other environments (Kiniry *et al*., 2003). The researchers investigated processes at the plant level, and attempted to simulate maize yields at the field and county levels in the high yielding region of the High Plains of Texas. In addition, they used the normalized difference vegetation index (NDVI) from satellite data of year 2000 to update leaf area index for yield simulation in three counties. In the field study, they measured maize leaf area index (LAI), the fraction of photosynthetically active radiation intercepted (FIPAR), and the harvest index (HI) in irrigated plots near Dumas, Texas. The light extinction coefficient (k) for Beers law was calculated with the FIPAR and the LAI. The radiation use efficiency (RUE) was determined with sequential measurements of the fraction of photosynthetically active radiation (PAR) intercepted and biomass harvests. The RUE was 3.98 g of above-ground biomass per MJ of intercepted PAR in 1999 and 3.41 in 2000 for three sampling dates prior to silking. These workers concluded that consistency in values of RUE, k, and HI in this study as compared with values reported in the literature will aid modelers simulating maize growth and grain yields in similar high-yielding, irrigated conditions.

There are two categories of many crop growth models often used: empirical statistical models which relate crop yields to climatic variables using methods such as regression analysis. These are locally calibrated, making extension to larger areas (or ‘porting’ to other regions) nearly impossible; process-based growth simulation models, on the other hand, simulate the physiological development, growth and yield of a crop on the basis of the interaction between environmental variables and growth physiological processes such as photosynthesis and respiration (Mo *et al*., 2005). These are capable of providing mechanical description of for spatial and temporal prediction. Operationally, yield can be predicted using remotely sensed data in three main ways: developing regression models, using the light use efficiency (Epilson Method) and developing process-based models that capture interactions between the SVAT (soil-vegetation-atmosphere transfer) and crop growth environment as measured by remote sensing instruments.

The light use efficiency method (Monteith, 1972) estimates net primary production (NPP) with remotely sensed data (Choudhary, 2001) and to predict crop yield (Seaquist *et al.*, 2003; Lobell *et al.*, 2003; Bastiaanssen and Ali, 2003). The challenge is that environmental factors greatly affect the results for different crop stages. Plummer (2000) suggested use of process-based models to trace processes of dry matter accumulation and final yield. Forcing a plant growth model with remotely sensed data provides a means to conduct site-specific modeling and allows crop water consumption and measurement of water use efficiency (WUE) to be modeled besides simulating crop yield (Mo *et al.*, 2005).

Work to predict maize growth and yield in variable climatic and water supply regimes showed that simulated biomass and grain yield of maize were close to the measured data in medium water-retentive sandy loam while for low retentive loamy soil, biomass was over-predicted for most of the water supply regimes (Arora and Gajri, 2000). The authors concluded that the maize grown in loose soils suffer more by soil related constraints rather than water stress but their prediction model was sufficient for the other soils under study.

Using the management-oriented cropping system model MODERATO, it was shown that grain yield variability between irrigation stands is quite large and may reach more than 2 Mg ha^{-1} for some specific years and configurations (Bergez and Nolleau, 2003). This variability depends on soil type, the flow rate, the amount of irrigation applied per irrigation cycle and the general strategy used to decide irrigation and other technical operations. The actual and simulated grain yields varied between 7.57 and 10.28 Mg ha^{-1}. The statistical analyses for seventeen year study of irrigation on monoculture maize yield and parameters with growth showed that 'N rate' had the most profound effect on the variability of maize yield at 72.03%.

Crop modeling work done in North China revealed a potential to increase grain yield of cereals such as wheat and maize when using irrigation compared to rain-fed conditions (Mo *et al*., 2005). The modeled evapotranspiration (ET) ranged from 350 to 520 mm and 140 to 350 mm for irrigated and rainfed conditions, respectively. The simulated grain based water use efficiency (WUE) of the maize crop varied from 350 to 520 mm and 11 to 19.26 kg/ha under irrigated and rainfed conditions, respectively. They noted that there is need to increase agricultural water use efficiency by either increasing the amount of food per unit of water consumed or reducing the amount of water consumed to produce the same amount of food. The crop yields reported for summer maize ranged from 5800 to 8600 and 1400 to 4800 kg ha^{-1} for irrigated and rainfed areas, respectively. The large gap between the irrigated and rainfed farms indicate that crop yield of maize can be greatly improved by using efficient irrigation methods and managing other resources better. Yields increased linearly with ET while maximum WUE and IWUE decreased with higher levels of irrigation water. Karam *et al*. (2003) found that grain and DM yield of maize are reduced by severity of water stress on the crop.

Shortage of irrigation water supplies motivates farmers to find ways to produce maize crop with less irrigation water, like using more efficient irrigation systems and changing from fully irrigated to deficit irrigated cropping systems (Ladha *et al*., 2005). Furrow irrigation is the most commonly used method used for irrigating row crops such as maize. Work done in Nigeria revealed using moisture regimes of 30, 40, 50, 60, 80 and 100% of the field capacity (FC) of the soil showed that the interaction of 80 kg N/ha with 60%, 80% and 100% FC significantly increased ($p < 0.01$) biomass yield and nitrogen uptake. In the study, the moisture regimes of 80% and 100% FC indicated that evapotranspiration from plants in the 80 kg N/ha was significantly greater ($p < 0.01$) than those in the 0 kg N/ha or 40 kg N/ha . Maize response to the applied nitrogen was influenced by availability of water in the soil. The authors concluded that it is important that fertilizer application to maize on Vertisols be done when soil water content is close to field capacity.

An increase in planting density has been shown to increase WUE of maize by 24% under irrigation but reduced WUE by 17% under rainfed conditions. The increase in WUE at high planting density under irrigated conditions was due to an increase in transpiration efficiency (TE) and a decrease in crop canopy while the decrease in WUE under rainfed conditions was as a result of the predominant decrease in transpiration efficiency at the University of Reading's Crops Research Unit (Ogola *et al*., 2013).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Site, Soils and Weather

The study was conducted in Embu West District one of the Sub-Counties of Embu County of Kenya (latitude: 03^o 30′ S, longitude: 37^o 30′ E, and altitude 1480 m above sea level). The climate is defined by two rain seasons that receives a total annual rainfall of between 1200 and 1500 mm in two rainy seasons, 'long rains' (March to June) and 'short rains' (Mid October to December). Mean monthly temperature ranges between 14 ^oC and 26.9 ^oC (Jaetzold and Smidt, 2006) but rainfall amounts have drastically dropped over the years to below 1000 mm per year, especially in the transitional areas where water application have become a necessity.

The Kenya Agricultural and Livestock Research Organization (KALRO-Embu) in conjunction with the local Kenya Meteorological Department provided the following data over the experimental period: rainfall amounts (mm), wind speed (km/day), daily maximum and mean temperatures (^oC), sunshine/radiation (MJm^{-2}) and relative humidity (%).

The soils are mainly Humic Nitisols (FAO, 1989) derived from basic volcanic rocks (Jaetzold and Schmidt, 2006). They are deep, well weathered with friable clay texture with moderate to high inherent fertility. Soils of the study area were samples and analyzed. The soil characteristics of the experimental site are described below:

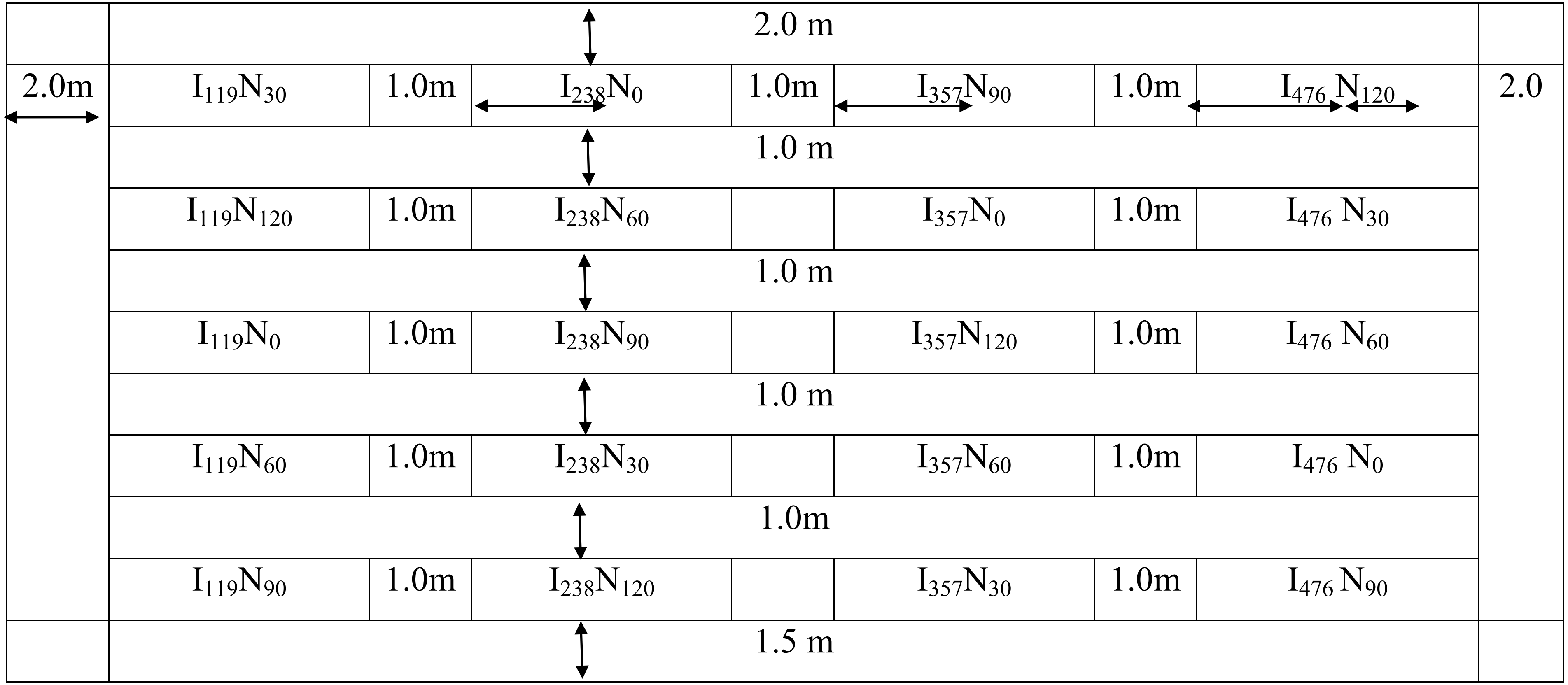
The soil was sandy loam with a bulk density of 1.3 g/cm^3, soil pH = 5.43 and hydraulic conductivity of 330 mm/h. The carbon content was 2.46% while the nitrogen, potassium and potassium levels were 0.29, 0.17 and 0.13%, respectively.

3.2 Experimental Design and Layout

The experiment was laid out in a randomized complete block design (RCBD) in a split-plot arrangement and the treatments allocated per block as shown in Figure 1. The irrigation levels (I) were allocated the main plots while the nitrogen fertilizer rates (N) formed the subplots. Since irrigation needed large plots for ease of management, they were randomly ordered, necessitating use of split-plot design. Each treatment plot measured 4 x 3 m^2. A 1.0 m footpath was left between the subplots and 1.5m spacing between blocks to minimize percolation effects of water and fertilizer between blocks. Nitrogen treatments were allocated to the subplots, which were 1.0 m apart. Each subplot had rows of DK8031 maize variety having six rows each at a spacing of 75 x 30 cm. This gave a population of 44,444 plants/ha. A total plot area of about 1,200 m^2 was used for the three blocks.

3.3 Crop Establishment and Management

Land was tilled to at least 20 cm depth and closed furrows made at 75 cm spacing using hand ridgers. Two seeds per hole of hybrid maize DK8031 variety at an intra-spacing of 30 cm were sown and thinned to one per pole a week after emergence, giving a population density of 44,444 plants per hectare. At sowing time a compound fertilizer 17:17:17 was used at a uniform rate of 30 kg-N/ha. The nitrogen fertilizer, calcium ammonium nitrate (CAN), was incrementally applied at rates of 0 kg/ha at sowing, 30 kg/ha two weeks after planting, 30 kg/ha six weeks after planting, 30 kg/ha ten weeks after planting and 30 kg-N/ha at fourteen weeks after planting. This gave cumulative nitrogen rates of 0, 30, 60, 90 and 120 kg-N/ha in combination with each of the irrigation levels. The fertilizer application coincided with the times of application of water for irrigation at a uniform rate of 119.05 mm, 238.10 mm, 357.15 mm and 476.2 mm (El-Hendaway *et al*., 2008). Two weed controls and other crop protection practices were carried out uniformly for all treatments. Manual weeding was first done four weeks after emergence and again at knee high in both seasons. Application of stalk borer dust was as per recommendations used in local agricultural practice.



	2.0 m							
2.0m	$I_{119}N_{30}$	1.0m	$I_{238}N_{0}$	1.0m	$I_{357}N_{90}$	1.0m	I_{476} N_{120}	2.0
	1.0 m							
	$I_{119}N_{120}$	1.0m	$I_{238}N_{60}$		$I_{357}N_{0}$	1.0m	I_{476} N_{30}	
	1.0 m							
	$I_{119}N_{0}$	1.0m	$I_{238}N_{90}$		$I_{357}N_{120}$	1.0m	I_{476} N_{60}	
	1.0 m							
	$I_{119}N_{60}$	1.0m	$I_{238}N_{30}$		$I_{357}N_{60}$	1.0m	I_{476} N_{0}	
	1.0m							
	$I_{119}N_{90}$	1.0m	$I_{238}N_{120}$		$I_{357}N_{30}$	1.0m	I_{476} N_{90}	
	1.5 m							

Figure 1. Layout plan of the experiment, showing treatment combinations for Block I (1.0 m between subplots, 2.0 m around the experimental layout and 1.5 m between blocks)

Legend: $I_{119}N_{60}$ – Irrigation level at 119 mm in combination with nitrogen at 60 kg-N/ha and similarly for other treatment combinations

3.4 Treatment combinations

Irrigation levels

I_{119}:- Irrigation (1190.5 m^3 ha^{-1} ≈ 119 mm) at sowing

I_{238}:- 119 mm applied two (2) weeks after sowing, making 238 mm total water applied

I_{357}:- 119 mm applied six (6) weeks after sowing, making 357 mm total water applied

I_{476}:- 119 mm applied ten (10) weeks after sowing, making 476 mm total water applied

Nitrogen nutrient levels (split applications)

N_0:- 0 kg-N/ha at sowing (Control)

N_{30}:- Compound fertilizer (17:17:17) applied at sowing at a rate of 30 Kg N/ha

N_{60}:- 30 kg-N/ha two weeks after sowing, totaling 60 kg-N/ha

N_{90}:- 30 kg-N/ha application of nitrogen 6 weeks after sowing, totaling 90 kg-N/ha

N_{120-}: 30 kg-N/ha application of nitrogen 10 weeks after sowing, totaling 120 kg-N/ha

The five nitrogen (N_0, N_{30}, N_{60}, N_{90} and N_{120}) rates were randomly combined with the four irrigation levels (I_{119}, I_{238}, I_{357} and I_{476} mm) to give a total of 20 treatment combinations per block.

3.5 Data Collection

3.5.1 Plant sampling

Growth and soil moisture data were progressively taken every two weeks and unique occurrences noted whenever observed. Three plants were randomly selected in each treatment plot and tagged for use throughout the growing period to measure various representative parameters. The plant parameters measured were plant height (cm) above ground surface; number of leaves per maize plant; time to 50% tasseling, milk stage and physiological maturity; leaf length and breadth, number of cobs per plant, number of lines per cob, length of cob, number of grains per cob, and test weight (100-grain weight).

3.5.2 Plant height

Plant height readings were taken every two weeks till physiological maturity was determined. The plant height was measured in centimeters (cm) using a steel tape measure with the help of a guide-pole as the plant grew taller with time of growth. The mean height of the three maize plants was then later calculated and recorded for each treatment plot.

3.5.3 Days to flowering (tasselling)

Observation for flowering or tassling was started once at least one plant in any one treatment plot was observed and recorded in terms of days after sowing (DAS) and the number of tasseled plants recorded every week thereafter until when more than half of the sub-plot plants had flowered. Graphs of tasseled plants against time of growth in DAS were plotted to determine the time taken for each sub-plot to attain 50% flowering.

3.5.4 Days to milk stage

The milk stage was determined when 50% of the plants had cobs with kernels beginning to yellow on the dough containing a milky white inner fluid of starch accumulation. Maize cobs observed to be similarly mature were counted over time to tally for this growth phase.

3.5.5 Physiological maturity

This growth phase is attained when all kernels have attained maximum dry weight and the starch has advanced completely to the kernel tip when a brown or black layer is present on the maize grain. Husks and many of the leaves are no longer green, though the stalk may be green. This latter observation was used to estimate time to 50% physiological maturity of the DK8031 maize variety. Opened cob whorls were tied to close them and avoid destruction by birds and other field pests.

3.5.6 Leaf area index (LAI)

The leaf area index was estimated using the leaf dimensions. The length of the collar leaf was measured using a steel tape and recorded in cm for all the sampled plants in each treatment plot. The widest part of the same leaf was measured and recorded as the leaf breadth. The means of these two parameters were used for analysis to represent the leave length and breadth, respectively. The LAI was then computed thus:

$$\text{LAI} = 0.75 \times \text{Leaf breath} \times \text{Leaf Length}$$

3.5.7 Biomass and grain yield

At harvest the three plants used for growth parameter measurements were cut at ground level after counting the number of leaves. The maize cobs were then removed together with the grains and sun dried to constant mass before shelling to obtain the grains, which were then dried and weighed. The difference between the total dry cob weight and the dry grains was taken to be the weight of the cob residue.

The dry cobs from the sampled plants from each treatment plot were shelled separately and the mean of their total grain weight recorded for the respective plots. Out of these grains the 100-seed weight was determined for each sub-plot.

Three plant samples from 0.03 m^2 were harvested and dried at 60 ^oC overnight to constant dry weight. The number of plants ha^{-1}, lines/cob and cobs/plant were determined. The aboveground dry matter, in kg ha^{-1}, at harvest was calculated after the residue plant was oven dried to constant weight at 60 ^oC (Eq. 1). In all biomass measurement cases, only the above-ground-biomass was be taken.

Biomass at harvest = mass of residue plant + mass of cobs + mass of grains ………… 1

3.5.8 Seasonal evapotranspiration

Seasonal crop evapotranspiration was computed using the water balance equation below then used to calculate water use efficiency in the next section (Sharma *et al*., 2015).

$$ET = P + I - D - R \pm \Delta S \quad \ldots\ldots 2$$

where: ET is the crop evapotranspiration, P is the precipitation (rainfall amount for the research area), I is the irrigation application, D is the capillary rise or loss due to deep drainage, R is the runoff loss (mm) and ΔS is the change in soil moisture storage. Since the furrow irrigation used did not reach 50 mm depth and the water table was deep and unaffected for the soils, then D and R were assumed negligible and therefore not factored in the equation.

3.5.9 Water use efficiency

Water use efficiencies were calculated for the grain and total biomass using the equations below:

WUE_g = Grain yield (kg/ha)/ET (mm) …………………………………………… 3

WUE_b = Plant aboveground biomass (kg/ha)/ET (mm) ……………………….. 4

where WUE_g and WUE_b are the water use efficiency of the grain yield and the total dry biomass in kg/ha/mm, respectively.

3.5.10 Partial factor and agronomic efficiencies

The commonly used nitrogen use efficiency is the partial factor productivity (PFP) which compares the grain (kg-grain/ha) or biomass (kg-DM/ha) produced by a crop to the applied nitrogen (kg-N/ha). The agronomic efficiency of nitrogen (AE_N) on the other hand looks at the change in yield (grain or biomass) per unit applied nitrogen fertilizer (Ladha *et al.*, 2005).

PFP_G = Grain yield (kg/ha)/(kg-N/ha)……………………………………………………..5

PFP_B = Biomass yield (kg/ha)/applied N (kg/ha)……………………………………..…..6

AE_{GN} = Change in grain yield (kg/ha)/applied fertilizer-N (kg/ha) = $(Y_G - Y_{G0})/N$ …….7
where Y_G and Y_{G0} are the grain yield values at N and no N fertilizer rates

AEB_N = Change in biomass yield (kg/ha)/applied fertilizer-N = $(Y_B - Y_0)/N$ …..………8

3.5.11 Soil water content measurement

Soil water content was monitored before each irrigation event starting at sowing and every two weeks after sowing within soil depths of 50 cm. Soil samples were taken at random positions in each of the treatment plots. Soil water content was determined by the gravimetric method (oven dry basis). The values were converted to a percentage volumetric basis by multiplying them by the bulk density of the soil of the respective layer. The equivalent depth of plant available water (mm) was estimated by the following equation (Marshall *et al.*, 1996):

$$De = \frac{Vc}{D} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

where De is equivalent water depth (mm), Vc is the volumetric water content (%), and D is the soil depth (mm).

3.5.12 Grain yield

After physiological maturity, the three marked plants from each plot were harvested and measured for weight of spikes per plant, number of grains per cob and weight of grain per plant. Grain yield was determined by hand harvesting an area of two rows 4.0 m in length, each on a split plot basis. Grain samples were collected from the yield samples for the determination of water content. Corn yield was adjusted to water content of 15.5%.

3.5.13 Harvest index

Harvest index (HI) was calculated according to the following formula:

HI (%) = [Grain (harvestable) yield / Biological (total dry matter) yield] x 100 ………6

3.5.14 Irrigation water use efficiency

Irrigation water use efficiency (IWUE) in kgm^{-3} was calculated as:

IWUE = (GY/I)100 ……………………………………………………………………7

where GY is grain yield (kg ha^{-1}) from a given irrigation treatment and nitrogen nutrient treatment, I is the amount of applied irrigation water (mm) for each irrigation application.

3.5.15 Nitrogen use efficiency

Nitrogen use efficiency (NUE) in kgm^{-3} was calculated as:

NUE = (GY/N)100 ……………………………………………………………………8

where GY is grain yield (kg ha^{-1}) from a given irrigation treatment and nitrogen nutrient treatment, I is the amount of applied irrigation water (mm) for each irrigation application.

3.6 Analysis of Data

Data collected were subjected to analysis of variance (ANOVA) using the GLM of SAS computer package (1997). Regression and correlation analyses were carried out and separation of means done using Fisher's method. The model for yield of hybrid maize used in the regression analysis was:

$Y_{ijk} = \bar{u} + \alpha_i + \beta_j + \beta_{ij} + \gamma_k + (\beta\gamma)_{jk} + \varepsilon_{ijk},$ ………………………………….. 9

(i=1,2,3; j=1,2,3,4 and k=1,2,3)

where Y_{ijk}= Total yield per treatment; $\bar{u}$= overall mean; α_i = ith blocking effect on yield; β_j= jth irrigation level effect on yield; β_{ij} = irrigation level error [Error (a)]; γ_k= kth nitrogen fertilizer level effect on yield; $(\beta\gamma)_{jk}$ = interactive effect of the jth irrigation level and the kth fertilizer rate on yield; ε_{ijk} = fertilizer level error.

Fisher's test for least significant difference (LSD at $P \leq 0.05$) was used to separate means of study factors where interactions for seasonal ET, grain-based nitrogen use efficiency (NUE$_g$) and biomass-based water use efficiency (WUE$_b$) were observed.

CHAPTER FOUR

RESULTS

4.1 Weather and Growth Degree Days

4.1.1 Weather

Appendix I gives a summary of the weather conditions at the experimental site as obtained from the Kenya Meteorological Department, Embu which was about 500m away from the experimental site. The experiment was conducted in two seasons in the 2012 to 2013 years. Season I (SI) ran from 19th April to 29th September 2012 and Season II (SII) from 13th October 2012 to 9th March 2013. This gave growing periods of 139 and 129 days for the two seasons, respectively. The seasonal rains were lower in SI which received 542.4 mm compared to S II which received 780.0 mm. The mean temperatures were 23.5 °C in Season I and 26.3°C in Season II, respectively. The crop evapotranspiration (ET_c) computed was 852.4 and 928.0 mm in the two seasons, respectively.

The wind run varied from 45.9 to 97.2 km/day and 102.3 to 156.4 km/day in SI and SII, respectively. The mean relative humidity (RH) ranged from 62.0 to 71.5% in Season I and 51.5 to 69.0% in season II, respectively. Therefore, the April to September 2012 season (SI) had less rain by 70.9 mm, lower mean temperature by 2.8 °C, slower winds by 43.1 to 59.2 km/day than the October 2012 to March 2013 season (SII) (Appendix I).

For this reason, the SI crop yields were lower than for the SII crop. Solar radiation (Rad.) for SI was also less than that of SII. Therefore, the crop took 139 days to physiologically mature in the cooler Season I compared to Season II maize crop which took 129 days to physiological maturity. The faster wind speeds influenced crop evapotranspiration (ET_c) in SII crop by 79.6 mm above that of SI crop.

4.1.2 Growth Degree Days of DK8031 Maize

The four developmental stages considered here were the time to 50% tasseling, 50% milk stage, 50% physiological maturity and biological maturity (period to harvest time). The time to 50% milk stage (R3) is a developmental stage that is reached when the kernels are in the dough stage, way after the blister stage (R2) exhibited by the forming grains. The tasseling stage (VT) is considered growth stage when the maize generally has eight leaves that have fully emerged and the tassel is beginning to form. The bottom-most branch of the tassel is by then completely visible but the silk has not emerged. The time to physiological maturity (stage R6) is when the milk line is no longer evident and a black layer has formed at the tip of the maize grains in the cob. At this time the grain has attained its maximum weight.

Table 1. Growth degree days of DK8031 maize grown in Embu (2012 – 2013)

	50% tasseling		50% Milk stage		50% Physiological Maturity		Biological (harvest) Maturity	
Season	No. Days	GDD	No. Days	GDD	No. Days	GDD	No. Days	GDD
SI	73	673	107	902	140	1173	164	1402
SII	70	688	100	974	129	1385	148	1481

The growth degree days (GDD), also called growth degree units (GDU) or heat units (HU), for the DK8031 maize increased with time of growth and development of the crop (Table 1). The GDD was measured in ^{o}C, using the collected weather data, used a base temperature of 10 ^{o}C (Gheysari *et al*., 2009). The Season I crop took 165 days to accumulate 1173 heat units by the time it attained physiological maturity. On the other hand, Season II crop needed only 148 days to accumulate 1385 heat units by the time it was physiologically mature. This was in spite of the fact that the Season I crop had taken longer to mature. This variation was attributed to the lower ambient temperatures recorded in April – September (Season I in 19th April to 29th September, 2012) that apparently slowed down the rate of crop growth. This delayed growth in all the stages of development which caused lower grain and biomass yields in Season I compared to the yields of Season II (13th October 2012 to 9th March, 2013). The Season II crop completed tasseling (VT) and milk stage (R3) earlier by three and seven days compared to the Season I crop. The cumulative GDUs by the time of tasseling and milk stages were 688 and 673 and 974 and 902 for the Season I and Season II, respectively. This reveals that the accumulation of GDD was slower in Season I compared to the Season II crop. This resulted in delayed maturity rates, leading to lower crop performance as presented in the subsequent sections of this chapter.

The October to March (Season II) had higher temperatures and thus GDD of 1481, that is, 79 HU's more than the April - September Season (I) by the time of harvest. Season II also had a higher rainfall by 73 mm over Season I. For these reasons, despite taking a period of 16 days shorter, (148 days), the SII crop had higher grain yields amounting to 3,978.5kg/ha (7.17%) than the SI crop with 3,693.2 kg/ha. It can be deduced that maize variety DK8031 can produce higher grain yields under a shorter 130 days to physiological maturity with 1385 heat units and 1,079 mm of incident water use during the October – March season.

4.2 Effects of irrigation on yields, water use efficiency and nitrogen use efficiency

4.2.1 Effects of irrigation on grain yield

The results revealed that irrigation treatments had significant effects on the grain yield of DK8031 maize variety in Seasons I and II (Table 2). The irrigation application level of 476.2 mm produced the greatest grain yields of 4,100 and 4,231 kg/ha in Season I and Season II, respectively. It was noted that the 119.05 mm irrigation treatment resulted in the least grain yields of 3,539 and 3,317 kg/ha in both seasons at $P \leq 0.05$, respectively. It was observed that the yields in Season II were relatively higher compared to those of Season I. This variation was attributed to the higher rainfall amount, it's better distribution and higher HU's in Season II than Season I. The better rains in Season II (780.0 mm) was well distributed in first the three months of the season that enabled better crop establishment leading to better utilization of the available moisture. Irrigation water applied after this season was thus important in post florescence stages such as grain filling compared to the Season I which received 70.4 mm less rainfall that was poorly distributed (Appendix I). The Season II rainfall thus encouraged better translocation of nutrients and assimilates to the grain, resulting in higher grain yields compared to Season I crop (Table 2).

Table 2. Effect of Irrigation and Nitrogen rate on grain yield, 100-grain weight and biomass yield of DK8031 maize variety grown at the University of Embu Farm (April – September, 2012 [SI] and October 2012 – March 2013 [SII] seasons)

	Season I				**Season II**			
Factor	Grain yield (kg/ha)	100-Grain weight	Biomass Yield (kg/ha)	Harvest index (%)	Grain yield (kg/ha)	100-Grain weight	Biomass Yield (kg/ha)	Harvest index (%)
Irrigation								
I_{119}	3539b	32.0b	5991b	37.7a	3317b	33.0b	9600c	57.7b
I_{238}	3606b	34.2a	6588ab	37.6a	4119a	34.2ab	11933b	57.0b
I_{357}	3639ab	34.4a	6888ab	33,4b	4231a	35.0ab	12417ab	63.7a
I_{476}	4100a	34.9a	7737a	32.6b	4246a	35.7a	13250a	65.6a
LSD	461	1.82	1583	3.75	301	2.25	1238	3.89
Nitrogen								
N_0	2493c	31.0d	4557c	34.9a	3575b	32.6c	10,000c	55.7c
N_{30}	3687b	32.7cd	6085bc	37.1a	3857b	33.4c	10271bc	59.6bc
N_{60}	3833b	34.1bc	7404ab	36.0a	3963b	34.5bc	11645b	62.1ab
N_{90}	4097ab	35.2ab	7582ab	35.2a	4227a	35.3ab	13500a	62.2ab
N_{120}	4493a	36.7a	8416a	33.3a	4369a	36.7a	13583a	65.4a
LDS	516	2.10	1770	4.18	336	2.52	1384	4.34

Values in the same column followed by the same letters under irrigation level and nitrogen treatments are not significantly different from each other using LSD ($P \leq 0.05$)

Legend: Season I - April to September, 2012; Season II - October 2012 to March 2013; I_{119} = 119.05mm, I_{238} = 238.1 mm, I_{357} = 357.15 mm, I_{474} = 476.2 mm; N_0 = 0 kg-N/ha, N_{30} = 30 kg-N/ha, N_{60} = 60 kg-N/ha, N_{90} = 90 kg-N/ha; N_{120} = 120 kg-N/ha

4.2.2 Effects of irrigation on 100-grain weight

The findings revealed that the 100-grain weight of the maize was significantly affected by irrigation treatments (Table 2). The 119.0 mm supplemental irrigation water produced the lightest grain weights of 32.0 and 33.0g for every 100 dry grains compared to the other irrigation treatments in Season I and Season II, respectively (Table 2). However, in SII, the grain weights of the 119.05 mm supplemental irrigation were not significantly different from those of the 230.0 and 357.0 mm supplemental irrigation treatments. In both seasons the 238, 357 and 476 mm supplemental irrigation water applied produced the similar grain weights. The test weight from the 476.0 mm irrigation was significantly heavier compared to the 119.0 mm treatment only in the October – March season. The other irrigation treatments produced maize grains with weights that were not significantly different from the 476.2 mm irrigation treatment. These results suggest that application of higher levels if irrigation water (I_{357} & I_{476}) were better supplementary irrigations for the natural rains and facilitated higher translocation of N assimilates from the leaves to the grain (sink), during the maturity phase of growth, resulting in heavier grains.

The findings implied that the rainfall in the two seasons (542.3 and 780.0 mm) is not sufficient for optimal grain production and such moisture stress can be alleviated by application of supplementary irrigation. It was thus concluded that the October – March season with higher and better distributed rainfall gave higher biomass and grain yields as well as signifying the need for supplement rainfall with irrigation to optimize on maize productivity in Embu.

4.2.3 Effects of irrigation on biomass yield

It was observed that irrigation treatments of caused significant differences in the dry aboveground biomass yields of the DK8031 maize variety (Table 2). The I_{476} irrigation treatment (476.2 mm of applied water + 542.4 rain = 1,018.4 mm), gave the highest biomass yield of 7,737 and 13,250 kg/ha in Season I and Season II, respectively, but it's yield was not significantly different from that of I_{357}. The 119.05 mm applied irrigation water produced the least dry matter yield of the maize crop of 5,991 and 9,600 kg/ha in both Seasons. The dry matter (DM) production by the other irrigation treatments was statistically similar ($P \leq 0.05$), and ranged from 5,991 to 6,888 and from 9,600 to 12,417 kg-DM/ha in seasons I and II, respectively.

It was noted that the biomass yield generally increased with higher irrigation applications in the both seasons, being higher in Season II than in Season I. In the October - September (II), total seasonal water received was 731.85 (with I_{119}), 850.9 (with I_{238}); 969.95 (with I_{357}) and 1,098.8 mm (with I_{476}), respectively, where 780.0 mm rain was received in each of the plots. The relatively higher DM yields in Season II was also attributed to the higher solar radiation ranging from 18.76 to 25.19 MJ/m^2, compared to 13.57 to 18.57 MJ/m^2 in SII, that would have enhanced photosynthesis; and higher rains that were well distributed (Appendix 1) encouraging better crop establishment and higher (by 75.6mm) crop evapotranspiration (ET_c) of 928 mm (Table 3) of Season II. The mean dry matter yield was 6,892 and 11,800 kg/ha in Season I and Season II, respectively. Season II thus produced 71.2% more dry matter yield than Season I, indicating that additional rainfall of 70 mm and thus, extra ET_C of 75.6 mm resulted in an additional 71.2% DM of 11.8 t/ha from the SII. These results show the significance and impact of rainfall and solar radiation variability on crop production.

The harvest index (HI) varied significantly among irrigation levels in both seasons (Table 2). In the cooler and drier April to September 2012 the HI index decreased with increasing supplemental irrigation but increased with increased levels of applied water, varying from 37.7% under the 119.0 mm to 32.6% under the 476.2 mm supplemental irrigation. In in the first season, the 119 and 238.0 mm water above the rains resulted in similar HI values. Extra water added was not beneficial for HI in this season, leading to low HI values. In the warmer and wet season (October 2012 to March 2013) the HI increased significantly beyond 357 mm added water, ranging from 57.7% under 119.0 mm to 65.6 mm of supplemental irrigation (Table 2). These differences in HI can be attributed to the amount and distribution of rainfall in the two seasons Therefore, there is an inverse relationship between biomass yields (resulting from increased seasonal water availability) and harvest index in Season I but a positive relation observed for season II.

4.2.4 Effects of irrigation on grain based water use efficiency

The grain based water use efficiency (WUE_g) of the dryland maize crop differed significantly between the irrigation treatments in both seasons (Table 3). The 119.05 mm irrigation water treatment resulted in the highest WUE_g of 5.3 and 4.9 kg/ha-mm in Season I and Season II, compared to the other irrigation treatments. The 357.15 and 476.20 mm and 238.10 and 357.15 mm irrigation treatments resulted in statistically similar grain-based water use efficiency in Season I and Season II, respectively. In both seasons, the 476.20 mm irrigation water gave the least WUEg, implying that more water availed through irrigation reduced the water use efficiency. This means that the additional irrigation water did not result in proportional utilization of water per grain or dry matter produced and the relationship was thus nonlinear. Increased irrigation water thus contributed to increased component of E in ET for the maize crop to transpire due to increased metabolic activity.

4.2.5 Effects of irrigation on biomass-based water use efficiency

The results in Table 3 reveal that the biomass based water use efficiency (WUE_b) varied significantly between the irrigation. The WUE_b was highest under the 119.05 mm irrigation treatments in both seasons being 10.2 and 13.7 kg/ha-mm in Season I and Season II, respectively. On the other hand, the 476.2 mm irrigation treatment resulted in the least WUE_b of 3.9 and 3.7 kg/ha-mm in Season I and Season II, respectively, as compared to the other irrigation treatments. The crop evapotranspiration increased with additional irrigation water and since the biomass yield did not increase proportionately with extra irrigation, the DM based water use efficiency was higher for lower irrigation treatments (Table 3). This implied that the maize crop utilized total water more efficiently at lower application levels.

Table 3. Effect of irrigation and nitrogen on crop evapotranspiration and water use efficiency of DK8031 maize grown at Embu (April 2012 to March 2013)

	Season I			**Season II**		
Factor	ET_c (mm)	WUE_g (Kg/ha-mm)	WUE_b (Kg/ha-mm)	ET_c (mm)	WUE_g (Kg/ha-mm)	WUE_b (Kg/ha-mm)
I_{119}	675.5d	5.3a	10.2a	749.3d	4.9a	13.7a
I_{238}	795.0c	4.6b	7.5b	870.2c	4.4b	13.4a
I_{357}	912.3b	4.0c	7.5b	987.1b	4.3b	12.8a
I_{476}	1027.0a	3.9c	7.2b	1105.5a	3.7c	11.2b
LSD ($P \leq 0.05$)	3.92	0.56	1.90	3.68	0.354	1.40
N_0	858.1a	3.6c	5.4c	929.9a	3.9b	10.9c
N_{30}	854.3ab	4.4b	7.1bc	929.7a	4.1b	11.2bc
N_{60}	852.0b	4.6b	8.8ab	928.4ab	4.2b	12.6b
N_{90}	851.9b	4.8ab	9.0ab	927.0ab	4.6a	14.6a
N_{120}	846.0c	5.4a	10.2a	925.1b	4.7a	14.7a
LSD ($P \leq 0.05$)	4.38	0.63	2.13	4.12	0.40	1.57
I x N	NS	0.0001	NS	NS	NS	NS

Values followed by the same letters in the same column under irrigation and nitrogen rates are not significantly different from each other ($P \leq 0.05$)
Legend: Season I - April to September, 2012; Season II - October 2012 to March 2013; I_{119} = 119.05mm, I_{238} = 238.1 mm, I_{357} = 357.15 mm, I_{476} = 476.0 mm; N_0 = 0 kg-N/ha, N_{30} = 30 kg-N/ha, N_{60} = 60 kg-N/ha, N_{90} = 90 kg-N/ha; N_{120} = 120 kg-N/ha

4.2.6 Effects of irrigation on grain-based nitrogen use efficiency

The grain-based nitrogen use efficiency (NUE_g) of the DK8031 maize crop was observed to vary significantly among the irrigation treatments in both seasons (Table 4). The NUE_g was greatest under the 476.2 mm applied irrigation water in both seasons, where it was 64.4 and 69.5 Kg-grain/Kg-N in Season I and Season II, respectively. On the other hand, the 119.05, 238.10 and 357.15 mm irrigation treatments produced the least NUE_g of 53.0 and 52.8 Kg-grain/Kg-N, respectively, that was not significantly different each other. The common observation was that the NUE_g and NUE_b increased with increasing irrigation water applied in both seasons and was better in Season II compared to Season I. More water availability in known to enhance solubility of nitrogen based fertilizers thereby making them available for plant uptake and hence utilization in synthesis of plant dry matter. This promoted assimilation of the nutrient that resulted in better vegetative growth that led to enhanced photosynthesis. The photosynthates were then readily translocated to the DM and seed grain sinks with increasing rates of nitrogen rates. This explains why the NUEg increased significantly with higher rates of nitrogen fertilizer.

Table 4. Effect of irrigation and nitrogen rates on grain and biomass nitrogen use efficiency (PFP) of DK8031 maize variety grown in Embu (April 2012 to March 2013)

	Season I		**Season II**	
Factor	NUE_g (Kg-grain/Kg-N)	NUE_b (Kg grain/Kg-N)	NUE_g (Kg-DM/Kg-N)	NUE_b (Kg DM/Kg-N
I_{119}	53.0b	83.6b	52.8b	158.5c
I_{238}	54.8b	100.6ab	67.2a	185.8b
I_{357}	55.1b	107.3ab	69.2a	197.0ab
I_{476}	64.4a	121.5a	69.5a	210.2a
LSD ($P \leq 0.05$)	10.12	34.80	4.86	25.34
N_0	63.1a	151.9a	119.2a	333.3a
N_{30}	61.5b	101.4b	64.3b	171.2b
N_{60}	51.1c	100.6b	51.5c	155.3b
N_{90}	45.5c	82.3b	47.0c	150.9bc
N_{120}	42.8c	80.2b	41.6d	128.6c
LSD ($P \leq 0.05$)	9.05	31.13	4.35	22.66
I x N	NS	NS	0.0007	NS

Values followed by the same letters for each column under irrigation level and nitrogen rates are not significantly different from each other at $P \leq 0.05$.
Legend: Season I - April to September, 2012; Season II - October 2012 to March 2013; I_{119} = 119.05mm, I_{238} = 238.1 mm, I_{357} = 357.15 mm, I_{476} = 476.0 mm; N_0 = 0 kg-N/ha, N_{30} = 30 kg-N/ha, N_{60} = 60 kg-N/ha, N_{90} = 90 kg-N/ha; N_{120} = 120 kg-N/ha

4.2.7 Effects of irrigation on biomass-based nitrogen use efficiency

The findings presented in Table 4 reveal that the biomass-based nitrogen use efficiencies (NUE_b) of the DK8031 maize variety were significantly different among the applied irrigation water treatments in both seasons. The rainfall amounts were 542.4 and 780.0 mm in the April 2012 to September 2012 and October 2012 to March 2013, respectively (Appendix I). Only the supplemental irrigation water is reflected in the following presentation and need to be understood to be above the seasonal rains. Therefore, the total water available to the maize crop then was: 661.90, 780.50, 899.55 and 1,018.60 mm in Season I and 731.85, 850.90, 969.95 and 1,089.00 mm in Season II.

The 476.2, 357.15 and 238.0 mm irrigation treatments resulted in the greatest NUE_b of 121.5, 107.3 and 100.6 kg-DM/kg-N ($P \leq 0.05$) in Season I that were not significantly different. However, the latter two irrigation treatments were not significantly different from the 119.05 mm irrigation treatment (Table 4). In Season II, the 476.20 mm applied water resulted in the same NUE_b of 210.2 and 197.0 kg-DM/Kg-N, respectively. The 357.15 and 230.10 mm supplemental irrigation produced NUE_b that were statistically similar in this second season. The 119.05 mm applied water produced the least NUE_b of 158.5 kg-DM/kg-N in Season II, differing significantly from the other applied water treatments. The other irrigation treatments had nitrogen use efficiencies between the 119 and 476 mm irrigation treatments and results were not significantly different from each other. This means that irrigation applied to supplement natural rains at 357.15 mm would be sufficient and any extra application of water may not be economical under the agro-climatic conditions of Embu County.

4.3 Effects of nitrogen on yield, water and nitrogen use efficiency

4.3.1 Effects of nitrogen on grain yield and harvest index

The results revealed that increase in nitrogen (N) application from 0 to 120 kg/ha resulted in significant differences in grain yield of maize in both seasons (Table 1). It was noted that the 120 kg-N/ha treatments resulted in significantly greater grain yield of maize compared to the 0, 30 and 60 kg/ha nitrogen rates in both seasons. The highest grain yields were 4,493 and 4,369 kg/ha in Season I and Season II, respectively. However, these grain yields were not significantly different from the 90 kg-N/ha nitrogen treatments in both seasons (Table 2). The results also showed that the 0 kg-N/ha treatments (control) produced the least grain yields of maize in both seasons compared to the other nitrogen treatments. But these yields were comparable to those of the 30 and 60 kg-N/ha treatments in Season II but not in Season I. In both seasons, the grain yields due to the 30 and 60 kg-N/ha treatments were not significantly different from each other.

These findings implied that at least 90 kg nitrogen per hectare produced highest grain yield production by DK8031 maize variety grown in Embu County. Nitrogen nutrient is used by the crop in vegetative growth thereby increasing chance to trap more photosynthetically active radiation (PAR) that leads to greater assimilate, biomass and grain formation. This then was readily translocated to the grain sink during reproductive phase leading to better grain filling and ultimately higher grain yields. Farmers in Embu should therefore apply at least 90 kg N/ha to harvest higher grain yields over 4.0 t/ha from DK8031 maize (Table 2).

The effect of nitrogen rates on harvest index of the maize in the April to September 2012 season was not significant, ranging from 33.3 to 37.1% (Table 2). In the October 2012 to March 2013 season, the HI varied significantly among the nitrogen rates applied. The HI in this season increased with increasing N rates from 55.7% under zero N to 65.4% under 120 kg-N/ha of fertilizer. The HI values were not significantly different with N rates of 60 kg-N/ha and above. The zero and 30 kg-N/ha rates resulted in the lowest HI in this second season (Table 2).

4.3.2 Effects of nitrogen on 100-grain yield

Increase in N application rates from 0 to 120 kg/ha was observed to increase 100 grain weight (test weight) (Table 2). The 120 and 90 kg-N/ha nitrogen rate treatment produced the heaviest ($P < 0.05$) 100-grain weights of 35.2 to 36.7g respectively compared to the other treatments in both seasons. Results also showed that the control nitrogen treatments resulted in the lightest grain weights in both seasons, being 31.0 and 32.6 g per 100 grains although they were not significantly different from those of the 60 kg-N/ha nitrogen treatments in both seasons. The 100-grain weights of the other treatments lay in between these two N treatments in both seasons (Table 2).

Generally, it was observed that the 100-grain weights increased with increasing N rates (Table 2). This meant that higher rates of nutrient nitrogen gave better crop growth that led to increased carboxylation and later the assimilates were partitioned to grain during grain filling resulting in increasing grain weights resulting from higher nitrogen rates. Maize growers whose objective is to harvest grains can thus improve their grain weights by applying nitrogen rates of between 90 and 120 kg-N/ha.

4.3.3 Effects of nitrogen on biomass yield

The aboveground biomass production of the dryland hybrid maize differed significantly among the nitrogen rate treatments in both seasons (Table 2). The 120 and 90 kg-N/ha rates resulted in the greatest dry matter production ($P \leq 0.05$) compared to the other nitrogen treatments in both seasons. The aboveground biomass was, however, relatively higher in Season II ranging from 13,500 to 13,583 kg-DM/ha compared to Season I which ranged from 7,582 to 8,417 kg/ha, respectively.

The lowest dry matter production ($P>0.05$) was realized in the control treatments and where 30 kg-N/kg was added in both seasons. These yields were 4,557 and 10,000 kg-DM/ha and were not significantly different with DM yields from the 30 kg-N/ha fertilizer treatments in both Season I and Season II, respectively. The relatively higher biomass production in Season II compared to Season I would be attributed to the prevailing weather conditions. The rains in Season I and Season II were 542.2 and 780.0 mm besides the irrigation water applied, and were better distributed in Season II (Appendix I). The temperatures were relatively cooler with higher relative humidity in Season I, thereby reducing metabolic activity necessary for better crop establishment and eventual dry matter formation during carboxylation. This was not the case in Season II where the mean temperature was 26.3 ^{o}C and the crop evapotranspiration was higher at 928.0 mm compared to 852.4 mm in Season I (Appendix I). Thus the Season II crop was able to establish well and trap more PAR for biomass formation, thus the relatively higher DM yields.

4.3.4 Effects of nitrogen on grain-based water use efficiency

The results showed that grain-based water use efficiency (WUE_g) of DK8031 maize variety was significantly different between the nitrogen rates in both seasons (Table 3). The 90 and 120 kg-N/ha nitrogen treatments resulted in the highest WUE_g in both seasons varying from 4.8 to 5.4 and 4.6 to 4.7 kg/ha-mm in Season I and Season II, respectively. The least WUE_g was realized under the control treatment in Season I but similar for the 0, 30 and 60 kg-N/ha rates in Season II. The grain based water use efficiency increased with increasing nitrogen rates in both seasons, meaning that there is a potential of optimizing water use efficiency of the maize grains with higher rates of nitrogen fertilization. Higher rates of fertilizer avail more nutrients for better crop establishment and vegetative growth which in turn captures more light for photosynthesis. The assimilates then are channeled to the seed sink during grain filling. This results in heavier grains and eventual higher WUE_g due to higher nitrogen applications.

4.3.5 Effects of nitrogen on biomass-based water use efficiency

The findings revealed that the biomass based water use efficiency (WUE_b) differed significantly ($P > 0.05$) between the nitrogen rate treatments in both seasons (Table 3). The 90 and 120 kg-N/ha rates produced the greatest WUE_b ranging from to 9.0 to 10.2 and 14.6 to 14.7 kg-DM/ha-mm compared to the other nitrogen treatments in Season I and Season II, respectively. This implied that there was no additional benefit of using nitrogen rates greater than 90 kg-N/ha The nitrogen rates of 0 and 30 kg-N/ha produced the least WUE_b values varying from 5.4 to 7.4 and 10.9 to 11.2 kg-DM/ha-mm in Season I and Season II, respectively (Table 3). The results further indicated that the dry matter water use efficiency values improved with increasing nitrogen application rates in both seasons and was relatively higher in Season II compared to Season I (Table 3). The higher nitrogen rates apparently provided more nutrition for vegetative growth in form of leaves that trapped more light for photosynthesis. This resulted in more dry matter formation by the crop with increased nitrogen rates. This was augmented by the increasing crop evapotranspiration with increasing nitrogen rates as revealed in the findings (Table 3). These two physiological activities of the crop thus resulted in higher WUE_b.

4.3.6 Effects of nitrogen on grain-based nitrogen use efficiency (partial factor productivity)

The grain-based nitrogen use efficiency (NUE_g) values differed significantly between the nitrogen rates in both seasons (Table 4). The zero nitrogen rate resulted in the greatest NUE_g compared to the other treatments in both seasons, the efficiencies being 63.1 and 119.2 kg-DM kg^{-1} N in Season I and Season II, respectively. The 120 kg-N/ha treatment was observed to produce the lowest ($P < 0.05$) NUE_g values of 42.8 and 41.6 kg-grain/kg-N compared to the other treatments. It was noted also that the NUE_g of the 30 kg-N/ha rate differed significantly from other treatments while the 60 and 90 kg-N/ha treatments gave statistically similar NUE_g values in both seasons, respectively (Table 4). The reduction of grain-based nitrogen use efficiency of the DK8031 maize variety with increasing nitrogen rates shows that the extra fertilizer application did not promote the NUE_g. The higher rates of nitrogen applied, resulted in lower NUE_g. It should be noted that despite this physiological response, the higher N application rates resulted in highest grain yields. The NUE_g values were higher in Season II compared to Season I because higher rains resulted in grain yields that were higher in the second than in the first season (Table 4).

4.3.7 Effects of nitrogen on biomass-based nitrogen use efficiency (partial factor productivity)

The nitrogen rates resulted in biomass-based nitrogen use efficiencies (NUE_b) that were significantly different ($P \leq 0.05$) amomg the nitrogen application rates (Table 4). Compared to the other treatments, the control treatment of 0 kg-N/ha resulted in the highest NUE_b of 151.9 and 333.3 kg-DM/kg-N, in Season I and Season II, respectively. On the other hand, the 90 kg-N/ha nitrogen rates resulted in the lowest NUE_b of 80.2 and 128.6 kg-DM/kg-N in Season I and Season II, respectively. The values of NUE_b for the 120 kg-N/ha nitrogen rate was, however, statistically similar to that of the 90 kg-N/ha rate in both seasons (Table 4). The 30 and 60 kg-N/ha rates had NUE_b that lay between that of 0 and 120 kg-N rates and were relatively higher in Season II compared to results of Season I. The average dry matter based water use efficiency was 103.3 and 187.6 kg-DM/kg-N per hectare (Table 4). These findings reveal that higher rates of fertilizer resulted in declining NUE_b values.

4.3.8 Effect of irrigation on agronomic efficiency of nitrogen (grain based)

The grain nitrogen agronomic efficiency (AE_{GN}) is the ratio of unit grain yield produced per unit N applied. The results given in Table 5 revealed that the AE_{GN} of the maize crop increased significantly with applied irrigation levels in both seasons from 19.5 and 10.2 Kg-grain/kg-N under the 119.0 mm to31.3 and 16.5 kg-grain/kg-N with the 357 mm supplemental irrigation applied, then reduced with extra water added (Table 5). The lowest AE_{GN} in both seasons was attained under the 476 mm supplemental irrigation. This may mean that supplemental irrigation in excess of 357 mm under Embu conditions in both season could be injurious to the maize crop as it may cause logging and loss of nutrients such as nitrogen through leaching.

The AE_{GN} ranging from 14.3 to 31.3 kg-grain kg^{-1} N and 10.9 to 16.5 kg-grain/kg-N for April to September 2012 season and the October 2012 to March 2013 crops, respectively (Table 5). The narrower range of AE_{GN} for SII maize would be attributed to the extra (70.2 mm) rainfall that would have provided sufficient water for crop uptake and thus confounded the irrigation treatment effects. Season I crop received lower rainfall (of 542 mm) and therefore supplemental water applied resulted in some significant benefits at I_{357} (357mm) level. For this reason max AE_{GN} was observed under I_{357} levels in SI but I_{238} and I_{357} in Season II (Table 5).

The AE_{GN} increased with increasing applied irrigation water up to 357 mm, (I_{357}) of irrigation water plus 542 mm (total = 899 mm) in SI; and 238 mm irrigation plus 614 mm rainfall (total = 852 mm) in season II. This total seasonal water received resulted into maximum grain yields of 3,639 and 4,119 kg/ha in seasons I (Apr – Sep 2012) and II (Oct 2012– Feb 2013), respectively. These yields were however not significantly different from those obtained with I_{476} (4,100kg grain/ha) in SI and I_{357} (4,231 kg grain/ha) and I_{476} (4,246kg grain/ha) in Season II (Table 2). This non-significant ($P<0.05$) Season I increase in grain yield due to 70.2 mm increase in incident water received, was 461 kg which translates to five

90 kg bags/ha of maize (@ 2,000/-, giving an extra 10,000/- KES). Economically this would have compensated for much needed irrigation water and fertilizer application. The multiplicative effect when translated into hectorage would be enormous particularly for medium to large scale farmers. Increase in water availability beyond 899mm (i.e., 542mm rain + 357mm irrigation) in SI and 852mm (i.e., 614mm rain + 238mm irrigation) resulted in a decline in the AE_{GN} (Table 5). Similar responses were reported by (Ladha *et al.*, 2005; Hammad *et al.*, 2012 and Quaye *et al.*, 2012). Their reported AE_{GN} range of 18 to 24 kg-grain/kg/N applied compares well with the findings of this study which was 14.27 to 31.28 kg-grain/ kg-N for season I and 10.91 to 16.48 kg-grain kg^{-1} N for SI and SII respectively.

Table 5. Effect of irrigation and nitrogen on agronomic efficiency of nitrogen use by DK8053 maize

	Season I		**Season II**	
Factor	**AE_{GN}**	**AE_{BN}**	**AE_{GN}**	**AE_{BN}**
I_{119}	19.5b	30.85b	10.16c	34.89b
I_{238}	21.79b	43.17a	15.48ab	39.31b
I_{347}	31.28a	46.21a	16.48a	55.19a
I_{476}	14.27c	31.82a	12.91bc	53.40a
LSD ($P \leq 0.05$)	4.49	15.11	2.85	9.92
N_{30}	18.18b	22.14b	8.50c	27.54c
N_{60}	22.38ab	39.15a	13.50b	43.00b
N_{90}	22.81a	41.58a	16.61a	56.06a
N_{120}	23.55a	49.16a	16.43a	56.19a
LSD ($P \leq 0.05$)	4.49	15.14	2.85	9.92
I x N	NS	NS	NS	NS
Mean	21.73	38.01	13.76	45.70

Means followed by the same letter under irrigation application and nitrogen rates are no significantly different from each other at $P \leq 0.05$.

Legend: I_{119} = irrigation application at 119 mm; I_{238} = irrigation application at 238 mm; I_{357} = irrigation application at 357 mm; I_{476} = irrigation application at 476 mm; N_0 = nitrogen rate 0 Kg-N/ha; N_{30} = nitrogen rate 30 Kg-N/ha; N_{60} = nitrogen rate 60 Kg-N/ha; N_{90} = nitrogen rate 90 Kg-N/ha; N_{120} = nitrogen rate 120 Kg-N/ha; AE_{GN} = agronomic efficiency of N (grain based); AE_{BN} = agronomic efficiency of N (biomass based)

Fig. 2 shows that increase in grain yield with added N application can be explained by either a quadratic ($Y = -0.0572 + 0.4361x - 0.002x^2$) and or linear ($Y = 50.19 + 0.1595x$) production function. Whereas the grain yield benefits would be realized with increase in N application even beyond 180 kg N/ha, NUE would be very low at about 14 kg grain/kg N.

Much N would be lost through leaching, nitrification and volatilization (Ladha *et al*., 2005). The AE_{GN} increased to a max of approximately 23.6 kg grain/ kg N with 100 to 120 kg N application rate of fertilizer.

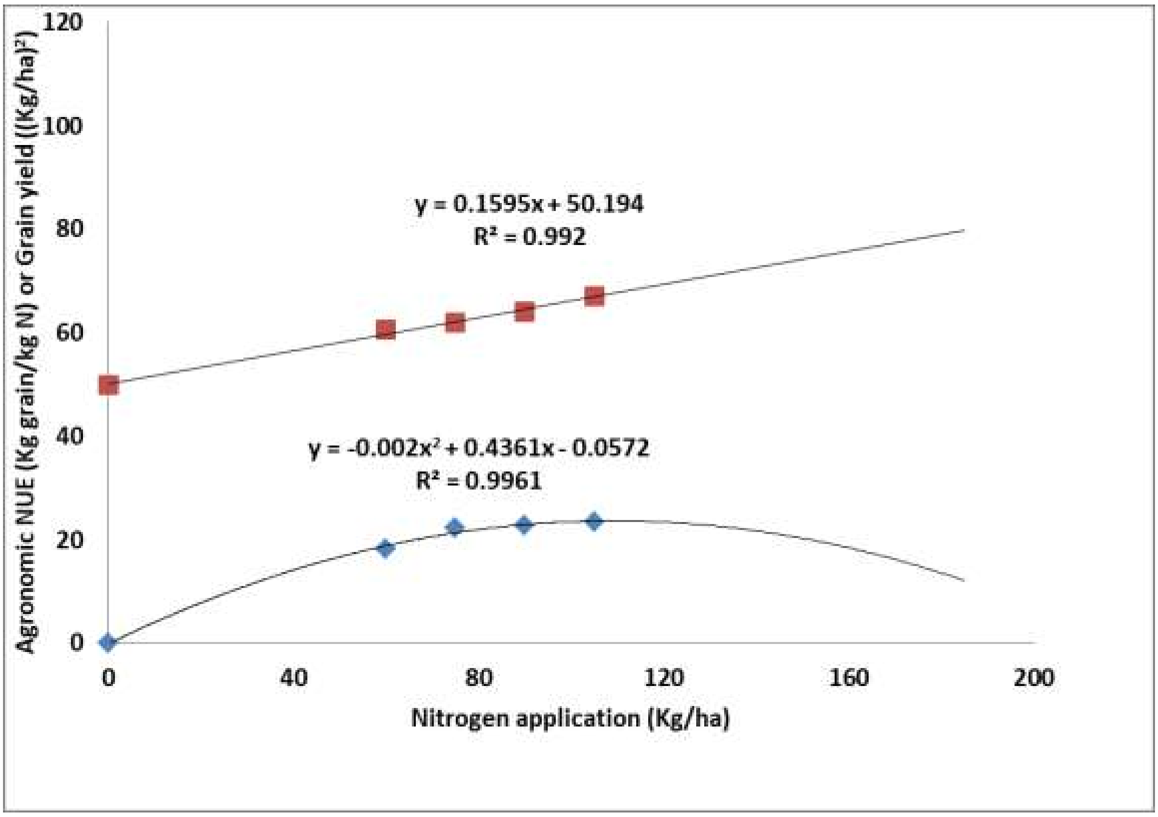


Figure 2. Relationship between grain yield and agronomic efficiency of nitrogen in maize with nitrogen rates in Season I at $P \leq 0.05$

Similar results were observed for Season II (Fig 3). The linear regression showed that the grain yield continued to increase marginally beyond 100 kg N/ha with increasing nitrogen rates but the agronomic efficiency of nitrogen (AG_{GN}) started to decline after about 90 kg-N/ha. The grain yield would thus increase with increasing nitrogen rates but the crop will be utilizing the nitrogen less efficiently beyond the 90 Kg N/ha rate (Table 2 and Fig. 2). This would therefore result in environmental pollution by the nitrogen fertilization in spite of the grain yield increases. In China, rates of up to 588 kg N/ha have been reported with 3.4-fold grain yield increases from 37-fold increase in N fertilization (Zhang *et al*., 2012). In a bid to balance between crop production and environmental sustainability, China is now adopting an integrated nutrient management strategy to maximize biological potential for improving crop productivity and resource use efficiency through root/rhizosphere management (Zhang *et al*., 2004, 2010).

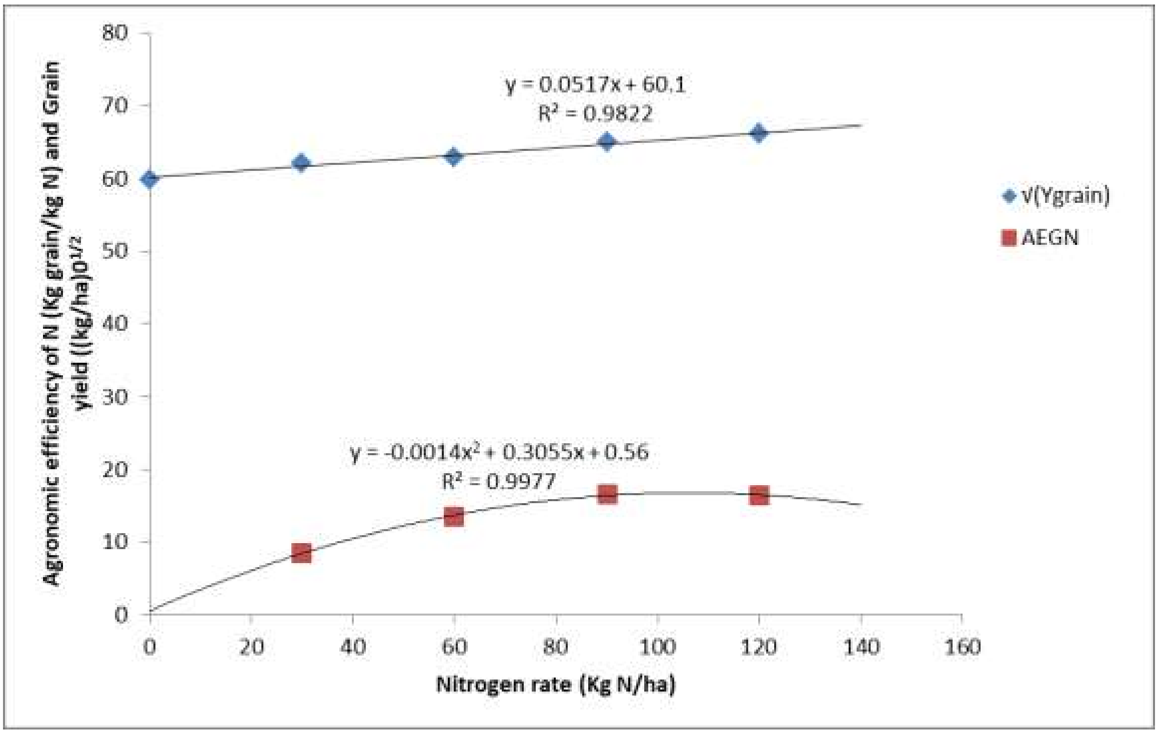


Figure 3. Relationship between grain yield and agronomic efficiency of nitrogen in maize in and nitrogen application for Season II at $P \leq 0.05$

4.3.9 Effects of nitrogen rates on grain-based agronomic efficiency of nitrogen

The effect of nitrogen on the grain based agronomic efficiency of nitrogen (AE_{GN}) of maize varied significantly between nitrogen rates in both seasons (Table 5). The AE_{GN} increased with increasing fertilizer rates up to the maximum of 23.1 and 16.1 kg grain/kg N/ha, under 120 kg N/ha in SI & SII, respectively. The 120 kg-N/ha application rates was however not significantly different from the 90 k-N/ha rates. It was observed that in both seasons, the 30 kg-N/ha nitrogen rate resulted in the least AE_{GN}, ranging between 18.18 and 8.05 kg-grain/kg-N in Season I and II, respectively.

Therefore, for optimizing NUE (expressed as AE_{GN}) farmers should apply N at rates ranging between 90 and 120 kg/ha. At these rates the AE_{GN} would be highest at about 23 to 16 kg grain/kg N applied depending on available soil moisture or rainfall. The higher the moisture availability the higher the N uptake and thus, assimilation in photosynthetic products that enhance crop production. However, according to extrapolated data given in Fig. 2 and 3, it is possible to increase grain yield to over 6.2 tons/ha with 200 kg N/ha application. This compares with the national average productivity from China of 5.4 tons grain/ha with 286 to 588 kg N/ha.

Excessive chemical N fertilizer has often been considered as the main practical hindrance to pursue high yields in China (Zhang, *et al.,* 2012). This excessive application of nitrogen (N) in China has however led to problems such as eutrophication of surface, soil acidification, and greenhouse gas emissions. To meet the demand for grain and to feed a growing population on the remaining arable land in Kenya by 2030, crop production must increase. This increase can be achieved by applying more N to high yielding cultivars that respond to added fertilizer and water inputs. Careful considerations must be made on the benefits accruing from such management. On a large scale, the immediate production, food security and economic benefits will be enormous, but the environmental consequences on the long term will be severe, as those observed in the Northern Central Plain (NCP) of China (Zhang, *et al.,* 2012). As a country, we have to reach a compromise between the increasing productivity of our arable lands and thus total production and enhancing the AE_{GN} and WUE of added inputs.

Further studies on these aspects especially the philosophy around integrated nutrient management (INM), which involves (1) optimizing nutrient inputs and taking all possible sources into consideration, (2) dynamically marching soil nutrient supply with crop requirement spatially and temporally and (3) effectively reducing N losses in intensively managed Kenyan cropping systems and (4) taking all possible yield increase measures in to consideration, is recommended. It has been observed that the response of maize to applied N can be significantly influenced by soil moisture availability when the input is applied when the moisture content is around field capacity (Quaye *et al*., 2009). This will call for prudent use of supplemental irrigation in moisture-deficit soils or lean seasons when rainfall amounts cannot satisfy crop demand. This was realized in the current study where supplemental irrigation up to 357 mm increased both grain yields and AE_{GN} of the crop (Table 2 and Table 5; Fig 3). Crop ET and aboveground biomass and crop increased with higher levels of input factors and showed significant differences in ET_c of the maize under different N rates and irrigation levels (Table 3).

The total amount of rainfall received in was 542.4 mm and 780.0 mm in Season I and Season II, respectively (Appendix I and II, Fig 4). The amount of rainfall received in the first two weeks differed only by 1.2 m in both seasons. The rains in Season I then reduced drastically by 107 mm in the following four weeks and a further decline of 125.2 mm in the next four weeks after sowing. The next eight weeks that followed showed a decline in amount of rainfall that was relatively well distributed but far below that received earlier during crop establishment. Very little rainfall of 12.9 and 3.8 mm was recorded in the last two-week phases in Season I (Fig 4).

The amount of rainfall received in Season II was almost double over the same phases of maize growth. Here, 116.3 mm of rainfall was received within the first two weeks of planting and increased 99.3 in the following two weeks and a further 16.3 mm in the next two weeks (Appendix I and II). This was followed by a sharp decline of 194.5 mm to record 34.4 mm during the 71-98 DAS period. The 99 – 126 period of crop growth received only 13.1 mm rainfall followed by a trace amount (0.3 mm) that preceded a dry spell. This observation reveals that the rainfall was better distributed in Season II compared to Season I at least up to about 84 DAS (14 weeks). This then made the irrigation effects more effective in Season I (three irrigation applications) than in Season II (two irrigation applications). The extra rainfall after three and two irrigations was 55.5 and 276.7 mm in Season I and Season II, respectively. The soil moisture due to the extra rains thus confounded the irrigation effects more in Season II compared to Season I. This was observed in the manner irrigation effects influenced grain yield and agronomic efficiency of nitrogen for the maize crop (Table 2 and Table 5).

It can therefore be argued that rainfall distribution affects crop performance and that irrigation effects are better in cases where rainfall deficits are recorded such as in Season I. In this Season I, rainfall amounts declined with time of growth, denying the crop sufficient soil moisture for better crop establishment, resulting in low biomass and grain yields (Table 2). It cab be concluded that soil moisture availability during crop establishment is critical in determining the final yields of maize and that supplemental irrigation application at 119 mm increments as in this study is effective up to ten WAS in Season I and six WAS in Season II. This observation is critical for farmers and other stakeholders involved in maize production.

The maximum agronomic efficiency of nitrogen (AE_{GN}), grain based, of 16 to 23.1 kg grain/kg-N was observed with a cumulative rain plus irrigation water received ranging from 889 to 962 mm for SI and SII, respectively (Table 5; Fig 10). Therefore, the variation in AE_{GN} was attributed to the variation in rainfall distribution (Fig 12). Therefore, application of irrigation at either I_2 or I_3 evened up the water availability and enhanced AE_{GN}. Supplemental irrigation water can therefore be useful in enhancing the agronomic nitrogen use efficiency for a given growing environment.

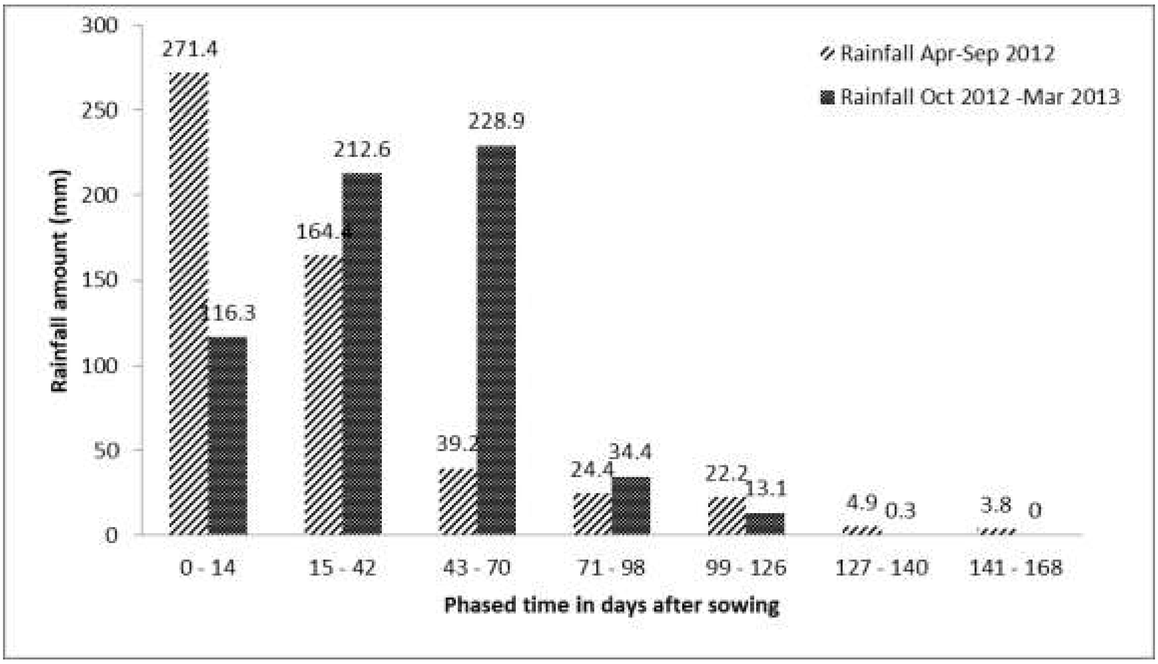


Figure 4. Rainfall distribution in SI (Apr-Sep 2012) and SII (Oct 2012 - Mar 2013) in University of Embu Farm, Embu County, Kenya

4.3.10 Effects of irrigation on agronomic efficiency of nitrogen use (biomass based)

The results in Table 5 reveal that the biomass based agronomic efficiency of nitrogen (AE_{BN}) of maize increased with increasing applied irrigation up to the 357 mm (I_{357}) but declined at the fourth application of 476 mm in both seasons (Table 4). The effects of irrigation treatments on AE_{BN} were significant ($P<0.05$) in both Season I and II. In both seasons, the 357 mm applied irrigation water resulted in the greatest AE_{BN} of 55.19 kg-DM kg^{-1} N applied fertilizer but was not significantly different from the 476 mm irrigation level. The 119 and 238 mm irrigation treatments gave the least and statistically similar AE_{BN} values of 34.89 and 39.31 kg-DM kg^{-1} N fertilizer applied (Table 5). The AE_{BN} averaged 38.01 and 45.70 kg-DM kg^{-1} N in Season I and Season II, respectively. This implied that the Season II maize crop was able to utilize irrigation water more efficiently in producing total aboveground biomass compared to the Season I crop. This observation would be attributed to the rainfall distribution pattern that was better in Season II compared to Season I (Table 5 and Fig 4). The rainfall declined progressively in Season I but increased in Season II up to about 70 days after sowing before declining progressively in the remaining period of the season. The Season II crop thus had enough moisture from the rains and irrigation applications which enabled it to establish better, resulting in higher biomass yields hence relatively higher AE_{BN}. Similar findings were reported by Quaye *et al*., (2012) who observed significant interactions between soil moisture availability and N applied to grow maize. They reported an increase in biomass yield of maize as irrigation water was increased to around field capacity level resulted in plants growing more vigorously and taller than those plants receiving less than 50% FC.

4.3.11 Effect of nitrogen rate on AE_{BN} (Biomass based)

The results revealed that the biomass based agronomic efficiency of nitrogen (AE_{BN}) increased with increasing fertilizer-N rates (Table 5). The AE_{BN} varied significantly between the nitrogen rates. In Season I, fertilizer application of 60 kg-N/ha and above resulted in the highest AE_{BN} while in Season II rates above 90 kg-N/ha were needed to produce significantly higher AE_{GN} values. The AE_{BN} of the maize crop ranged from 22.14 to 49.16 and 27.54 to 56.19 kg-DM/ kg-N applied in Season I and Season II, respectively. The lower and upper limits of the AE_{BN} were higher in Season II compared to Season I, implying that the maize crop utilized fertilizer nitrogen more efficiently in the production of total aboveground biomass in the second season. This would be due to the fact that Season II was warmer with a higher ET_c of 928.0 mm compared to the cooler Season I with ET of 852.4 mm (Appendix I). Season II also received more rainfall that was better distributed compared to Season I crop (Appendix I and Fig 4).

The rainfall distribution in Season I and Season I differed markedly. In season initial rainfall received in first 14 days was much higher at 271 mm compared to only 119 mm in SII. However during the rapid growth phase between 42 and 72 DAS, Season I received only 39.2 mm rain while Season II crop got 228.9 mm rainfall. For this reason irrigation given at I_{238} (238 mm) & I_{357} (357 mm) boosted the April – September 210 crop. Therefore where there was only 119 mm of irrigation in Season I, growth and yield were significantly reduced.

4.4 Interaction Effects

There were no irrigation and nitrogen interaction effects observed on grain, biomass yields, and water use efficiency of maize. However, interaction effects were observed on seasonal crop evapotranspiration (ET_c) and nitrogen use efficiency (grain based, NUE_g) in Season I only and for the biomass based water use efficiency (WUE_b) in Season II but at $P<0.087$ confidence level. These are presented in the following sections.

4.4.1 Interaction effects of irrigation and nitrogen on seasonal ET_c

The interaction effects of applied irrigation water and nitrogen rates on seasonal crop evapotranspiration, ET_c, of the maize crop was significant only in Season I (Table 6). It was observed that the water use (ET_c) of the crop increased with increasing application of irrigation water but generally decreased with increasing nitrogen rates starting at 30 kg-N/ha. The more irrigation water applied meant the crop was able to utilize the additional moisture more effectively for growth and production, hence the higher ET_c values.

Interaction effects were tested for each irrigation level at varying nitrogen rates. It was observed that in all cases incremental application of nitrogen at 30, 60 and 90 kg-N/kg resulted in the highest crop evapotranspiration (ET_c) ranging from 680.5 to 1,030.1 mm with 119 and 476 mm of applied supplemental water (Table 6). However, the ET_c was similar for 60, 90 and 120 kg-N/ha rates, hence no advantage would be realized using N rates of over 60 kg-N/ha under any of the irrigation levels (Table 6).

It was observed that that the ETc increased with increasing irrigation levels but decreased with increasing rates of nitrogen application. Higher application of water meant there was more water for evaporation while increasing nitrogen rates encouraged canopy growth that reduced surface evaporation. The crop under the trial without applied N-fertilizer was observed to be of poor growth with limited canopy hence more exposed ground surface for evaporation, resulting in greater evaporative demand.

Table 6. Interaction effects of irrigation water treatment and nitrogen rates on ETc of maize in Season I

Factor	**N_{30}**	**N_{60}**	**N_{90}**	**N_{120}**
I_{119}	680.5a	677.6ab	675.0ab	669.6b
I_{238}	802.6a	795.8ab	796.4ab	790.3b
I_{357}	919.1a	914.0ab	912.8ab	906.6b
I_{476}	1030.1a	1029.6ab	1023.8ab	1017.7b
Mean	858.1	854.3	852.0	846.0

Values having the same letter across the irrigation treatments are not significantly different from each other

Legend: I_{119} – irrigation application at 119 mm water; I_{238} irrigation application at 238 mm water; I_{357} irrigation application at 357 mm water; I_{476} irrigation application at 476 mm water; N_{30} – nitrogen application rate at 30 Kg-N/ha; N_{60} – nitrogen application rate at 60 Kg-N/ha; N_{90} – nitrogen application rate at 90 Kg-N/ha; N_{120} – nitrogen application rate at 120 Kg-N/ha

4.4.2 Interaction effects of irrigation and nitrogen on Nitrogen Use Efficiency (grain based) in Season I

The irrigation and nitrogen interactions effects on grain based nitrogen use efficiency (also called agronomic efficiency, AE_{GN}) revealed that the mean NUE_g of the DK8031 maize decreased with increase in nitrogen rates but increased with increasing applied irrigation up to the 357 mm applied water except under the 120 kg-N/ha rate in the April – September season (Table 7). The interactions were considered across each irrigation application level. With 119 mm of supplemental irrigation, the best interaction was observed under the $I_{119}N_{60}$ treatment combination, giving NUEg of 10.90 kg-grain/kg-N in Season I. The other treatment combinations were not significantly different from each other. The highest interaction under the 238 mm applied water was $I_{238}N_{30}$ treatment combination with 12.19 kg-grain/kg-N. The other treatment combinations were statistically similar results.

Table 7. Interaction effects of irrigation and nitrogen rate on grain based NUE_g of maize in Season I

Factor	N_0	N_{30}	N_{60}	N_{90}	N_{120}
I_{119}	9.73b	9.73b	10.90a	9.85b	9.88b
I_{238}	9.88c	12.19a	11.25b	10.54c	10.36b
I_{357}	9.72e	14.82a	13.58b	12.09c	10.79d
I_{476}	11.11	16.29a	14.70b	13.15c	11.33d

Values having the same letter across the irrigation treatments are not significantly different from each other. Legend: I_{119} – irrigation application at 119 mm water; I_{238} irrigation application at 238 mm water; I_{357} irrigation application at 357 mm water; I_{476} irrigation application at 476 mm water; N_{30} – nitrogen application rate at 30 Kg-N/ha; N_{60} – nitrogen application rate at 60 Kg-N/ha; N_{90} – nitrogen application rate at 90 Kg-N/ha; N_{120} – nitrogen application rate at 120 Kg-N/ha

The best interaction was attained when 357 mm of irrigation water was applied together with nitrogen rate of 30 kg-N/ha, giving 14.82 kg-grain kg^{-1} N in Season I (Table 7). The agronomic efficiencies of other treatment combinations differed significantly among each other under the 357 mm irrigation level. It was observed that under the 357 and 476 mm supplemental irrigation, the best treatment combinations for agronomic nitrogen use efficiency was at $I_{357}N_{30}$ and $I_{476}N_{30}$ with efficiencies of 14.82 and 16.29 kg-grain/kg-N. The agronomic efficiencies of other treatment combinations differed significantly among each other under the 476 mm irrigation level. The highest interactions were thus observed with

$I_{119}N_{60}$, $I_{238}N_{30}$, $I_{358}N_{30}$ and $I_{476}N_{30}$ treatment combinations. Farmers growing maize in Embu can thus maximize agronomic efficiencies of nitrogen at these treatment combinations in the April – September season.

4.4.3 Interaction effects of irrigation and nitrogen on biomass based water use efficiency in Season II

The results in Table 8 shows the interaction effects of applied irrigation water and nitrogen rates on the biomass based water use efficiency (WUE_b) of DK8031 maize in Season II at 8.96% ($P<0.0896$) confidence level. The values of WUE_b increased with increasing nitrogen rates at all irrigation treatments. The WUE_b values were also observed to increase with increasing levels of applied irrigation water up to 357 mm under all nitrogen rates. This implied that the interactive effects of irrigation and nitrogen rates caused the maize crop to utilize additional water more efficiently to produce dry matter with increasing nitrogen rates. The crop was also able to utilize nitrogen efficiently up to 357 mm of applied irrigation water in producing more dry matter, measured as aboveground biomass. The highest interaction for WUE_b was obtained when 357 mm of irrigation water and 105 kg-N/ha of nitrogen were used. There was a decline in WUE_b values when 476 mm of irrigation water was applied to the maize crop at all rates of nitrogen (Table 8). This meant that the crop utilized nitrogen less efficiently to produce biomass at higher levels of applied irrigation water, hence extra irrigation beyond 357 mm water would not be useful to a maize grower in Embu.

Table 8. Interaction effects of irrigation and nitrogen rates on biomass-based water use efficiency (kg-DM/mm-ha) of maize in Season II

Factor	N_0	N_{30}	N_{60}	N_{90}	N_{120}
I_{119}	10.71d	12.80c	12.61c	15.20b	16.33a
I_{238}	9.44e	12.14d	13.81c	15.76b	16.82a
I_{357}	9.46e	12.76d	14.69c	16.50b	17.40a
I_{476}	9.20e	10.18d	11.60c	13.28b	14.07a

Values having the same letter across the irrigation treatments are not significantly different from each other. Legend: I_{119} – irrigation application at 119 mm water; I_{238} irrigation application at 238 mm water; I_{357} irrigation application at 357 mm water; I_{476} irrigation application at 476 mm water; N_{30} – nitrogen application rate at 30 Kg-N/ha; N_{60} – nitrogen application rate at 60 Kg-N/ha; N_{90} – nitrogen application rate at 90 Kg-N/ha; N_{120} – nitrogen application rate at 120 Kg-N/ha

The interaction effects between supplemental irrigation and nitrogen rates on biomass-based water use efficiency (WUE_b) of maize grown in Embu were observed to be significantly different across all irrigation treatments in Season II (Table 7). The interactions with the highest effects were noted under 120 kg-N/ha rates for all irrigation levels tested. The WUE_b increased with increasing \nitrogen rates and decreased with increasing irrigation levels. It was apparent that the 357 mm supplemental irrigation (exclusive of rainfall received = 357 + 780.0 = 1137.0 mm) produced the highest WUE_b after which the values decreased, implying that the this would be optimal level of irrigation combined with 120 kg-N/ha. The low WUEb values at 476 mm applied water would be due to leaching effects at higher water levels in the soil. The highest WUE_b values in the October 2012 to March 2013 season were 16.33, 16.82, 17.40 and 14.07 kg-DM/ha-mm at 120 kg-N/ha under 119, 238, 357 and 476 mm applied water levels, respectively.

4.5 Development of production functions

4.5.1 Relationship of grain yield to plant height at R4 under varying irrigation levels

A linear equation was developed to explain the relationship between grain yield and plant height at physiological maturity under varying irrigation levels in the two seasons. It had a poor fit only able to explain 32.1% of the variations (Fig 4). The regression showed, at physiological maturity stage, one kg/ha of grain was produced at the rate of every extra 17.9 cm increase in height of maize. The growth and production of the crop behaved differently in the two seasons although the same amount of irrigation water was added (Appendix II). This variation was attributed to the variation of rainfall amounts and its distribution as well as the relatively high mean ambient temperatures in Season II compared to Season I (Fig 4; Appendix I).

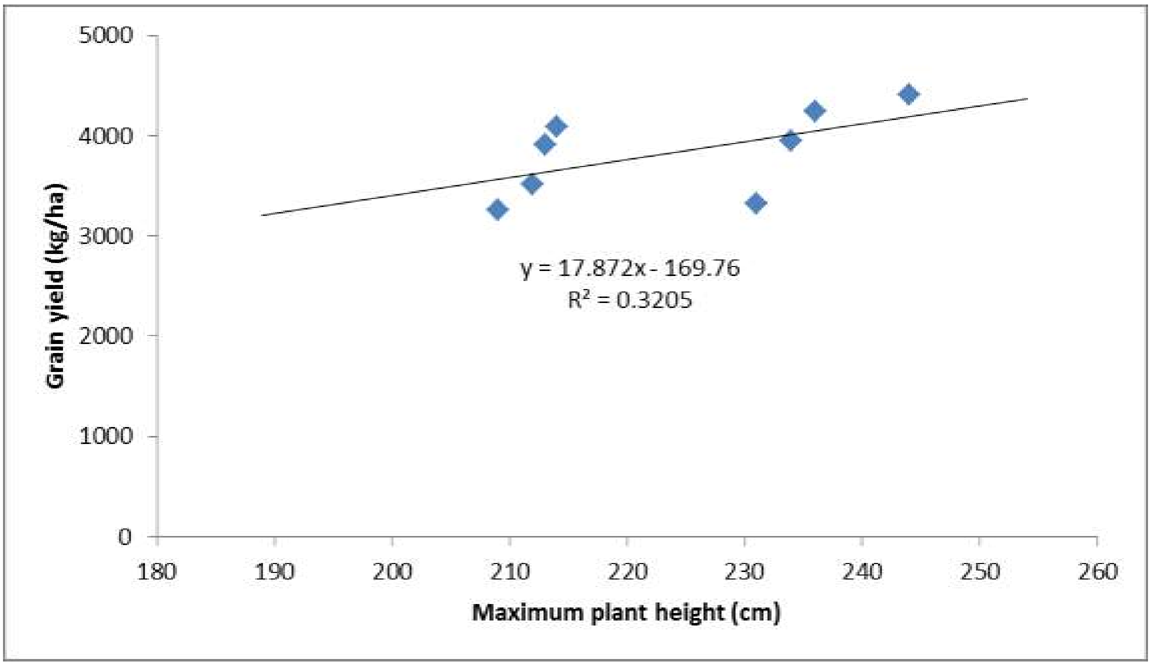


Figure 5. Relationship of grain yield to plant height under varying irrigation levels in two seasons at $P \leq 0.05$

4.5.2 Relationship of grain yield to plant height at R4 under varying nitrogen rates

When mean grain yields were regressed against the maximum plant heights of the maize crop in both seasons, a polynomial curve gave the best fit that explained 79.9% of the variations (Fig 6). The relationship showed a rapid increase of grain yield with plant height up to about 210 cm under varying nitrogen rates. After this the relationship revealed a declining increase of grain yield with increase in plant height. An optimum grain yield of 4253.4 kg/ha was observed to peak at 245.6 cm maize height in both seasons. This was a bit higher than the 3,639 and 4,119 kg grain/ha mean yield of measured data sets in Season I and Season II, respectively (Table 2). Beyond optimum value, grain yields began to decline, meaning incremental maximum plant height recorded beyond the 245 cm height did not increase crop grain productivity.

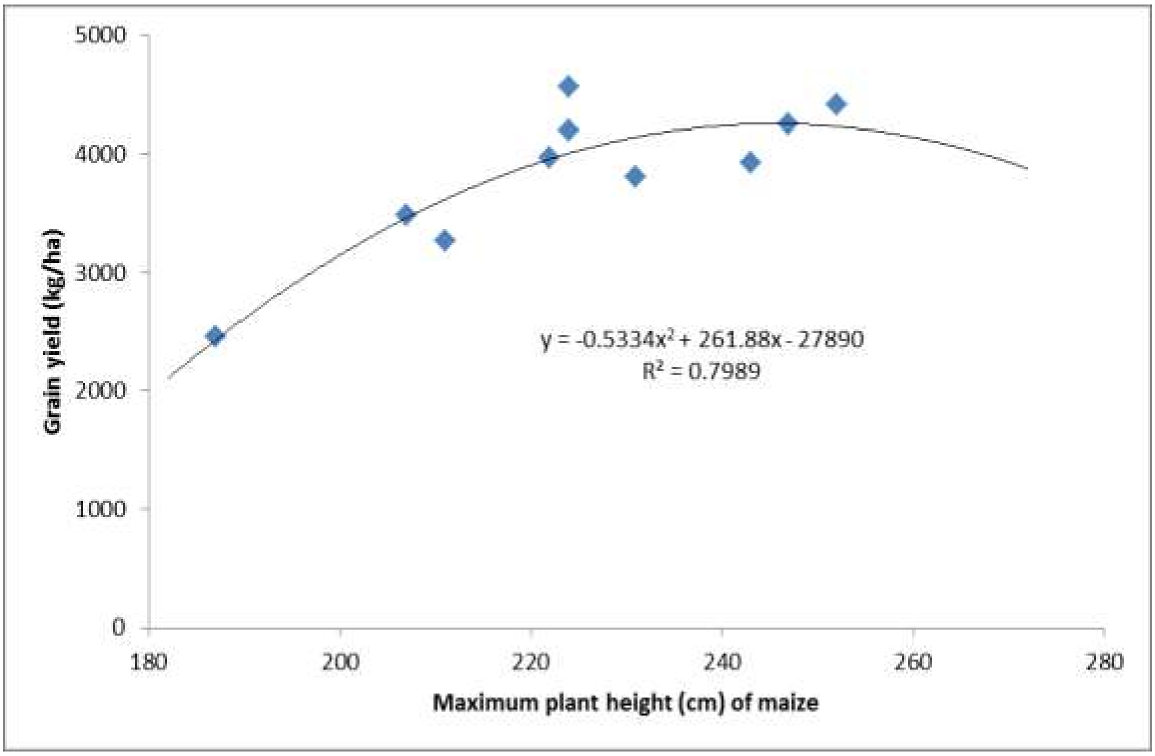


Figure 6. Relationship of grain yield to maximum plant height of DK8031 maize under varying nitrogen rates in two seasons

4.5.3 Relationship of aboveground biomass to plant height under varying irrigation levels

A quadratic curve was fitted to relate the dry matter biomass to plant height of the DK8031 maize under varying irrigation treatments at physiological maturity (Fig 7). The production function could explain 91.5% of the variations, indicating a high reliability in predicting DM from the maximum plant height of maize. When the differential of the regression equation was performed, a predicted maximum plant height of 307.6 cm would be associated with a maximum aboveground biomass yield of 18,252.5 kg-DM/ha. It would be recommended to breed and study taller lines of DK8031 maize to result in yielding higher DM yield. The predicted values of DM and plant height of the maize crop were both higher than those measured in the field in the two seasons under irrigation treatments which averaged from 212 to 236 cm and 6,801 to 11,800 kg-DM/ha under irrigation treatments in Seasons I and II, respectively.

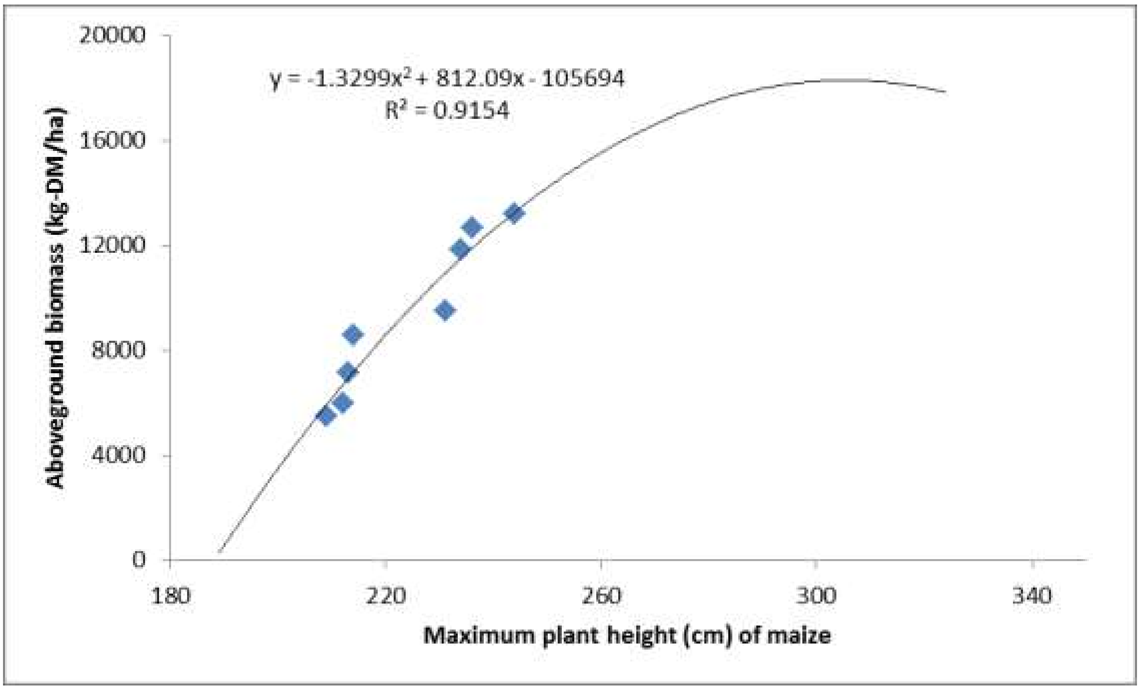


Figure 7. Relationship of aboveground biomass to maximum plant height of DK8031 maize under varying irrigation rates in two seasons

4.5.4 Relationship of aboveground biomass to plant height under varying nitrogen rates

Under varying nitrogen rates, a linear function with a very high coefficient of determination (R^2 = 0.833) best related aboveground biomass to plant height at optimum plant height of the DK8031 maize grown in the University of Embu Farm, Embu County in two seasons (Fig 8). The production function showed that 147 kg/ha of aboveground dry matter of the crop was produced with every 1 cm increase in plant height under varying nitrogen rates.

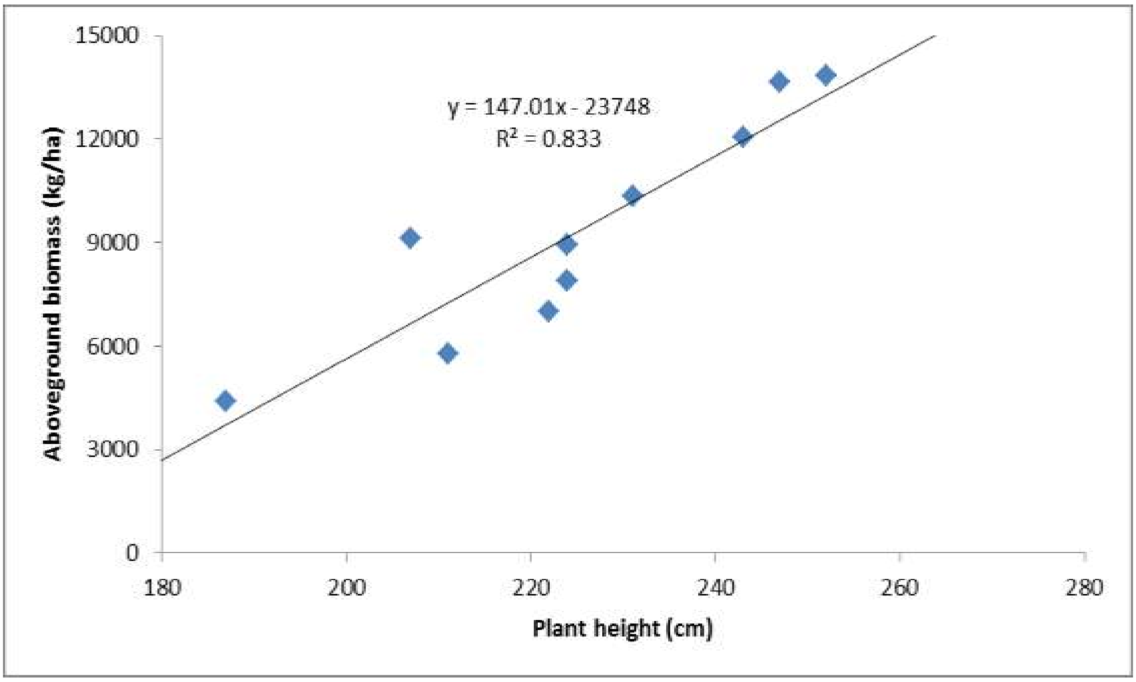


Figure 8. Relationship of aboveground biomass to plant height under varying nitrogen rates in two seasons

When the grain yield was regressed against the plant height at R4 stage of maize irrespective of the irrigation levels and nitrogen treatments, a quadratic production function with relatively good fit ($R^2 = 0.6455$) was observed (Fig 9). These two plant parameters had a correlation coefficient of 0.75. The function shows that the maize crop will grow to a height of 248.6 cm at this developmental stage and yield 4,488.6 kg/ha of grain. This compares well with the seasonal grain yield average of the two seasons that averaged 3,693.2 and 3,978.5 kg/ha in Season I and II, respectively, but is higher than the mean yield of the two seasons. This would be expected from the regression for yield if the crop can attain the higher plant height predicted by the production function.

Validation of the actual to computed grain yield of the DK8031 maize using the 1:1 ratio revealed an even distribution of data (Figure 10). This shows that the production function is sufficient in estimating expected grain yield values in the two cropping seasons for the Embu environment.

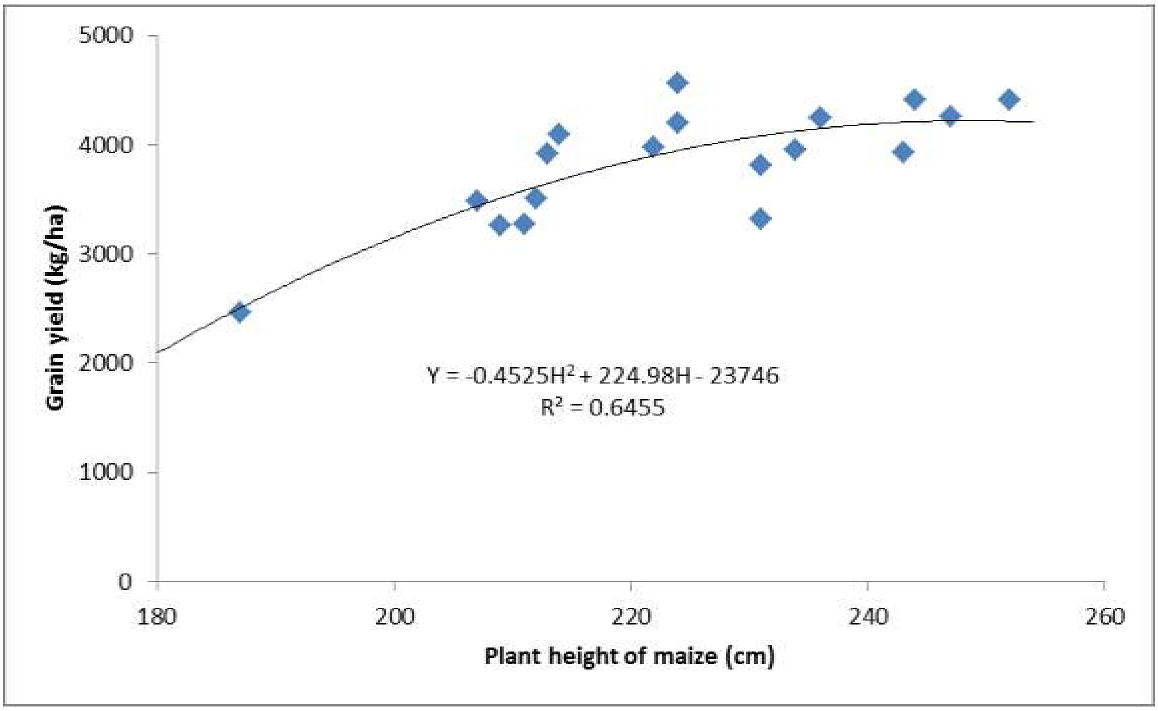


Figure 9. Relationship of grain yield with plant height of DK8031 maize under both irrigation and nitrogen treatments in the two seasons

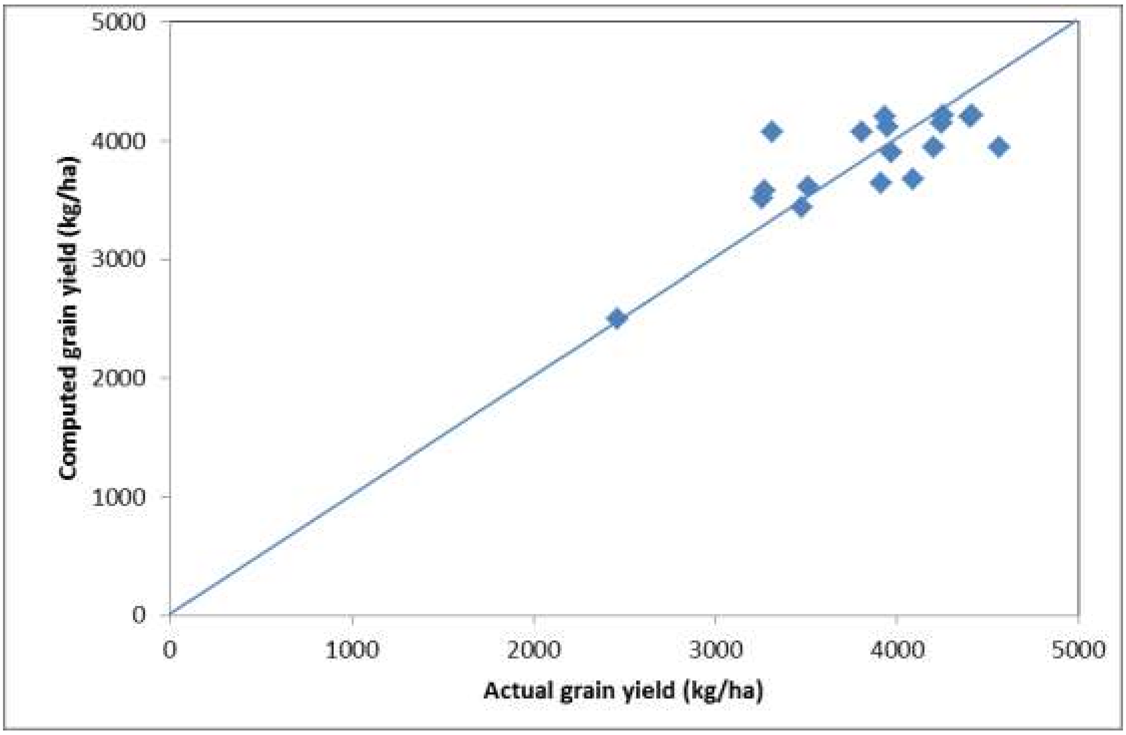


Figure 10. Comparison of computed to actual grain yield of DK8031 maize under irrigation levels and nitrogen treatments in the two seasons

A linear regression equation best described the relationship between aboveground biomass yield and plant height of DK8031 maize under both irrigation levels and nitrogen rates in the two seasons (Fig 11). The production function had a high coefficient of determination (R^2 = 0.8394) and a correlation of 0.9192. This meant that the production function could reliably be used to estimating potential grain yields using plant height at physiological maturity. The function indicated that DM was increased by 1 kg/ha for every 164.39 cm increase in maize height at physiological maturity.

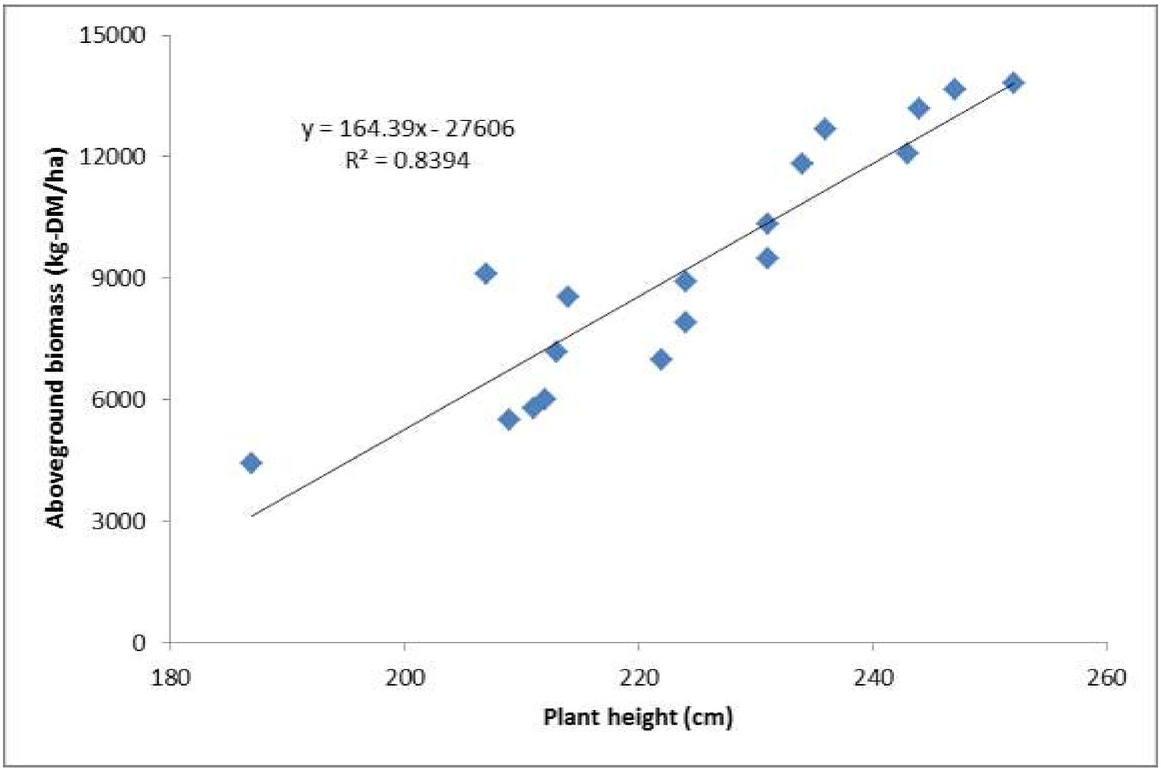


Figure 11. Relationship of aboveground biomass to plant height of maize under irrigation levels and nitrogen rates in two seasons (r=0.9162)

4.5.5 Relationship of evapotranspiration to grain yield under varying irrigation levels

A quadratic curve best described the relationship between seasonal evapotranspiration and grain yield of DK8031 maize under varying irrigation levels in two seasons (Fig 12). The function has a high coefficient of determination ($R^2 \approx 0.94$). It estimates that the maize crop started to produce grains at reproductive phase after accumulating more than 186.1 mm of evapotranspiration. The rate of increase in grain production was relatively high up to between 400 and 500 mm seasonal ET after which grain yield increased at a declining rate with cumulative ET_c. When the rate of change of grain yield with measured ET is determined by differentiation, a maximum grain yield of 4,849 kg/ha can be expected for a seasonal ETc of 1,616.6 mm as can be observed from the graph and equation (Fig 12). The curve thus suggests that more grain yields can be achieved at higher evapotranspiration under the experimental conditions in Embu. More study on the use of more irrigation water is recommended to confirm this observation.

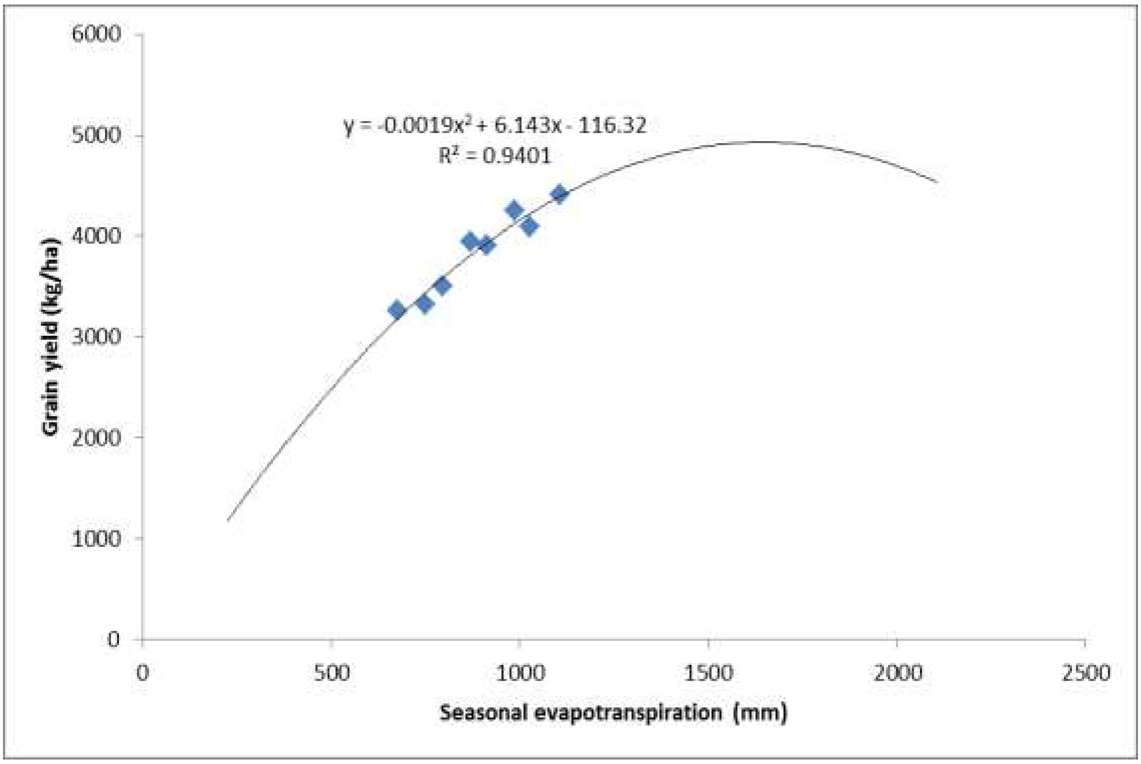


Figure 12. Relationship of seasonal crop evapotranspiration to grain yield of DK8031 maize under varying irrigation levels in two seasons

When the computed grain yield was compared to the actual grain yield in the two seasons for purposes of validating the developed quadratic function, a good fit was observed, implying that the quadratic production function was sufficient in predicting the actual to simulated grain yields (Fig 13). There is a good distribution of the data set showing that the computed values predict well the observed yields at $P \leq 0.05$. Similar results have been reported for chickpea biomass implying that seasonal ET can be used to predict grain yield of certain cereals (Kibe and Onyari, 2007). This is because the relationship between grain yield and biomass for these two test crops have been shown to be linear (Fig 20).

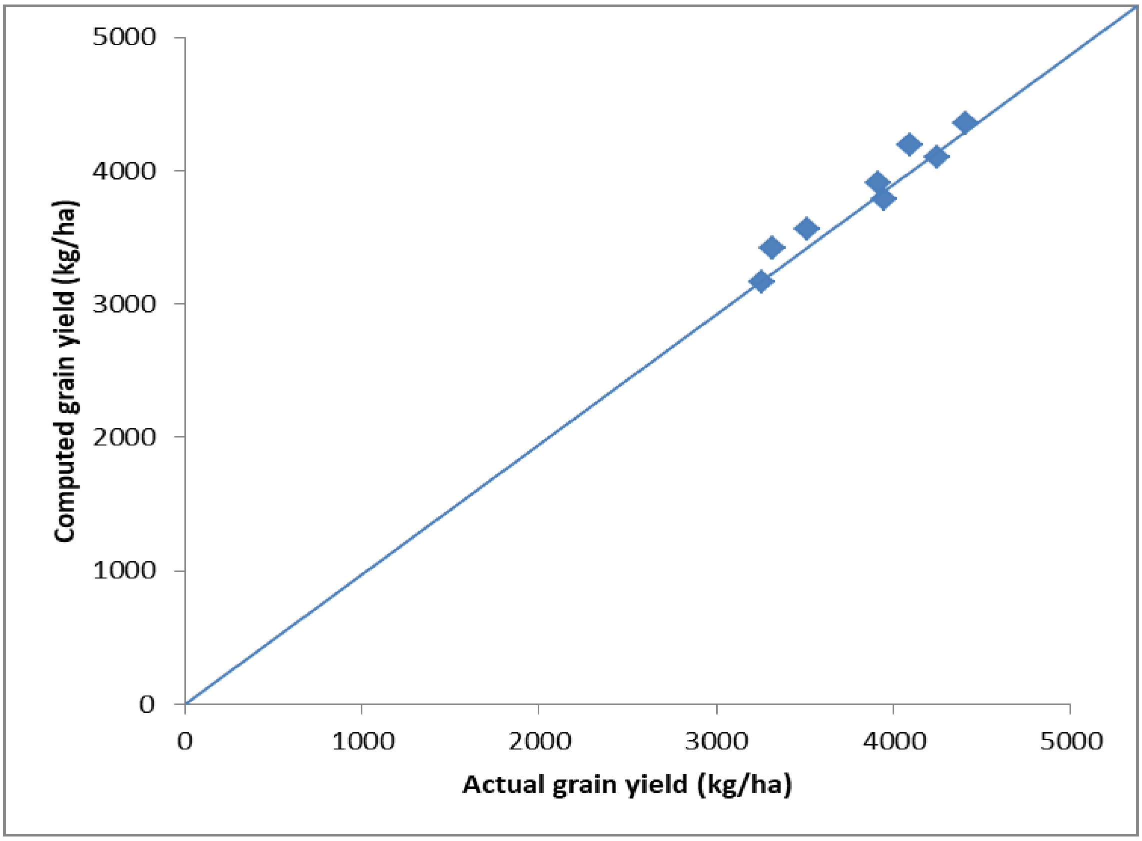


Figure 13. Comparison of computed to actual grain yield of DK8031 maize as affected by seasonal evapotranspiration under varying irrigation levels in two seasons

4.5.6 Relationship of total water received to grain yield under varying irrigation levels

It was observed that a quadratic production function was best able to describe the relationship between the grain yield and total water received (W_r = irrigation + rainfall) by the DK8031 maize under varying irrigation levels (Fig 14). The equation quadratic equation ($Y = -0.0019x^2 + 6.1626x + 0.3872$) suggests that the potential yield for the maize of can be obtained with 1.621.7 mm total water. Since the rainfall amount was 542.4 and 780.0 mm in Seasons I and II, respectively, then 1079.4 and 841.7 mm of the water will have to be provided through irrigation for the DK8031 maize to yield above 5.0 t/ha. The total water received when four irrigations were applied was 1006.3 and 1081.3 mm in Season I and II, respectively. The extra irrigation water to be applied will then be 540.4 and 615.4 mm over and above the four irrigations in Seasons I and II, respectively. This will increase the cost of production and will have to be weighed against the extra grain yields harvested to assess the benefit accrued. Further studies to determine the economic value of providing supplemental irrigation to maximize water application and evaluate grain yield benefits is recommended.

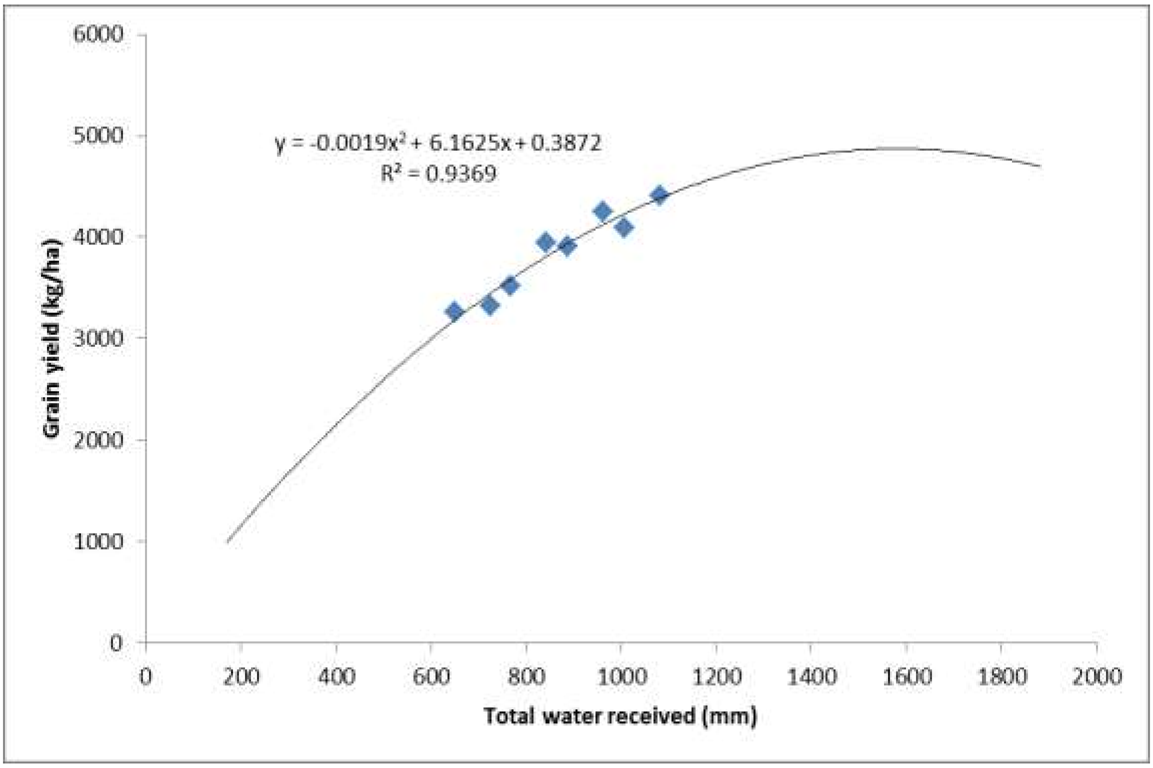


Figure 14. Relationship of total water received to grain yield of DK8031 maize under varying irrigation levels in two seasons

The developed function from Season I data set was used to compute simulated yields using water received in Season II, then the computed yield data was related with the second season data sets. It was observed that the function was useful in predicting the Season II (September 2012 to March 2013) grain yield by fitting a 1:1 line (Fig 15).

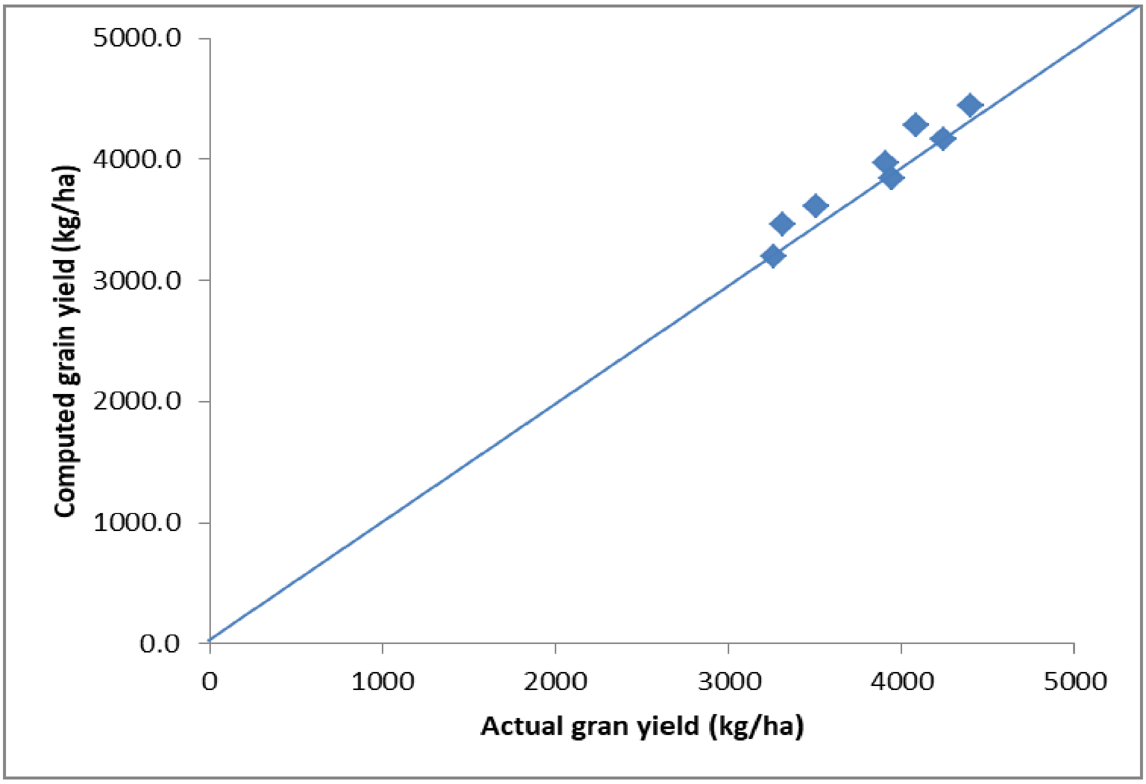


Figure 15. Comparison of computed to actual grain yield of DK8031 maize under varying irrigation levels in two seasons

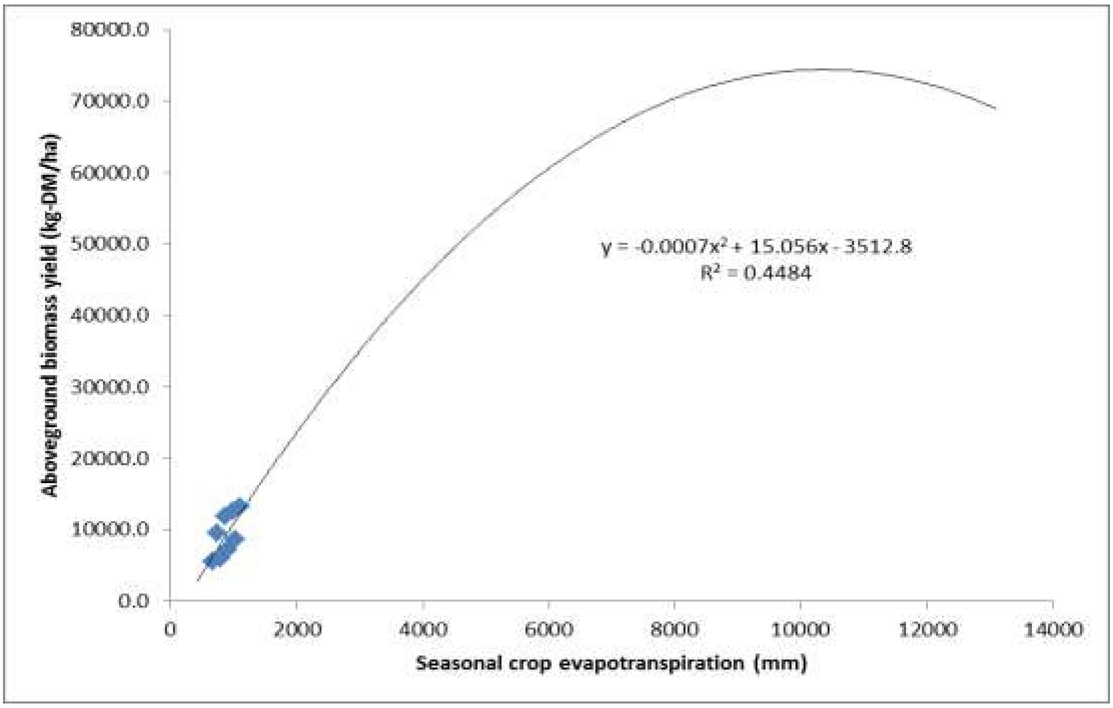


Figure 16. Relationship of seasonal evapotranspiration to aboveground biomass yield of DK8031 maize under varying irrigation levels in two seasons

4.5.7 Relationship of seasonal crop evapotranspiration to aboveground biomass yield under varying irrigation levels in two seasons

The relationship between aboveground biomass to seasonal crop evapotranspiration was described by the logarithmic equation, which best fitted the data, with a low R^2 value of 0.448 under varying irrigation in two seasons (Fig 16). The function showed that aboveground biomass yield increased progressively with increasing seasonal evapotranspiration. The dry matter (DM) accumulation increased rapidly at a slow declining rate up to between 600 and 700 mm ETc after which the rate of increase reduced rapidly with increasing seasonal ET. The DM production was observed to peak at 77,445.5 kg-DM/ha when the seasonal ET was 10,754.3 mm. Since these values were beyond the scope of the current study, more work is recommended to determine the potential maximum production of aboveground dry biomass with respect to seasonal ET of the maize crop. When the simulated DM yields were validated using the 1:1 line, a poor distribution of data points was observed (Fig 17).

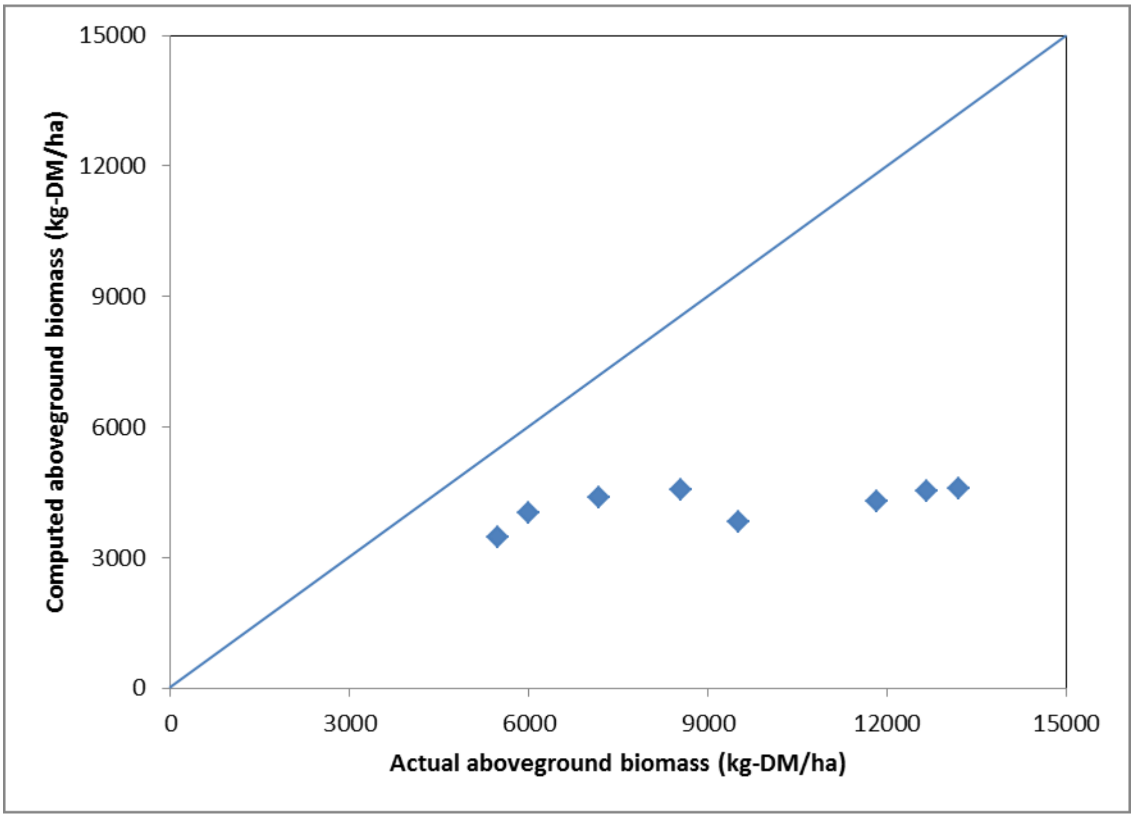


Figure 17. Comparison of computed to actual aboveground biomass yield of DK8031 maize under varying irrigation levels in two seasons

4.5.8 Relationship of total water received to aboveground biomass yield under varying irrigation levels

A polynomial (quadratic) production function was used to describe the relationship of aboveground biomass yield to total water (Wr) received by the DK8031 maize in two seasons under varying irrigation levels (Fig 18). The relationship predicted a steady increase of DM yield with additional total water received up to about 1300 mm; beyond this amount of total water received, the aboveground biomass yield increased at a reducing rate with increase in total water received. The production function implied that the crop has a potential optimum of 28,020.8 kg-DM/ha with 3,596 mm total water.

The validation test showed a separated distribution of data points for the two seasons, confirming that the relationship was a poor predictor as it was only 44.4% reliable (Fig 18 and Fig 19).

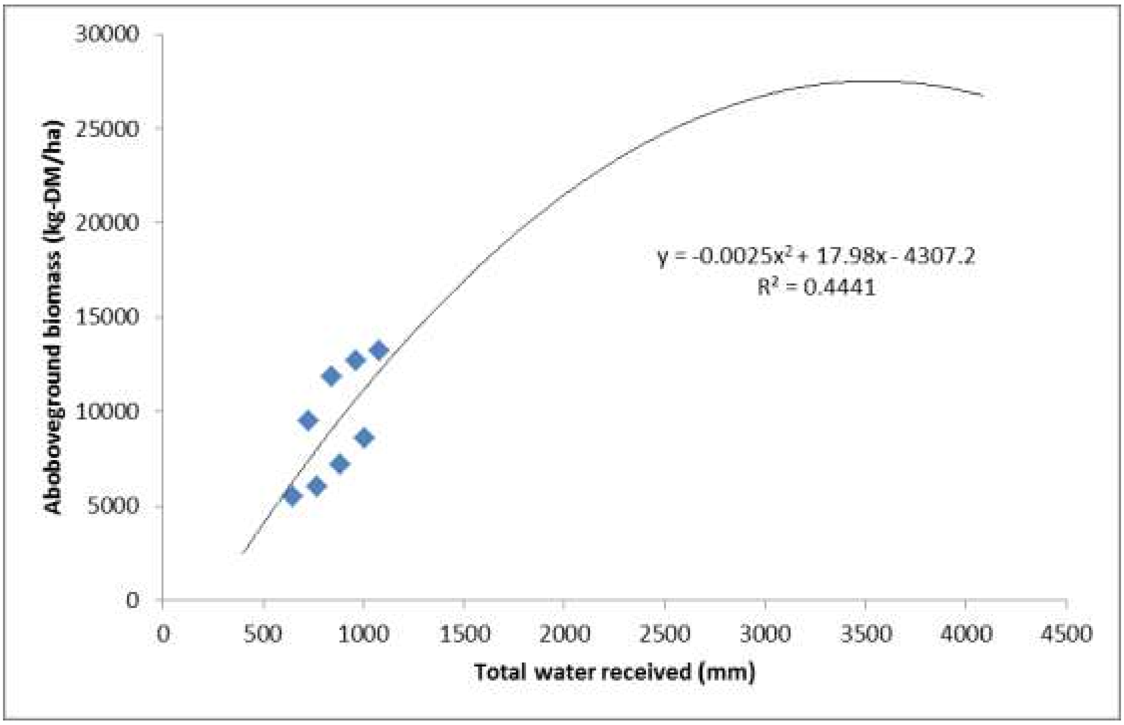


Figure 18. Relationship of total water received to aboveground biomass yield of DK8031 maize under varying irrigation levels in two seasons

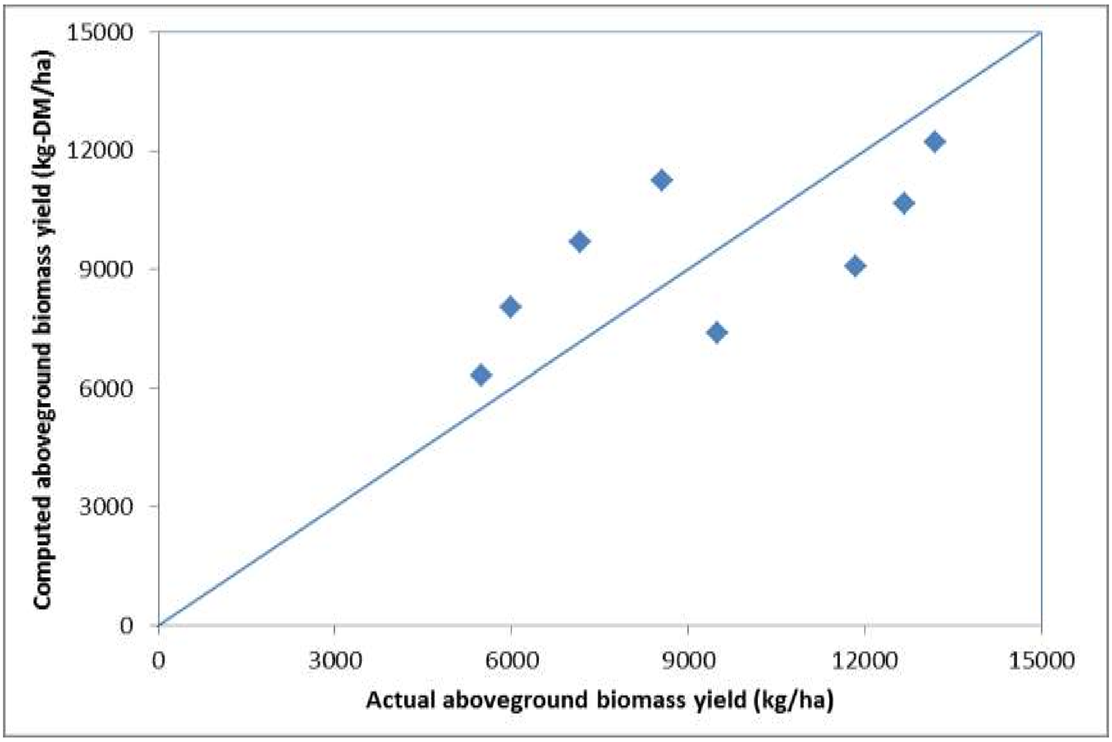


Figure 19. Comparison of computed to actual to aboveground biomass of DK8031 maize as affected by total water received under varying irrigation levels in two seasons

4.5.9 Relationship of aboveground biomass to grain yield under varying nitrogen rates

The relationship between aboveground biomass against grain yield of DK8031 maize was given by a quadratic curve with R^2 of 0.6344 in two seasons under varying nitrogen rates (Fig 20). The grain yield increased with increased accumulation of dry matter produced but with a declining rate beyond production of 6,000 kg-DM/ha. The production function suggested that the maize crop can produce a maximum 4007.4 kg/ha grain associated with 11,028.3 kg-DM/ha of aboveground biomass at harvest. After this DM yield, the grain yield will decline for every additional DM at harvest accumulated under varying nitrogen rates in the two seasons.

Validation of the computed grain yield as influenced by actual grain yield of the DK8031 maize showed a fair distribution as suggested by the R^2 value of 63.4% (Fig 20 and Fig 21).

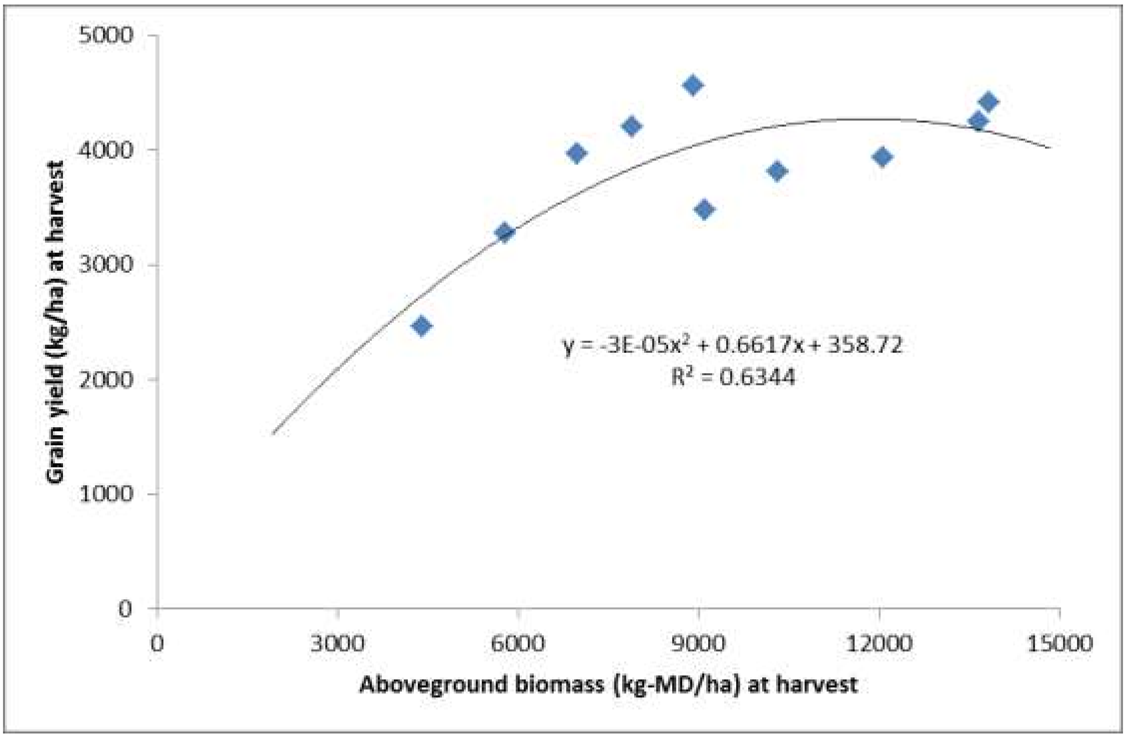


Figure 20. Relationship of grain yield to aboveground dry biomass of DK8031 maize at harvest under varying nitrogen rates

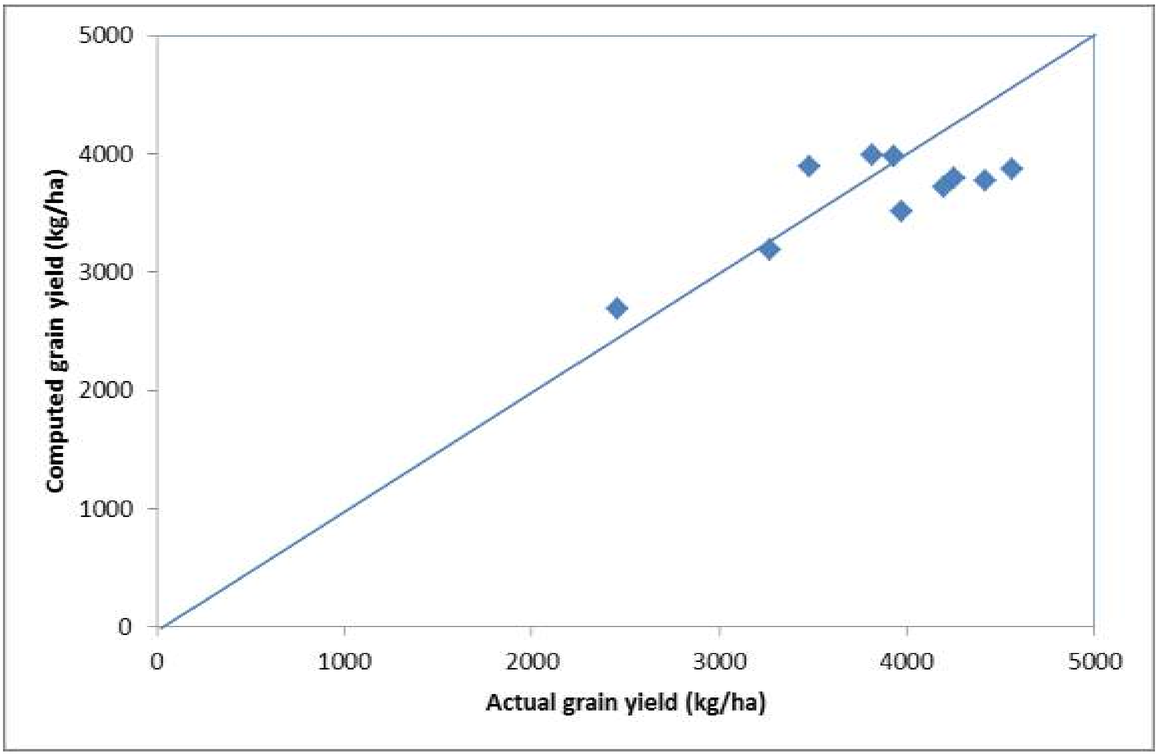


Figure 21. Comparison of actual to computed grain yield of DK8031 maize under varying nitrogen rates in two seasons

4.5.10 Production functions relating irrigation levels and nitrogen rates to growth parameters of maize

The multiple regression analysis to evaluate the individual effects of irrigation levels and nitrogen rates showed that nitrogen effects were greater than those of irrigation effects in all cases of growth parameters measured (Table 9). The contribution of nitrogen was four and eleven times more than that of total water received, $W_{r,}$ in determining the maximum maize height attained at milk stage (R3) in Seasons I and II, respectively. The influence of nitrogen on height of maize was thus almost four-fold in Season II. The additive effects of irrigation (Wr) and nitrogen were such that both inputs positively contributed to plant height at milk stage. The production function was able to account for 63 and 75% of the variations observed in both seasons, respectively.

Table 9. Production functions showing multiple effects of total water received (Wr) and nitrogen rates on plant height and leaf area index of maize (DK8031) at milky stage (R3) grown in Embu in seasons I (Apr 19, 2012 - Sep 29, 2012) and II (Oct 13, 2013 – Mar 8, 2013)

Maize Parameter at R3 in Season I & II	Production function	R^2	W_r:N ratio
Plant height (SI)	$H_1 = 196.572 + 0.00343Wr + 0.274N$	0.6314	1:4
Plant height (SII)	$H_2 = 243.563 – 0.0234Wr + 0.268N$	0.7511	1:11
Leaf Area Index (SI)	$LAI_1 = 2.787 + 0.00137Wr + 0.0178N$	0.8941	1:13
Leaf Area Index (SII)	$LAI_2 = 2.017 + 0.00258Wr + 0.0249N$	0.9034	1:9

Legend: R^2 – coefficient of determination; Wr – total water received (irrigation + rains); N – nitrogen rate;SI – Season I (Apr 2012 – Sept 2012); SII – Season II (Oct 2012 – Mar 2013); H – plant height; LAI – leaf area index

The leaf area index at maximum maize height (84 DAS) responded to the combined (interaction) effects of total water received (Wr) and nitrogen applied as depicted by the production functions in Table 10. These functions had high R^2 values of 0.8941 and 0.9034 in Seasons I and II, respectively (Table 10). The effect of nitrogen rates influenced leaf area index of the maize at R3 stage thirteen and nine times compared to that of total water applied in Season I and Season II, respectively. This observation could be attributed to the cooler and drier conditions of Season I compared to Season II which was warmer with more rainfall. The additive effects of the input factors (irrigation and nitrogen) contributed to height with varied degrees, with nitrogen fertilizer having a greater influence on maize height than the total water received. In all the cases, the ratio of W_r:N in the equations showed that nitrogen had a greater effect on both plant height and LAI in both seasons (Table 9).

In Season II, the amount of rainfall received was 780.0 mm compared to 542.4 mm in Season I, i.e., 237.6 mm higher than SI. The greater impact of nitrogen compared to applied irrigation on plant height in higher rainfall Season II can be associated with the higher mobility of elemental N in solution during water uptake. Nitrogen is highly mobile in water solutions and therefore can either be readily leached or taken up by maize. The efficiency of water and N use depends on whether the threshold of water and N availability meets crop requirement. Under very low water and N availability, the efficiency of utilization of both the factors is very high, but crop growth and yield is limited (Liebig law of minimum). Under high nutrient and water availability above the limiting threshold, there is a likelihood of water and nutrient N loss through deep percolation (leaching) and drainage beyond the root zone.

With respect to the maize height, it is apparent that the lower relative water received by maize in SI (1006.3 mm), resulted in a higher water use coefficient (0.00343) and N use coefficient (0.2742) than in SII (0.02342 and 0.268, respectively). With respect to production of leaves (i.e., LAI) however, the more the water, the higher the water use (0.001369) and N use (0.01779) coefficients (which is a measure of efficiency of utilization in relation to height and leaf production) in SI and 0.00258 and 0.02494, in SII, respectively. Therefore, under high water availability scenarios (>1007 mm), the effectiveness of water and N use is more on production of leaf area than on height as given by production functions in Table 10.

4.5.11 Production functions relating irrigation and nitrogen interactions to grain and biomass yield of maize

The degree of influence of irrigation (Wr) and nitrogen (N) on total aboveground biomass production of DK8031 maize by harvest time was 1:4 and 1:5 in Seasons I and II, respectively (Table 10). The two factors contributed positively to the dry matter production of the maize crop, but in a declining rate. The production functions were reliable as they explained 96 and 93% of the observed variations in Seasons I and II, respectively.

The additive production functions developed for grain yield of maize revealed that the effects of nitrogen was eight and nine times more than that of Wr by the crop in Seasons I and II, respectively (Table 10). The multiples regressions had very high R^2 values of 0.8896 and 0.9345 and may therefore be relied upon to explain the variations observed in the two respective seasons. These findings suggest that application of more nitrogen will be more useful to maize growers in Embu than the addition of more water. Farmers in regions receiving more than 500 mm seasonal rainfall should be encouraged to apply more nutrient N so as to enhance / increase grain yields of the maize. More work is recommended to validate the predictive potential of these production functions for different agro-ecological zones under varied "what–if" water and N interaction levels scenarios. Consequently, similar observations could be derived / inferred for grain yield and other yield production attributes (Table 10).

The production function developed explaining effect of Wr and N on the 100-grain weight of the DK8031 maize is given in Table 11. It indicates that the contribution of nitrogen was more compared to that of irrigation water in both seasons. Nitrogen contributed to the test weight nine and two times more than total water applied to the DK8031 maize crop in Season I and II, respectively. This variation was attributed to the growing time that was longer in Season I (164 and 148 DAS) which provided greater opportunity for the Season I crop to complete grain filling, hence heavier grains. The greater effect of nitrogen on the 100-grain weight of maize was, however, about 5 times less in Season II compared to the Season I crop, implying that seasonal weather variations influences the effects of nitrogen on grain test weight. For maize growers interested in heavier grains, prudent use of nitrogen and received water are recommended for in both seasons. It is therefore proposed that more work be done to validate these functions under varied rainfall and irrigation application levels and combined nitrogen rates on the test weight of DK8031 maize. The predictive ability of these functions on measured field yields (outcomes) will be at the given R^2 values in Table 11 above.

Table 10. Production functions of the effects of irrigation levels and nitrogen rates on yield and yield components of DK8031 maize grown at the University of Embu Farm in Embu in two seasons

Crop Parameter and Season	**Regression equation**	**R^2**	**I:N ratio**
Aboveground biomass, kg/ha (SI)	$DM_1 = -3205.19 + 9.292Wr + 42.0144N$	0.9567	1:5
Aboveground biomass, kg/ha (SII)	$DM_2 = -725.63 + 11.881Wr + 50.646N$	0.9294	1:4
Grain Yield, kg/ha (SI)	$Y_{G1} = 347.407 + 2.605Wr + 19.565N$	0.8896	1:8
Grain Yield, kg/ha (SII)	$Y_{G2} = 2{,}000.47 + 1.558Wr + 14.781N$	0.9345	1:9
100 grain weight, g (SI)	$T_{w1} = 26.896 + 0.00522Wr + 0.045N$	0.7894	1:9
100 grain weight, g (S II)	$T_{w2} = 28.668 + 0.00612Wr + 0.0125N$	0.2296	1:2
Number of cobs/ha (SI)	$Cob_1 =24{,}017.49 + 12.781Wr + 105.835N$	0.6091	1:8
Number of cobs/ha (SII)	$Cob_2 = 40{,}548.86 + 11.889Wr + 90.972N$	0.6292	1:8
Number of lines/cob (SI)	$Line_1 = 11.136 + 0.000758Wr + 0.012N$	0.6050	1:18
Number of lines/cob (SII)	$Line_2 = 11.205 + 0.00165Wr + 0.0029N$	0.2561	1:2
Cob length, cm (SI)	$Length_1 = 10.448 + 0.00254Wr + 0.0338N$	0.6784	1:13
Cob length, cm (SII)	$Length_2 = 11.255 + 0.00511Wr + 0.0302N$	0.9278	1:6

Legend: R^2 – coefficient of determination; I:N – ratio of coefficients of irrigation level to nitrogen rate in the regression equation; SI – Season I; SII – Season II; DM_1 and DM_2 – dry matter biomass in Season I and Season II; Y_{G1} and Y_{G2} – grain yield in Season I and Season II; T_{w1} and T_{w2} – test weight in SI and SII; Cob_1 and Cob_2 – number of cobs per ha in Season I and Season II; $Line_1$ and $Line_2$ – number of lines per cob in Season I and Season II; Wr – total water (mm) received in form of irrigation

Production functions developed to relate the number of cobs/ha of DK8031 maize to applied irrigation water and nitrogen rates had a good fit with R^2 values of 0.6091 and 0.6292 in Seasons I and II, respectively (Table 10). The multiple linear regression functions revealed that the additive effects of the total water applied and nitrogen were similar in both seasons although that of nitrogen was eight times greater than that of irrigation effects (Wr).

When multiple regression equations were developed to relate the number of lines per/cob of DK8031 maize to the combination of total water received and nitrogen rates, it was observed that irrigation to nitrogen (I:N) effect ration was 1:18 and 1:2, in Seasons I and II, respectively (Table 10). The additive effect of nitrogen was much greater by nine times in Season I compared to Season II maize crop. These differences in contribution of the input factors to the number of lines per cob of the maize was associated with the prevailing seasonal weather conditions, especially rainfall and air temperature as discussed above (Appendix I). The number of maize lines per cob ranged between 14 and 19 depending on growing environment. Maize farmers should therefore apply more nitrogen fertilizers and water to their maize crop in order to maximize the number of lines per cob in both season and ultimately grain yields. More study to determine the additive effects of combined water application (Wr) and nitrogen levels on the number of lines per cob of the DK8031maize in the varied AE-zones is recommended.

A multiple regression analysis on the effect of Wr and nitrogen rates on the cob length of DK8031 maize resulted in a production function having a good (R^2 = 0.6784) and very high (R^2 = 0.9278) fit in Season I and II, respectively (Table 10). The additive effects of nitrogen on cob length were greater than those of irrigation in both seasons and more pronounced in Season I than in Season II. The I:N ratios were 1:13 and 1:6 in Seasons I and II, respectively. It was observed that the effect of nitrogen application was more than double in the first season compared to the second season. Maize farmers who desire enhance production of longer cobs when using supplemental irrigation coupled with nitrogen treatments can therefore utilize the greater effects of nitrogen in Season I to promote longer maize cobs. However, this need to be confirmed against overall yields expected and the cost implications involved. The cob lengths of the Season II crop were relatively longer than those of Season I crop. Therefore, further investigation to determine the overall multiplicative effect of applied water levels and nitrogen rates on the length of DK8031 maize cobs is recommended

4.5.12 Production functions relating Wr and N with water use efficiency

The findings in Table 11 showed that the ratios of coefficients of the effect of irrigation to nitrogen treatments (1:6 and 1:5) on the grain based water use efficiency (WUE_g) of the DK8031 maize was comparable in both seasons (Table 11). The effects of nitrogen were more pronounced by six and five times greater than that of irrigation treatments in Season I and II, respectively. When validated, the variations on the output of the multiple regression equation were generally within the confidence levels ($P>0.05$), being 0.006 and 0.057 in Seasons I and II, respectively. These production functions can be used reliably in estimating WUE_g of the DK8031 maize grown in Embu. Farmers can therefore utilize these equations in planning on the possible combination on supplemental irrigation levels and nitrogen rates to maximize on the most efficient use of applied water to the crop. More work is recommended to validate these functions in different AEZ for varied water and N application scenarios, e.g., in the Galana Galore Irrigation scheme.

The development of production functions relating the effects of Wr and the nitrogen rates on the biomass based water use efficiency (WUE_b) of the DK8031 maize indicated that the effects of nitrogen were forty five times that of irrigation levels (W_r) in Season I but were the same (1:1) in Season II when seasonal Wr was 1079.3 mm (Table 11). When the production function was validated using the RMSE method, the variations of the estimated WUE_b was 15.7% and 7.0%. This showed that the equations were not within the $P \leq 0.05$ confidence level of confidence.

4.5.13 Production functions relating irrigation levels and nitrogen rates to nitrogen use efficiency of maize

The nitrogen use efficiency (NUE) used here is the agronomic efficiency of nitrogen (AE_N) of the DK8031 maize grown in Embu. Only the grain and aboveground biomass based NUE were considered. The multiple regression analysis revealed that the effects of nitrogen rates on NUEg were five and six times more the effects of total water received in Seasons I and II (Table 11.) The effects of irrigation levels on NUE_g were reductive while those of nitrogen rates were positive in both seasons. When validated, the regression equations estimated variations of 33 and 22% of the yields in Season I and II, respectively. These variations could be explained by 7.46 and 57.9% reliability in the respective seasons.

Table 11. Regression analysis of the effects of irrigation levels and nitrogen rates on water use efficiency of DK8031 maize grown in Embu in two seasons

Crop Parameter and Season	Production function	R^2	Wr:N ratio
WUE_g, kg/ha-mm, (SI)	$WUE_{g1} = 6.159 - 0.00385Wr + 0.0236N$	0.8280	1:6
WUE_g, kg/ha-mm, (SII)	$WUE_{g2} = 6.495 - 0.00354Wr + 0.0165N$	0.9354	1:5
WUE_b, kg/ha-mm (SI)	$WUE_{b1} = 4.122 + 0.00115Wr + 0.0514N$	0.9097	1:45
WUE_b, kg/ha-mm (SII)	$WUE_{b2} = 13.7971 - 0.0048Wr + 0.0553N$	0.8831	1:1

Legend: WUE_g – grain based water use efficiency; WUE_b - aboveground based water use efficiency; SI – Season I; SII – Season II

The multiple regression equations for the biomass based nitrogen use efficiency (NUE_b) had a good fit ($R^2 = 0.5575$) in Season I but a very poor fit ($R^2 = 0.00628$) in Season II (Table 12). The effects of nitrogen on NUE_b were five and thirty one times more than that of total water received (irrigation treatments) in Seasons I and II, respectively. The nitrogen and irrigation treatments were observed to positively and reductively influence the NUE_b respectively in both seasons. When validation was done using the RMSE method, the variations were 26 and 25% in Seasons I and II respectively. The variations in WUE_b were thus way above the 5% confidence levels used in actual measurements and therefore not good for predicting NUE_b outcomes.

The October 2011 to March 2013 season (Season II) had higher temperatures and thus growth degree days (GDD) of 1481, i.e., 79 heat units (HU) more than the April - September 2012 season (Season I) by harvest time (Table 1 and Appendix 1). Season II also had a higher rainfall by 237.6 mm over Season I. For these reasons, despite taking a short period of 148 days (16 days), the SII crop had higher grain yields amounting to 3,978.5kg/ha (7.17%) than the SI crop with 3,693.2 kg/ha. It can be concluded that maize variety DK8031 can be produce higher grain yields under a shorter 130 days to physiological maturity with 1385 heat units and 1,018.4 mm of incident water.

Table 12. Regression analysis of the effects of irrigation levels and nitrogen rates on nitrogen use efficiency of DK8031 maize grown in Embu in two seasons

Crop Parameter and Season	Regression equation	R^2	W_r:N ratio
NUE_g, kg-grain/kg-N, SI	Y = 25.906 – 0.0087Wr + 0.0425N	0.0746	1:5
NUE_g, kg/kg-N, S II	Y = 18.627 – 0.0132Wr + 0.0810N	0.5792	1:6
NUE_b, kg-DM/kg-N, SI	Y = 61.736 – 0.0470Wr + 0.2193N	0.5575	1:5
NUE_b, kg-DM/kg-N, SII	Y = 16.403 – 0.00027Wr + 0.00853N	0.0068	1:31

Legend: R^2 – coefficient of determination; Wr – total water received (irrigation + rainfall) in season; N – nitrogen rate (kg-N/ha); RMSE – root mean square of error; SI – season I; SII – Season II; Y – response factor (output) for the respective crop parameter

CHAPTER FIVE

DISCUSSION

5.1 Effects of total water received on maize growth and yield

Higher seasonal rainfall has been reported by Hao *et al.*, 2013 and Ndamali and Watanabe, 2015 to increase grain productivity where temporal rainfall patterns with water partitioning impacts on maize yield. Rainfall distribution is important for realizing higher productivity as was noted in the current study (Appendix I and II). Dry spells occurring over critical growth stages like flowering in maize (tasselling to silking) are known to severely reduce grain yields as they adversely affect opening of stomatal apertures (Nielson, 2012). This in turn results in reduced transpiration and lower carbon assimilation (Duffy and Masere, 2015), leading to reduced grain yields. Within-season rainfall distribution is known to affect maize yields particularly in low-rainfall seasons. Rainfall or water availability was reported to affect the total number of leaves, shoot growth, vigor (Sing and Singh, 2002) and yield (Vermeulen *et al*., 2012) of maize.

The total water received by the maize crop (Wr = Rainfall + irrigation) was higher in SII while the ambient temperatures were warmer (12.9 to 25.8 ^{o}C) compared to SI season which was cooler (14.1 to 29.0 ^{o}C) and had less rainfall. Conversely the grain yield, biomass accumulation and water use efficiency (3,671 and 4,173 kg-grain/ha; 6,971 and 12,119 kg-DM/ha and 4.4 and 4.6 kg/ha-mm) were observed to be higher in the second season. Water availability and its efficient use is thus an important factor for sustaining crop productivity in rain-fed agriculture where supplemental irrigation can be applied. Farmers in areas that receive inadequate rainfall can thus enhance production by availing more water through supplemental irrigation (IFCD, 2007). By adopting the most efficient way of its application and utilization by crops, farmers can mitigate the effects of variable rainfall (Ndamani and Watanable, 2014) and that may be due to changing climatic patterns.

It has been reported that under drier early season conditions (0 to 45 days after sowing), maize yields are distinctively reduced with yields increasing at 32.2 kg ha^{-1} per mm of precipitation (Nielson *et al.*, 2010). The available moisture positively correlates with vegetative biomass development that leads to greater collection of solar radiation and greater photosynthesis during tasseling, silking and grain filling. This ultimately leads to greater yield development when water stress is availed by precipitation during these critical phases.

Stress (low soil moisture, high temperature, limited nutrient) from one week before to one week after flowering delays silking until after most of the pollen is shed resulting in poor pollination, especially on the tip of the ears (Fayza *et al*.,., 2016). Since grain production occurs between flowering and maturity, drought stress during this period can result in unfilled kernels, less weight per kernel and light, chaffy ears. The grain filling period covers about 55 days for most corn breeds. Plant physiological maturity is achieved when the kernel has reached its maximum weight. In the current study, rainfall distribution was better in the first three months of Season II compared to Season I which declined over the same period of crop establishment (Appendix II). The relatively higher grain and biomass production in Season II was attributed to the more favorable weather conditions compared to the cooler and more humid SI. Erratic rainfall in critical stages of crop growth has been reported by Ndamani and Watanabe (2014) to affect crop development at the early stages if farmers attempt to delay crop planting. They revealed that seasonal rainfall is more important than annual rainfall in respect to crop production.

According to Rugumayo *et al* (2003), findings on rainfall variability and its relationship with crop production should provide the basis for which policy makers can plan for irrigation to effectively respond to the incidence of recurring droughts. Thus, it is important that maize farmers adjust their land preparation and crop planting dates to avoid periods of dry spell and drought in the production season (Ndamani and Watanabe, 2014). For areas receiving limited rainfall, supplementary irrigation can be used to boost production. Since maize in Kenya is primarily used as a source of food, significant result of supplementary rain fed irrigation on grain weight and harvested plant stand with its cobs confirms the need for high water supply for maize production in arid regions (Bello, 2008). This contributes to the ongoing efforts by the government to increase maize production through irrigated farming in Galana area along river Tana. Much water can be saved if applied to supplement precipitation in the scheme, particularly, when its application scheduling is synchronized with critical stages in maize phenology.

The mean solar radiation received was 92.1 MJs^{-1} 129.5 MJs^{-1} in Season I and Season II, respectively (Appendix I). On the other hand the relative humidity ranged between 58.7 to 79.3% and 52.6 to 72.8% in the respective seasons. The maize crop in Season II thus established early due to higher photosynthetically active radiation (PAR) and more moisture availability from rainfall. The higher relative humidity conditions in SI were attributed to lower solar radiation compared to that of SII. Therefore, better crop growth and yield observed in Season II for the DK8031 maize was attributed to the more favorable weather conditions of higher availability of water, radiant energy and lower relative humidity, which resulted into higher evapotranspiration compared to the SI crop.

While adapting to climate variability and change that brings about higher temperatures, higher evaporation and transpiration in either an atmosphere with lower RH, such as in the October to March Season II, farmers can increase and optimize production of DK8031 maize under supplementary irrigation. The higher temperatures reported at the Embu experimental site in Season II, (i.e., short rains), are reminiscent of drought conditions particularly in the January - February months. The relatively better crop performance of this maize can be attributed to its ability to tolerate drought compared to other maize varieties (Micheni *et al*., 2015). It was observed that RH varied simultaneously with the mean solar radiation received, i.e. higher radiation resulted in evaporation of available water and therefore, increased RH in the months of November and December when rainfall was available (Figure 22; Appendix I). Beyond this however, in the months of January to March, when there was no rain, the RH was low because there was little or no available soil / surface water to evaporate and transpire. Maize under supplementary irrigation therefore benefited and evapotranspired more and thus, the crop increased in growth and yield. Therefore, increased evapotranspiration rates led to increased crop growth and ultimate grain yields in Season II compared to the cooler Season I (Tables 2).

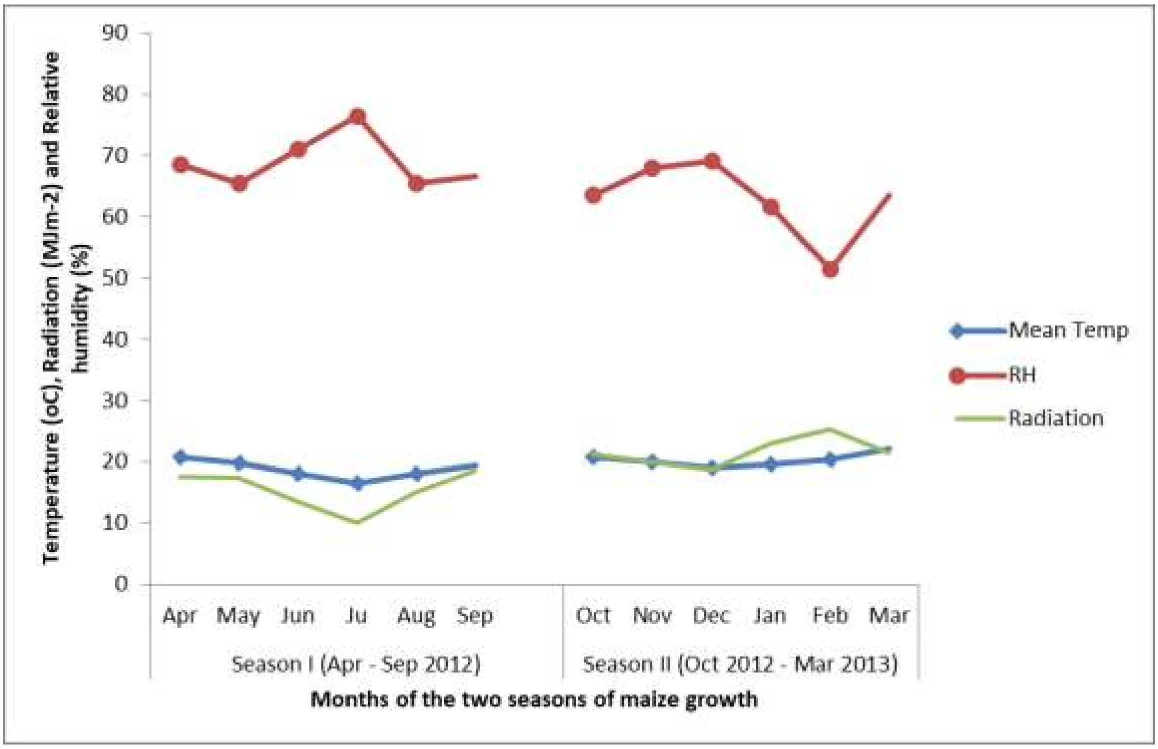


Figure 22. Variation of mean temperature, mean RH and mean solar radiation over two seasons of DK8031 maize growth

Photosynthesis is indirectly affected by RH such that when RH is low, transpiration increases causing water deficits in the plant. Water deficits cause partial or full closure of stomata and increase mesophyll resistance blocking entry of carbon dioxide. Miroslav *et al.* (2007) noted that solar radiation is an indispensable input variable because it drives photosynthesis. Solar radiation is also used to estimate potential and actual evapotranspiration which is an essential part of the water balance in all crops. The yield potential of a given genotype such as DK8031 maize is determined by a particular combination of solar radiation, temperature and plant population at a specific location (Lindquist *et al.*, 2005; Grassini *et al.*, 2009). As can be seen from Figure 20, the solar radiation was relatively constant over the two seasons and thus relative humidity, temperature and ET_c had greater impact influencing the growth and yields of the maize DK8031 crop. However, the relatively higher radiation in Season II (86.7 MJm^{-2} compared to 84.4 MJm^{-2} in Season I) was associated with greater DM and grain yields. The relatively higher ambient humidity levels restricted transpiration and promoted intake of carbon dioxide that led to greater biomass accumulation and higher grain yields.

5.2 Effects of total water received on water use efficiency

Plant height was observed every two weeks after sowing of the DK8031 maize grown in Embu while leaf area index (LAI) was measured only at the 50% flowering stage of the crop. It was observed that taller plants had a higher LAI, better water use and subsequently higher crop yields (Table 9). The grain and DM based water use efficiency of the maize reduced with increasing total water applied but was observed to increase with higher rates of nitrogen application. Taller plants were obtained under treatments with higher levels of irrigation application which also enhanced ETc. Thus, biomass and grain yields of maize increased as crop evapotranspiration increased, due to increase water availability either through rainfall or irrigation (Table 2 and Figure 17).

Similarly Payero *et al.* (2008) noted that ETc (averaging 633 mm) increased linearly with applied irrigation water up to a point where irrigation was excessive; grain yields ranged from 9,680 to 10,850 kg/ha in two seasons. In the current study, ETc varied from 675.5 to 1105.5 mm with grain yields ranging from 3,224 to 4,100 kg/ha, the lower yields being attributed to a different maize variety used. They explained that excessive irrigation most likely reduced the amount of oxygen in the crop root zone and increased the likelihood of nitrogen leaching, making less of it available for crop uptake. When seasonal irrigation was not excessive, higher yields were obtained with the same amount of irrigation in Season II compared with Season I. These results are not surprising since the relationship between yield and irrigation is not unique and varies with season and location.

Water use efficiency (WUE) of DK8031 varied greatly among irrigation and nitrogen treatments and were observed to decrease with increasing water and nutrient input (Table 2). Nitrogen treatments that received between 90 and 120 kg N/ha had large LAI and used more water compared to the other treatments, resulting in large canopy and ETc. Similar findings have been reported by Ogola *et al.* (2002) where an increase in crop canopy resulted in increased ETc through an increase in the transpiration component of the crop water balance. Increased crop growth and production are therefore promoted by enhanced water use as reflected by high ETc values of the maize.

However, beyond a critical maximum, WUE and NUE decline (Table 3). Effort should therefore be made to determine the optimum levels of water and nitrogen application that result into optimum water and nitrogen use efficiencies within given maize growing environments. In the current study, for the University of Embu Farm (about 500 m Embu KALRO Station), supplemental water and nitrogen utilization was optimized at $I_{476}N_{120}$ (1029.6 mm) and $I_{476}N_{90}$ (1,107.2 mm) for DK8031 maize variety in Season I and Season II, respectively (Figure 3). It can be inferred that, with higher water availability (of about 1,040 mm), lower nitrogen application rates of 90 kg/ha were sufficient because crop utilized the water and nitrogen more efficiently. With total water received beyond 1,100 mm, nitrogen was used less efficiently, because it was lost either by leaching or volatilization. The grain and dry biomass yield of the crop was, however, observed to continue increasing beyond the maximum WUE levels (Figure 3). This is useful in increasing maize production in marginal areas where supplementary irrigation in excess of 476 mm and nitrogen rates above 120 kg-N/ha will boost production to feed an ever increasing human population in developing countries such as Kenya. The differences in grain yield among nitrogen levels were mainly due to a significant variation in maximum leaf area index, leaf area duration and crop growth rate (Valero *et al.*, 2005). They noted that there was a decreasing pattern in nitrogen use efficiency values with increasing fertilizer rates, indicating that crop production could be sustained with lower fertilizer applications. This agrees with the findings of the current study (Table 4).

In case the maize such as DK8031 is to be grown for DM production, then investments in irrigation must find sustainable supplies of water as suggested by the developed relationships. Such production functions can be utilized and further improved to carter for specific growing needs and niches. Since seasonal evapotranspiration increased with increasing irrigation, it is possible to increase grain and biomass yields of the maize by enhancing plant height. A strong linear relationship between ETc and irrigation amounts has been reported in which case the growth and yields varied proportionately with seasonal ET but affected with seasonal weather variations (Zhang *et al.*, 2004; Farre and Faci, 2009; Irmak *et al*., 2013). It has been reported that significant effect is usually expected in the use of irrigation water and rainfall in crop production during cultivation (Bellow, 2008).

In this study, the effect on moisture content, improvement effect on fresh grain weight and its dry grain weight and harvested plant stand with number of cobs suggested that the use of supplementary irrigation would aid maize production. Similar observations were made in the current study in which lower ETc values and irrigation water amounts were associated with shorter maize plants and yields in cooler and drier Season I compared to Season II which was warmer and received higher rainfall amounts (Table 1).

5.3 Production functions of DM with Leaf Area Index (LAI) and grain yield

Plant foliage density expressed as leaf area index (LAI) is used in many ecological, meteorological and agronomic models, and as a means of quantifying crop spatial variability (Walthall *et al*, 2012). The leaf area index was measured at 50% flowering and varied between 4.73 to 6.08 and 5.09 to 7.08 in Seasons I and II, respectively. The values of maize height, LAI and grain yields for the $I_{357}N_{90}$ and $I_{476}N_{120}$ treatment combinations were statistically similar in both seasons. The aboveground biomass increased by 323% and 150% compared to means for the control treatments (I_0N_0) which yielded 2,609 and 6,967 kg-DM/ha in Seasons I and II, respectively. This was related with the increase of plant height with increasing N rates. The increase of plant height with different rates of nitrogen can be attributed to the fact that nitrogen promotes plant growth, increases the number and length of internodes which results in the progressive increase in plant height (Amin, 2010).

The leaf area index (LAI) was observed to increase with both applied irrigation water and nitrogen rates. The marginal difference in LAI was lower under irrigation (0.74 to 1.16) compared to nitrogen (2.15 to 3.22) treatments. This revealed that LAI was more sensitive to incremental N compared to available water levels but there were interactive effects between these two inputs. The best LAI was noted under the $I_{357}N_{120}$ treatment combinations in both seasons. This interaction combination also produced the tallest maize which also had the highest grain and dry matter yields. This revealed that combinations of supplemental irrigation (357 mm, Wr = 899.4 [SI] and 1137.0 mm [SII]) with nitrogen rates of 120 kg/ha are ideal for optimal performance of DK8031 maize at the experimental site. The relative supplemental irrigation were thus 39.7% and 31.4% in seasons I and II, respectively. For areas receiving marginal rainfall and declining soil fertility, farmers can take advantage of supplementing rainfall and adding nitrogen to enhance maize LAI and ultimately high crop yields.

Hammad *et al.* (2012) noted that photosynthesis and grain yields are significantly affected by irrigation amounts and that irrigation and N treatments greatly affected yield parameters of maize in both seasons of the experiment. They further noted that a significant interaction was observed between the irrigation and N treatments for grain yield, and the effect of N fertilizer on grain yield was quadratic during both study years. Under favorable moisture conditions, the LAI of maize was amplified with the application of N fertilizer and declined with a decrease of N doses, as observed by Valero *et al.* (2005) and Zhao *et al.* (2005). Nitrogen affects crop production through different mechanisms. Since it accelerates formation of chlorophyll, it increases cell counts and volume per leaf. The treatments affected biological yield due to an increase in biomass of the maize plants during the early parts of the growing seasons. Increased application of N fertilizer is not a sound strategy for obtaining maximum grain yield (Gheysari *et al.* 2009; Hammad *et al.* 2011a) as it ultimately results in lower NUE. The use of N rates above 225 kg ha^{-1} resulted in lower NUE. As observed by Paolo and Rinaldi (2008), NUE could be increased only at a specific application rate of N in the presence of lower soil moisture content.

Maize height was enhanced by supplemental irrigation (plus seasonal rainfall) significantly, with Season II maize plants growing much taller (240.3 cm) by 11.3% over the Season I crop (215.9 cm). The tallest maize plants were observed under the 357 mm and 120 kg-N/ha treatment combinations in both seasons. The highest leaf area index (LAI) of 6.07 and 7.58 was observed in the 357 mm and 120 kg-N/ha treatment combinations. These input treatment combinations also yielded the highest grain yields of 5.1 and 5.1 t/ha in Season I and Season II, respectively (Table 2 and Figure 2). Crop evapotranspiration was observed to increase with rainfall amount and irrigation water application levels up to I_{357} in Season I and I_{238} in Season II. Evapotranspiration was also enhanced by irrigation and nitrogen interaction, with $I_{357}N_{120}$ treatment combination giving the highest LAI of 6.07 in Season I and $I_{357}N_{90}$ 7.58 in Season II. Maize leaf area is of importance to photosynthesis and yield since the photosynthetic capacity of crops is a function of leaf area (Aikins *et al.*, 2012). Leaf area is important for crop light interception and therefore has a large influence on crop yield.

It has been observed that, for each irrigation level, there is an associated optimum amount of N which increases as the amount of irrigation applied is increased (Gheysari *et al.*, 2009). In the current study the highest LAI was produced at $I_{357}N_{120}$ treatment combination in both seasons. This is the same treatment combination that gave the highest grain and biomass yields as well as the tallest plants although these were not significantly different from the $I_{476}N_{120}$ treatment combinations. Therefore, farmers can opt to use 357 mm of supplemental irrigation water with 120 kg-N/ha rate when growing the DK8031 maize to optimize on grain production of the crop (Table 9; Figure 9). This is important for policy makers who have to decide on promoting the growing this stable food crop in a bid to enhance food security in Kenya.

Conversely DM and grain yields were also enhanced by increasing levels of irrigation and nitrogen application, either alone or in combination, which correlated positively with increase in height and LAI. This was in agreement with Quaye *et al.*, (2009) who noted that ETc correlated positively with biomass yield. This agrees with the current study where the highest grain (5,831.9 and 4,770.8 kg-grain/ha) and biomass (11,312.2 and 14,750.0 kg-DM/ha) yields of were obtained under the $I_{476}N_{90}$ treatment combinations in the two respective seasons (Table 2; Figure 2). This showed that grain yields required less extra water at a higher nitrogen rate compared to the production of biomass. As observed elsewhere, production of more dry matter is achieved at the expense of grain yields of maize. However, the two treatment combinations had comparable yields in both seasons. Therefore, farmers can choose to apply these input combinations to enhance both grain and biomass production of the DK8031 maize in Embu and similar agro-climatic zones.

5.4 Effect of Irrigation and Nitrogen on yield and yield attributes of maize

Grain yield was observed to increase with increase in water use (ETc) upto 4,100 kg/ha with 1027.0 mm in SI and 4,246 kg/ha with 1,105.5 mm in SII. As ETc increased from 675.5 to 1,027.0 mm in Season I, grain yield attributes such as number of cobs/plant and number of rows/cob increased. The water use increased with irrigation application and so were the yield and yield attributes. The yield and yield attributes of the DK8031 maize increased with nitrogen rates. The grain yield increased from 2,493 to 4,493 kg/ha (44.5%) in SI and 3,575 to 4,369 kg/ha (18.2) in Season II as N rates were increased from 0 to 120 kg-N/ha (Table 2). It is reported that irrigation causes significant variations on growth characters viz., plant height, number of leaves plant^{-1}, stem girth, leaf area index, crop growth rate of the crop and periodical dry matter accumulation plant^{-1} (Bouzzana *et al.*, 2012). They further noted that these parameters of the crop were significant due to nitrogen levels and they tended to increase with the increase in levels of nitrogen from 75 to 175 kg N ha^{-1}. The increase in plant height with different rates of nitrogen can be attributed to the fact that nitrogen promotes plant growth, increases the number and length of internodes which results in progressive increase in plant height (Amin, 2010). Nitrogen levels had pronounced effect on grain yield (Table 2). Farmers can therefore increase their yield of DK8031 maize in areas such as Embu where rainfall may be deficient by application of supplemental irrigation of between 357 mm (Wr = 899.4 mm in Season I and 1137.0 mm in Season II) and 476 mm (Wr = 1018.4 mm in Season I and 1256.0 mm in Season II) with nitrogen rates of between 90 and 120 kg-N/ha. Further research may be needed to monitor the effects of irrigation water and nitrogen rates over several seasons as climate change effects may influence on crop performance.

It has been reported by Sharma (2009) that a large grain production potential exists in rainfed crops, with hydroclimatic deficiency determining the boundary conditions of potential yields According to Sharma *et al.* (2010) up to 12% increase in crop production can be realized in both drought and normal rainfall seasons with supplemental irrigation. Work done in Mississippi, USA revealed that the grain yield of DK (Dekab) maize varieties ranged from 1,930 to 2,430 kg/ha with maturity differing from 114 to 116 days after sowing (Report, 2012). This finding suggested that it was possible to realize higher yield in irrigated corn when planted at plant densities greater than 31,000 seeds/ha. Mansouri-Far *et al*. (2010) found out that the 100-grain weight and yield of maize grown under deficit irrigation decreased under water deficit conditions. This is in agreement with the findings of the current study where the test weight and grain yields were observed to increase significantly with increased irrigation water.

The lowest test weight (32.0 and 33.0 g/100-seed) and grain yields (3,529 and 3,317 kg/ha) were attained with 119 mm of supplemental irrigation water, the least water applied in both seasons. The final yield of maize depends on successful development of flowers, their full fertilization, embryo development and starch and protein accumulation in grains continuous supply of assimilates (Moosavi, 2012). However, moisture stress decreases assimilate supply by decreasing leaf area and duration and disrupting nutrient intake and transfer and hence, it decreases grain yield components and yield. Grant *et al*., (1989) stated that water deficit severely decreased yield through abnormal development of embryo sac and grain sterility and finally, it decreased fertile grain number. Therefore, to obtain heavier grains and increased yields, water deficit conditions can be avoided in the growing of maize by using supplemental irrigation in water limited rainfed conditions as was the case in the experimental site.

It has further been observed that maximum yield of a crop is possible if crop evapotranspiration is met by a combination of soil water, in-crop rainfall and irrigation (GRDC, 2008). In the current study, this was achieved by use of irrigation to supplement rainfall and using higher nitrogen rates to promote maximum yield of the DK8031 maize. Seasonal crop evapotranspiraion increased with irrigation amounts up to 357 mm, hence optimizing yields of the crop. Farmers and policy makers can thus utilize 357 mm and between 90 and 120 kg-N/ha to optimize on maize yield production.

Dingkuhn*et al.* (2006) noted that low adoption and economic impact of annual grain crops is mainly due to highly variable rainfall and infertile soils besides pests and disease incidences in West Africa. On the other hand, Mavedia *et al.* (1998) reported in their analysis of the economic impact of food improvement research that maize and wheat with at least 50% adoption rate are more likely to be improved through breeding in Southern and Eastern Africa in hydrologically favorable environments. Such breeding had greater impact on irrigated and moist environments for maize (Dingkuhn*et al.* 2006). The government of Kenya through the Ministry of Water and Irrigation has reported harvesting 62,000 bags of maize from the 2,500 acres model irrigation farm at Galana Kulalu Irrigation Scheme and projects to increase the land area to 10,000 acres in the coming years. This initiative is good and can be supported by the findings of the current study where specific research on maize production under full and supplemental irrigation can complement each other in ensuring food security in the country. Maize is a stable food crop among many communities in Kenya and with yields of up to 5,100 kg/ha obtainable under the $I_{476}N_{120}$ (476 mm and 120 kg-N/ha) treatment combinations in rainfed conditions in Embu, collaborative work to determine the best input combinations and appropriate maize varieties is strongly recommended in this important national initiative.

A study to evaluate the performance of maize varieties in Kenya showed that the water use efficiency was higher where there was greater evapotranspiration rate accompanied by late seasonal drought (Mburu *et al.*, 2011). This was the case in the current study, especially in the second season where a drier spell in the later part of the season (January to early March, 2013) occasioned by high temperatures resulted into higher ETc and better grain yields compared to the Season I crop, under supplemental irrigation of 357 to 476 mm.

Work done in Kansas to evaluate grain yield response to irrigation and nitrogen rate at various sites concluded that a split application of 185 kg-N/ha was sufficient to achieve maximum yields of the maize crop at every location and that 125 kg-N/ha was often sufficient (Gehl *et al.*, 2005; Spalding *et al.*, 2001). Al-Kaisi and Yin (2003) found no significant differences in soil moisture extraction from the soil profile for the entire season of growth. This was similar to the observations made in the current study where significant soil moisture content was recorded at planting and harvest only when the crop by then is hardly extracting any soil moisture for growth or productive use.

Significant effects of interaction have been reported between irrigation and maize varieties for growth, yield and yield components (Spalding *et al*., 2001). These findings revealed that grain yield per hectare was positively and significantly correlated with plant height, number of ears/plant, ear length, 100-grain weight and grain yield per plant, among others. Marouf *et al.* (2013) noted that traits such as 100-grain weight, total number of grains per ear of maize should be target traits to improve maize grain yield under drought stress. Work at the Agricultural Research and Experimental Centre at Ranha University (2008-2009) showed that increasing soil moisture content from 40 to 100% FC can cause a significant growth, yield and yield components between 80 and 100% in some maize yields (Mahasen and Elgizawy, 2010). Similar observations were made in the current study where the grain and biomass yields increased with additional irrigation water applied.

5.5 Effects of irrigation and nitrogen on input use efficiency

The grain based irrigation water use efficiency (IWUE) of the DK8031 maize was observed to reduce with increasing irrigation application and reduced from 18.4 to 14.9 kg-grain/ha-mm and 18.6 to 17.3 kg-grain/ha-mm of irrigation water in Season I and Season II, respectively. Therefore, maize utilized the water more efficiently at lower irrigation applications with averages of 16.1 and 17.6 kg-grain/ha-mm in the respective seasons. This observation corroborates with the findings of Fan *et al*. (2005) who noted that the values of IWUE decreased with increasing amounts of supplemental irrigation. They further indicated that the yield depression of drought-stressed corn can be greatly reduced by small amounts of supplemental irrigation applied at critical growth stages. Farmers can therefore optimize their maize production using supplemental irrigation of between 119 to 238 mm in Embu in the two seasons.

Research work has shown that a linear regression under the experimental conditions in Australia was able to predict at least 83% of the yield for the measured maize crop ET requirements, the decline of yield depending on the severity, timing and duration of water stress (Allan *et al.*, 1998; Payero *et al.*, 2008). Their work further revealed that maize yields averaged 11.5 t/ha over the period of study with seasonal irrigation depths from 200 to 427 mm. The grain-based irrigation use efficiency ($IWUE_g$) here varied between 23.8 and 52.8 kg/ha-mm, with high rainfall amounts resulting in higher grain yields. It has been reported that irrigation treatments impact IWUE much more than water use efficiency (WUE), WUE increases non-linearly with seasonal ETc and with yield (Payero *et al.*, 2006). Similar finding were made in the current study for which a quadratic function provided the best fit. The IWUE and WUE tended to a maximum before starting to decline with increasing irrigation application and hence ET. The best interaction of between the study factors has shown that for each irrigation level there is an optimum N rate and increasing N rate reduced the optimal irrigation and vise versa. Maize is therefore best produced under moderately high irrigation levels due to the sensitivity of the maize to water deficits (Ko and Piccinni, 2008).

Yield and yield parameters of maize have been shown to increase with increasing nitrogen fertilizer amounts (Jaliya *et al.*, 2008). In the current study yields of grain (2.2 to 4.9 t/ha) and biomass (5.5 to 13.8 t/ha) increased with increasing rates of nitrogen application in both seasons. The WUE_g and WUE_b also followed the same incremental trend, ranging from 2.6 to 5.6 kg/ha-mm in both seasons. The best interaction treatments for WUE_g and WUE_b were achieved at $I_{238}N_{120}$ and $I_{119}N_{120}$ treatment combinations in Season I and Season II, respectively (Table 3). The cooler and drier Season I needed more irrigation water than the wetter-warmer Season II to utilize supplemental irrigation water more effectively. Quaye *et al.* (2009) reported that maize response to applied nitrogen is influenced by availability of water in the soil and that the WUE_g (6.53 to 6.76 kg-grain/ha-mm) is significantly but differently affected by the irrigation amounts among seasons. The control irrigation treatment (119 mm) gave the highest WUE compared to other treatments. On the other hand the agronomic nitrogen use efficiency decreased with increasing rates of nitrogen rates, varying from 8.5 to 23.6 kg-grain/kg-N and 15.1 to 56.2 kg-DM/kg-N in the combined seasons. The best interaction for NUE was achieved at $I_{357}I_{30}$ of 33.2 kg-grain/kg-N. Abbas *et al.*, (2005) reported a range of 8.32 to 15.72 kg-grain/kg-N, a range within what was observed in the current study. Such wide range differences are caused by factors such as climate, irrigation schedules and length of the growing period.

Sharma *et al.* (2015) have postulated that achieving synchrony between nutrient supply and crop demand without excess or deficiency under various moisture regimes is the key to optimizing trade-offs among yield and environmental protection in both large scale commercial systems in developed countries and small-scale systems in developing countries. Maize farmers in Embu and related agroecological zones can thus choose between NUE and grain (or DM production) in determining the best level of input combination of supplemental irrigation and nitrogen rates. This knowledge would be relevant for food security initiatives such as the Galana Irrigation scheme where maize is grown under irrigation but the optimal nitrogen rates and irrigation water levels may be wanting and unknown. A supplemental irrigation depth of 238 mm and 90 kg-N/ha is hereby recommended under current experimental conditions in Embu, KALRO agro-climatic region.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

a) Irrigation applications had significant effects on the yield, water use efficiency and nitrogen use efficiency of the dryland maize (DK8031 variety) in both seasons, with optimal levels being 357 and 238 mm depth of supplemental irrigation in Seasons I and II, respectively.

b) The nitrogen rates had significant effects on the yield, water use efficiency and nitrogen use efficiency of the dryland hybrid maize (DK8031) grown, with the best rates varying from 90 to 120 kg-N/ha.

c) Interactive effects of the study factors (irrigation application and nitrogen rates) were observed for seasonal evapotranspiration (ET_c), grain based irrigation use efficiency in Season I and biomass based water use efficiency in Season II. The best treatment combinations were 476 mm of irrigation and 120 kg-N/ha nitrogen.

d) It was possible to develop production functions relating the various yield, water use efficiency and nitrogen use efficiency with respect to the irrigation levels and nitrogen fertilizer rates. The Season I functions were able to predict the growth and yield values of Season II with at least 70% reliability. Linear and quadratic functions gave satisfactory functions of good fit.

6.2 Recommendations

Farmers in Embu who grow maize such as DK8031 and other stakeholders should:

a) Use supplemental irrigation of at least 238 mm water depth to boost grain and biomass yields as well as the respective water and nitrogen use efficiencies of the crop grown under rainfed conditions, applicable in similar agroecological zones.

b) Apply nitrogen of at least 90 kg-N/ha to the DK8031 maize to promote grain and biomass yields as a measure in addressing food security in the Embu County and similar agro-ecological zones.

c) Optimize production of DK8031 maize by applying the best interaction levels of 238 mm and 90 kg-N/ha to enhance crop productivity under similar rainfed conditions.

d) Utilize developed and improved linear and quadratic production to help in predicting and estimating parameter performance of the crop over the growing conditions and seasons.

6.3 Further work

The following are proposed further research work:

a) Effect of supplemental irrigation and nitrogen rates for other low yielding and drought tolerant maize varieties to enhance decision-making as well as policy formulation and implementation

b) The effects of residual nitrogen and optimum application rates for environmental integrity and conservation

c) The effect of organic inputs in the production of maize in marginal areas in Embu County and in areas of equivalent agro-ecological zones

d) Develop other models (regression equations and functions) for other maize varieties grown in similar agro-ecological conditions

REFERENCES

Abbas, G., Hussain, A., Ahmad, A. and Wajid, S. A. (2005). Effect of Irrigation Schedules and Nitrogen Rates on Yield and Yield Components of Maize. *Journal of Agriculture and Social Sciences, 1 (4),* 335-338.

Addo-Quaye, A. A., Darkwa, A.A, and Ocloo, G.K.. (2011). Yield and productivity of component crops in a maize - soybean intercropping system as affected by time of planting and spatial arrangement. *Journal of Agriculture and Biological Sciences, 6(9)*:50-57.

ASDS. (2010). Agricultural Sector Strategy Development, 2010 -2020, Government of Kenya, Government Printers, Nairobi.

Ahmad, B and Qahar, A. (2016). Effect of nitrogen and sulphur on maize hybrids yield and post-harvest soil nitrogen and sulphur. *Sarhad Journal of Agriculture, 32(3)*:239-251.

Aikins, S.H.M., Afuakwa, J.J. and Owusu-Akuoko, O. 2012. Effect of different tillage practices on maize performance under rainfed conditions. *Agriculture and Biology Journal of North America, 3(1):* 25-30

Al-Kaisi, M.M. and Yin, X., (2003). Effects of nitrogen rate, irrigation rate and plant population on corn yields and water use efficiency. *Agronomy Journal, 95*:1475-1482.

Allen RG, Pereira LS, Raes D, Smith M. (eds). (1998). Crop evapotranspiration - Guidelines for computing crop water requirements (Irrigation and Drainage Paper No. 56). Food and Agriculture Organization of the United Nations, Rome, Italy.

Amanullah, Kakar, K. M. and Khan, A. (2014). Growth and yield response of maize (Zea mays L.) to foliar NPK-fertilizers under moisture stress condition. *Soil & Environment. 33*:116–123

Amin, M. El-Murtada H. (2011). Effect of different nitrogen sources on growth, yield and quality of fodder maize (*Zea mays L.*). *ournal of Saudi Society of Agricultural Science,10(1):*17-23.

Arora, V.K. and Gajri P.R. (2000). Assessment of a crop growth-water balance model for predicting maize growth and yield in a subtropical environment. *Agricultural Water Management, 46:157-166.*

Ash, G.H.B., Shaykewich, C.F. and Raddatz, R.L. (1992). Agricultural Climate of the Eastern Canadian Prairies - A Technical Report. Environment Canada, Manitoba Agriculture, and Univ. of Manitoba, Winnipeg, MB, Canada.

Ashraf, U., Salim, M.N., Sher, A., Sabeeh-ur-Rasool, S., Khan, A. Pan, S. S, and Tang X. (2016). Maize growth, yield formation and water-nitrogen usage in response to varied irrigation and nitrogen supply under semi-arid climate. *Turkish Journal of Field Crops 2016, 21(1):* 87-95

Bastiaanssen, W.G.M., and Ali, S. (2003). A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. *Agriculture, Ecosystem and Environment, 94:*321-340

Bationo, A., Waswa, B., Kihara, J. and Kimetu, J. (Eds.), (2007). Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities, XIV, 1094p. Accessed 7/9/2011. http://www.springer.com/life+sciences/agriculture/book/978-1-4020-5759-5

Bello O.B., Afolabi M.S., Ige S.A., Abdulmaliq S.Y., Azeez M.A., and Mahmud J. (2012). Nitrogen use efficiency and grain yield in a diallelic cross of maize populations. *International Journal of Plant Research, 2:* 94–102.

Benincasa, P., Guiducci M. and Francesco Tei, (2011). The Nitrogen Use Efficiency: Meaning and Sources of Variation – Case Studies on Three Vegetable Crops in Central Italy. *Horticultural Technology, 21(3):*266-273.

Bergez, J.E. and Nolleau, S. (2003). Maize grain yield variability between irrigation stands: a theoretical study. *Agricultural Water Management, 60*:43-57.

Boegh, E., Thorsen, M., Butts, M.B., Hansen, S., Christiansen, J.S., Abrahamsen, P., … and Thomson, A. (2004). Incorporating remote sensing data in physically based distributed agro-hydrological modeling. *Journal of Hydrology, 287*:279- 299.

Bouzzama, B., Xantholis, D., Bouaziz, A.M., Ruelle, P. and Maihol, J.C., (2012). Effect of water stress on growth, water consumption and yields of silage maize under flood irrigation in a semi-arid climate of Tadha, Morpcco. *Biotechnology Society of Environment, 16(4):* 468-477.

Cassman, K.G., Dibermann, A., and Walters, D., (2002). Agroecosystems, nitrogen use efficiency and nitrogen management. *Ambio 31:*132 – 140.

CEEPA, (2006). Discussion Paper No. 19. Special Series on Climate Change and Agriculture in Africa, Centre for Environmental Economics in Africa. Republic of South Africa. Pretoria.

Choudhury, B.J., (2001). Estimating gross photosynthesis with remote sensing and ancillary data: approach and preliminary results. *Remote Sensing and Environment,75*:1-25.

Coops, N.C., Warring, R.H., Brown, S.R. and Running, S.W., (2001). Comparisons of predictions of net primary production and seasonal patterns in water use derived with two forest growth models in southwestern Oregon. *Ecological Modeling, 142*:61-81.

Dingkuhn, M., Singh, B.B., Clerget B., Chantereau J. and Sultan B. (2006). Past, present and future Criteria to breed crops for water-limited environments in West Africa. *Agricultural Water Management 8*:241-261.

Doberman, A., Yang, H.S., Linquist, J.L., D.T. Walters, D.T., Arkerbauer and Cessman, K.G., 2004. Hybrid-Maize – a maoze simulation model that combines two crop modeling approaches. *Field Crops Research, 87*:131-154.

Dobermann, A. and Cassmann, K.G. (2004). Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Science in China Series C. Life Sciences, 48*:745-758.

Duffy, K.J. and Masere, T.P., (2015). Effect of within-season daily rainfall distribution in maize crop yields, *SAGE Journals, 44(4):* 267-271

El-Hendaway, S.E., (2010). Optimal coupling combinations between irrigation frequency and rate for drip-irrigated maize grown on sandy soil. *Agricultural Water Management,97(3):*439-448.

El-Hendaway, S.E., El-Lattief,, E.A.A., Ahmed, M.S. and Schmhalter, U., (2008). Irrigation rate and plant density effects on maize yield and water use efficiency on drip-irrigated corn. *Agricultural Water Management, 95*:836-844.,

Elvio D.P. and Rinaldi, M., (2007). Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. *Field Crops Research, 105(3):* 202-210

Fan, T., Stewart, B.A., Payne, W.A., Wang, Y., Song, S., Luo, J. and Robinson C.A., (2005). Supplemental irrigation and water-yield relationships for plastic culture crops in the Loess Plateau of China. *Agronomy Journal, 97*:177-188.

Fan, X.M., Yin, X.M., Zhang, Y.D., Bi, Y.Q., Chen, H.M., and Kang, M.S., (2016). Combining Ability Estimation for Grain Yield of Maize Exotic Germplasm Using Testers from Three Heterotic Groups. *Crop Science, 56*:2527-2535.

Farre, I. and Faci, J.M. (2009). Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agricultural Water Management*, *96(3)*:383-394.

Farre, L.J., (2005). A revised Thornwaite-type global climate classification. *Physical Geography. 26(6):*442-466.

Fayza A. Faheed, F.A, Mohamed, E.I., and Mahmoud, H. M. (2016). Improvement of Maize Crop Yield (Zea mays L.) by using of Nitrogen Fertilization and Foliar Spray of Some Activators. *Journal of Ecology of Health & Environment 4*, (1):33-47

FEMA (1995). Disaster Declaration for 1995: Report on Costs and Benefits of National Hazard Mitigation. Federal Emergency Management Agency. California, USA.

Gary, C., Jones, J.W. and Tchamitchian, M. (1998). Crop modeling in horticulture: state of the art. *Scientia Horticulturae, 74*: 3-20.

Gehl, G.R., Schmidt J.P., Maddux L.D. and Gordon, W.B. (2005). Corn yield response to nitrogen rate and timing in sandy irrigated soils. *Agronomy Journal, 7:*1230-1238

Gheysari, M., Mirlatifi, S.M., Bannayan, M., Homae, M. and Hoogenboom, G. (2009). Interactions of water and nitrogen on maize grown for silage. *Agricultural Water Management. 9(5)*:809-821.

Gower, S.T., Kucharik, C.J., Norman, J.M. (1999). Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems. *Remote Sensing and Environment, 70*:21-59.

Grant, C.A., Peterson G.A. and Campbell C.A. (2002). Nutrient considerations for diversified cropping systems in the northern great plains. *Agronomy Journal, 94:* 186-198.

GRDC, (2008). Optimizing maize yield under irrigation. Grain Research Development Cooperation. Australian Government.

Grassini, P., Yang, H., and Cessman, K.G. (2009). Limits of maize productivity in Western Corn-Belt: A simulation analysis for fully irrigated and rainfed conditions. *Agriculture and Forest Meteorology, 149*:1254-1265.

Gregory, P. J. (1988). Plant and management practices affecting the water use efficiency of dryland crops, pp. 171-175. *In*: Proceedings of International Conference on Dryland Farming, Armarillo, Bushland, Armarillo, Bushland, Wiley and Sons, NY.

GoK, (2015). Strategic Plan 2013 – 2017. Government of Kenya, Ministry of Agriculture, Livestock and Fisheries: Government Printers, Nairobi, Kenya.

GoK, (2005). Strategy for Revitalizing Agriculture. Ministry of Agriculture and Livestock and Fisheries Department, 2004 – 2014. Government Printers. Nairobi, Kenya

Guohua M., Fanjun C. and Fusuo Z. (2007). Physiological and genetic mechanism for nitrogen-use efficiency in maize. *Journal of Crop Science and Biotechnology. 10(2)*:57-63.

Hammad, H.K., Tasneem, K. and Wajid, F. (2011). Optimizing rate of nitrogen application for higher yield and quality in maize under semi-arid environment. Agro-Climatology Laboratory, Department of Agronomy, University of Agriculture. Faisalabad, Pakistan.

Hammad, H.M., Abass, F., Farhad, W. (2012). Optimizing water and nitrogen use for maize production under semi-arid conditions. *Turkish Journal of Agriculture and Forestry, 36*:519-532.

Hanjra, M.A., Ferede, T., and Gutha, D.G. (2009). Reducing poverty in Africa through investments in water and other priorities: *Agricultural Water Management, 96:*1596-1604.

Hao, F., Chen, S., Ouyang, W., Shan, Y., and Qi, S. (2013). Temporal rainfall patterns with water partitioning impacts on maize yield on a freeze-thaw zone. *Journal of Hydrology, 486(0):*412-412.

Hedge, B. R. (1995). Improving water use efficiency under dryland conditions, pp. 177-175. *In Sustainable Development of Dryland Agriculture in India*, R.P. Singh (Ed.), Scientific Publishers, Jodhpur, India.

Heuvelink, E., Marcelis, L.F.M., Barker, M.J. and van der Proel, A. (2007). Use of crop growth models to evaluate physiological traits in genotypes of horticultural crops. *In: Scale and Complexity in Plant Systems Research: Gene-Plant-Crop Relations*, pp.223-233. Wageningen, The Netherlans.

Inamullah, N.R., Nazeer H. S., Muhammad A., Muhammad S., and Ishaq A.M., (2011). Correlations among grain yield and yield attributes in maize hybrids of various nitrogen levels. *Sarhad Journal of Agriculture,* 27(4), 2011.

IFA/FAO (2002). Fertilizer and the future. Agriculture Conference on Global Food Security and the role of Sustainability Fertilization. International Fertilizer Association/Food and Agriculture Organization, Rome, Italy.

IFDC (2007). Fertilizer Supply and Costs in Africa. The Bill and Melinda Gates Foundation. In collaboration with the Chemonics International Inc. and the International Center for Soil Fertility and Agricultural Development

Irmark, S., Haman, D. Z., and Jones, J. W., (2002). Evaluation of Class A pan coefficients for estimating reference evapotranspiration in humid location. *Journal of Irrigation and Drainage Engineering, 128*: 153–159.

Jaetzold R, Schmidt H, Hornet B, Shisanya C (2006). Farm Management Handbook of Kenya, Vol. II/C1. Ministry of Agriculture, Kenya and German Agency Technical Cooperation team (GTZ).

Jaliya, M.M., Falaki, A.M., Mahmud , M., and Sani, Y.A. (2008). Effect of sowing date and NPK fertilizer rate on yield and yield components of quality protein maize (*Zea mays L.*). *Journal of Agricultural and Biological Science, 3:*23-29

James, F. (2014). Temporal price trends for selected non-tradable staples in Northern Ghana: The case of major cereal foods. *Academia Journal of Agricultural Research 2(1):* 16-22.

Jordan, W.R.; Sinclair, T. R. and Taylor, H. M. (1990). *Limitations to Efficient Water Use in Crop Production.* Ecological Society of China. Elsevier B.V., New York.

Kamara A.Y., Ekeleme F., Chikoye, D. and Omoigui, L.O. (2008). Planting Date and Cultivar Effects on Grain Yield in dryland Corn Production. *Agronomy Journal, 101*:91-98.

Kanashiro, G.H., Vasquez, C.G., Laclette, E.I., Estrella, L.H., and Simpson J. (2010). Analysis of gene expression and physiological responses in three Mexican maize landraces under drought stress and recovery irrigation. RosettaCon 2010 Collection: Recent developments to the Rosetta Framework for macromolecular modeling, prediction and design. US National Library of Medicine, 4(10):e7531. New York

Karanja, F.K. (2006). 'CROPWAT Model Analysis of Crop water Use in Six Districts in Kenya', CEEPA DP35, University of Pretoria, South Africa.

Ketiem, P.K., Kipkorir, E.C. and Omondi, P. (2008). Modeling Effects Of Climate Change On Maize Production In Kenya: A Case Study Of Two Agro – Climatic Zones. Proceedings of the 11th KARI Biennial Scientific Conference, 10-14 November 2008 at KARI Headquarters. Kenya Agricultural Research Institute KARI, Kenya.

Kibe, A.M. and Onyari, C.N. (2007). Production functions and their use in predicting chickpea biomass yields when grown under varying tillage and sowing dates in Naivasha, Kenya. *Agricultural Journal, 2(4):*514-519.

Kiniry, J.R., Bean, B., Xie Y, Pei-yu C. (2004). Maize yield potential critical processes and simulation modeling in a high-yielding environment. Elsevier Ltd. Science Direct: Agricultural Systems www.elsevier.com/locate/agsy

Ko J. and Piccinni, C. (2008). Corn yield responses under crop evapotranspiration- based irrigation management. *Journal f Agricultural Water Management, 96*:799-808.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J and van Kessel C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and Prospects. *Advances in Agronomy, 87*:85-156.

Lindquist, J.L., Arkebauer T.J., Walters, D.T., Cessman, K.G., and Doberman, A. (2005). Maize radiation use efficiency under optimal growth conditions. Agronomy and Horticulture Department, Agron-Hort-Faculty Publications. University of Nebraska, USA.

Lobell, D.B., Asner, G.P., Ortiz-Monasterio, J.I., and Benning, T.L. (2003). Remote sensing of regional crop production in the Yanqui Valley, Mexico: estimates and uncertainties. *Agricultural Ecosystems and Environment, 94*:205-220.

Mahasen, S.A.S. and El-Gizawy N.K., 2010. Evaluation of some maize varieties to soil moisture stress. Proceedings of the International Conference on Agronomy. *Al-Arish, 5:*26-38.

Mansouri-Far, C., S. Ali, M.M. Sanavy and S.F. Saberali. (2010). Maize yield response to deficit irrigation during lowsensitive growth stages and nitrogen rate under semi- arid climatic conditions. *Agricultural Water Management, 97*: 12-22.

Markovic, M., Josipovic, M., Sostaric, J., Jambrovi, A. and Brkic, A., (2017). Response of maize (*Zea mays* L.) grain yield and yield components to irrigation and nitrogen fertilization. *Journal of Central European Agriculture, 18(1)*:55-72

Marouf K., Mohammad R. N., Alizera P. A., and Houshang N. R. (2013). Evaluation of relationships among grain yield and related traits in maize (*Zea mays. L.)* cultivars under drought stress. *International Journal of Agronomy and Plant Production, 4(6):* 1251-1255

Marshall, T.J., Holmes, J.W., Rose, C.W. (1996). *Soil Physics*. The University of Cambridge, New York.

Martin W. (2014). A Calculation Tool for Analyzing Nitrogen Use Efficiency in Annual and Perennial Crops. *Agronomy Journal, 4(4):470 – 477.*

Mavedia, A.C., Phillips, J.G., and Rosenzweig, C., (1998). ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. *Agriculture and Forest Meteorology, 90*:39-50.

Mburu, D.M, Lenga, F.K. and Mburu, M.W.K. (2011). Assessment of maize yield response to nitrogen fertilizer in two semi-arid areas in Kenya with similar rainfall pattern. *Journal of Agriculture, Science and Technology, 13 (1):* 1561-7645

Medeiros, J.C., Albuquerque, J.A., Mafra, A.L., Dalla Rosa J., and Gitiboni, L.C. (2008). Calcium:magnesium ration in amendments of soil acidity. Nutrition and initial development of corn plants in a Humic Alic Cambisol. *Semina Ci. Agrar., 29*:799-806.

Micheni, A. N. , Kanampiu F., Kitonyo O., Mburu D. M., Mugai E.N., Makumbi D. and Kassie M. (2015). On-farm experimentation on conservation agriculture in maize-legume based cropping systems in Kenya: water use efficiency and economic impacts. *Experimental Agriculture, 52*:51-68. Cambridge University Press, London.

Mikova, A. P. and Dimitrov, I. (2013). Maize Grain Yield Response to N Fertilization, Climate and hybrids. *Bulgarian Journal of Agricultural Sciences, 19(3)*:454-460

Miroslav, T., Eitzinger, J., Kapler, P., Dobrosky, M., Semaradova, D., and Formayer, H. (2007). Effect of estimated daily global solar radiation data on the results of crop growth models. *Sensors, 7:*2330-2362.

Mo, X., Liu S., Lin Z., Y. Xu Y., Xiang, Y. and Mcvicar, T. R. (2005. Prediction of crop yield, water consumption and water use efficiency with a SVAT crop using remotely sensed data on the North China Plain. *Ecological Modeling, 183*:301-322.

Moll. R.H., Kamprath E.J., and Jackson W.A., (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agronomy Journal, 74:*562 – 564.

Monteith, J.L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology, 9*:747-766.

Mousavi, M. B., Farhangfar, S., Bannayan, M., Khazaei, R. H. (2015). Vulnerability assessment of wheat and maize production affected by drought and climate change. *International Journal of Disaster Risk Reduction, 13:*37-51.

Mugendi, D.N., Mucher-Muna, M.M. and Mugwe, J.N. (Eds.), (2006). Soil Fertility: Enhancing Community Extension. Manilla Publishers. Nairobi, Kenya.

Munir A. H., Ferede T. and Gutta, D.G. (2009). Reducing poverty in sub-Saharan Africa through investments in water and other priorities. *Agricultural Water Management 96:*1062-1070.

Namara, R. E., Munir A. H., Gina E. C., Helle M. R., Ndamani, F., and Watanabe, T., (2015). Effects of rainfall on arable land-use and recommendations for adaptation. *International Journal of Agricultural Sciences, 5(1):*367-374

Namara, R., Hanjra, M. A., Castillo, G.E., Ruvnborg, H.M., Smith, L., and van Koppen, B., (2010). Agricultural water management and poverty linkages. *Agricultural Water Management 97(4):*520-527.

Nielsen, B. (2012). Historical corn grain yields for Indiana and the U.S. Purdue University Department of Agronomy. Accessed March 9th, 2017. http://www.kingcorn.org/news/timeless/YieldTrends.html. Accessed19/04/2016.

Nielson, R.L. (2012). Advanced farming systems and new technologies for the maize industry. Proceedinggs of the FAR Maize Conference, Hamilton, Purdue University, New Zealand.

Ogola, J. B. O., Wheeler, T. R. and Harris, P. M. (2006). Predicting the effects of nitrogen and plant density on maize water use efficiency in semi-arid Kenya. *South African Journal of Plant and Soi, 24*:1, 51-5

Ogola, J.B.O., Wheeler, T.R., and Harris, P.M., (2002). Effects of nitrogen and irrigation on water use of maize crops. *Field Crops Research, 78*:105-117.

Onyari, C.A.N., Ouma, J.P. and Kibe, A.M., (2010). Effects of tillage method and sowing time on phenology, yield and yield components of chickpea (*Cicer arietinum L.*) under semi-arid conditions in Kenya. *Journal of Applied Biosciences, 34*:2156-2165.

Paolo, D.E. and Rinaldo, M., (2008). Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. *Field Crops Research, 105(3):*202-210.

Payero, J.O., D.D. Tarkalson, S. Irmak, D. Davison and J.L. Petersen, (2008). Effect of irrigation amounts applied with sub-surface drip irrigation on corn evapotranspiration, yield and water use and dry matter production in a semi-arid climate. *Turkish Journal of Field Crops 18(1):*13-19.

Payero, J.O., Klocke, N.L., Schneekloth, J.P., and Davidson, D.R. (2006). Comparison of Irrigation Strategies for surface-irrigated corn in West Central Nebraska. *Irrigation Science, 24(4):*257-265.

Perret, S. (2006). New paradigms, policies and governance in the water sector, in S. Perret, S. Faroli and R. Hassan (sds.), 'Water Governance for Sustainable Development'. London, Great Britain.

Plummer, S.E. (2000). Perspectives on combining ecological process models and remotely sensed data. *Ecological Modeling, 129*:169-186.

Quaye, A.K., Laryea, K.B. and Mickson, S.A. (2009). Soil water and nitrogen interaction effects on maize (*Zea mays* L.) grown on a vertisol. *Journal of Forestry, Horticulture and Soil Science, 3(1)*:1-11.

Raouf S. S. and Reza T. (2010). Response of maize (*Zea mays* L.) cultivars to different levels of nitrogen fertilizer. *Journal of Food, Agriculture and Environment, 1(4)*:518-521.

Raouf, S.S. and Reza, T. (2009). Response of maize (*Zea mays L*) cultivars to different levels of nitrogen fertilizer. *Journal of Food, Agriculture and Environment, 7(3&4)*:518-521.

Report (2012). Learning Centre Demonstration Report, MIT Community Innovators Lab, Annual Report. Boston, Mississippi

Rugumayo, A., Kiiza, N., and Shima, J. (2003). Rainfall reliability for crop production. A Case Study in Uganda. Diffuse Pollution Conference. Dublin, South Africa.

Sanchez P.A. and Swaminathan, M.S. (2005). Hunger in Africa: the link between unhealthy people and unhealthy soils. *Lancent, 365*:442-444.

Seaquist, J.W., Olsson, L., Ardo, J., and Ekludh, L. (2006). Broad-scale increase in NPP quantified for the African Sahel, 1982 – 1999. *International Journal of Remote Sensing, 27:*5115-5122.

Shanahan, J and Groeteke, J. (2011). Corn Irrigation Practices With Limited Water. The Crop site, Corn / Maize Featured Articles. Accessed 5th Aug 2011. (http://www.thecropsite.com/articles/765/corn-irrigation-practices-with-limited-water).

Sharma, B.R. (2009). Rainwater harvesting in the management of agro-ecosystem: In: Barron, J. (Ed.). *Rain Water Harvesting: A Lifeline for Huma Wellbeing*. United Nations Environment Programmes/Stockholm Environment Institute, Nairobi, Kenya.

Sharma, B., Molden, D., and Cook, S. (2015). Water Use Efficiency in Agriculture: Measurement, Current Situation and Trends. *In*: Managing Water and Fertilizer for Sustainable Agricultural Intensification (Eds. P. Dreschel, Patrick A., Hillel M., Robert M., and Dennis W.). International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). Paris, France.

Sharma, L., Prasanna, B.M., and Ramesh, B. (2010). Analysis of phenotypic and microsatellite-based diversity of maize landraces in India, especially from North east Himalayan region. *Genetica, 138(6)*:619-631

Sharma, R.K. and Sharma, T.K. (2009). *Irrigation Engineering (Including Hydrology)*. S. Chand and Company Ltd, Ram Nagar. New Delhi, India.

Shenk, H.J. (2006). Nutrient efficiency of vegetable crops. *Acta Hort. 700:*25 – 38.

Shenk, H.J., 2006. Root competition: beyond resource depletion. *Journal of Ecology, 94*:725-739

Singh, B.R. and Singh, D.P. (1995). Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. Field Crops Research, 42(3): 57-67.

Spalding, R.F., Watts D.G., Schepers J.S., Burback M.E., Exner M.E., Poreda R.J. and Martin G.E. (2001). Controlling nitrate leaching in irrigated agriculture. *Journal of Environmental Quality, 30*:1184-1194.

Stanhill, G. (1966). Water Use Efficiency. *Advances in Agronomy, 39:* 53-85.

Steiner J. L, Day J. C., Papendik R. I., Meyer R. E. and Bertrand A. R. 1988. *Advances in Soil Science*, Vol. 8. Springer-Verlag, New York.

Suzette S. and du Toit, A.S. (2001). Identification of maize cultivars tolerant to low soil fertility in South Africa. Seventh Eastern and Southern Africa Regional Maize Conference, 11th – 15th February, 2001, pp.202-205. ARC-Grain Institute, Potchefstroom, South Africa.

The Kenya Vision 2030. Development Blue Print for the Republic of Kenya, 2007. Government Printers, Nairobi. Kenya

United Nations (UN), 2000. Millennium Declaration adopted by the Millennium Summit of World leaders at the General Assembly on 8th September, 2000. NY, USA

Thorup-Kristensen, K., Magid, J., and Jensen, S.L. *(*2003*)*. Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy. 79 :*227–302

Valero, J.A., Mutarano, M., Ramires, A.A., Martin-Benito, J.M.T. and Alvalez, J.F.O., (2005). Growth and nitrogen use efficiency of irrigated maize in a semi-arid region as affected by nitrogen fertilization. *Spanish Journal of Agricultural Research, 3(1):* 134-144.

van Eerd, L.L. (2007). Assessing different nitrogen use efficiency indices using field-grown green bell peppers. *Canadian Journal of Plant Science, 87:*565–569

Varvel, G.E. J.S. Schepers, and Francis D.D. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. *Soil Science Society of America Journal, 61*:1233–1239.

Varvel GE and Peterson P.A., 1990. Nitrogen Fertilizer Recovery by Corn in Monoculture and Rotation Systems. *Agronomy Journal, 82(5):* 935-938.

Vermeulen, S.J., Aggarwal P.K., Ainslie A., Angelone C., Campbell B.M., Challinor A.J., Hansen J.W., Ingram J.S.I., Jarvis A., Kristjanson P., Lau C., Nelson G.C., Thornton P.K. and Wollenberg E. (2012). Options for support to agriculture and food security under climate change. *Environmental Science and Policy, 15*:136-144

Walthall, C.L., Hatfield, J.L., Marshall, E., Lengnick, L., Backlund, … and Mcclung, A.M. (2013). Climate Change and Agriculture: Effects and Adaption. USDA Technical Bulletin 1935. Washington, DC, USA.

Weih, M. (2014). A calculation tool for analyzing nitrogen use efficiency in annual and perennial crops, *Agronomy 4*:40-47.

White Paper #105. (2011). Regional Corn Modeling at a High Resolution Scale: A Yield Based Approach and Blue Vs Green Water Assessment. http://www.sustainabilityconsortium.org/wp-content/themes/sustainability/assets/pdf/whitepapers/2011_NCGA_Crop_Modeling_Final_Report.pdf. Accessed 17th June, 2016.

Widtose, J.A., 2010. *Irrigation Practices*. AGROBIOS, India.

Wood, E.F., Roundy, J.K., Troy, T.J., van Beek, L.P.H., Bierkens, M.F.P. … and Whitehead, P. (2011). Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth’s terrestrial water. *Water Resources 47(5):1-10*

Xiukang, W. and Xing, Y. (2017). Effects of irrigation and nitrogen on maize growth and yield components. In: Global Changes and Natural Disaster Management: Geo-Information Technologies by S. Pirasteh and J. Li (eds.), Springer International Publishing AG. Accessed August 22, 2018. https://www.researchgate.net/publication/315365538_Effects_of_Irrigation_and_Nitrogen_on_Maize_Growth_and_Yield_Components

Xiying Z. Suying C., Mengyu L., Dong P. and Hongyong S. (2005). Improved water use efficiency associated with cultivars and agronomic management in North China. *Agronomy Journal, 97*:783-970.

Zhang, F., Zhenlin C., Xinping C., Xiaotang J., Jianbo S., Qing C., Xuejun L., Weifeng Z., Guohua M., Mingshen F., and Rongfeng J. (2012). Integrated nutrient management for food security and environmental quality in China. *Advances in Agronomy, 116*:1-40.

Zhang, F.S., Cui, Z.L., Fan, M.S., Zhang, W.F., Chen, X.P., and Jiang, Q.F. (2011). Integrated soil-crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient se efficiency in China. *Journal of Environmental Quality, 40*:1-7.

Zhang, F.S., Shen, J.B., Li, L., and Liu, X. (2004). An overview of rhizosphere processes related with plant nutrition in major cropping systems in China. *Plant and Soil, 260*:89-99.

Zhao, D., Reddy K.R., Kakani, V.G., and Reddy, V.R. (2005). Nitrogen deficiency effects on plant growth, leaf photosynthesis and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy, 22*:391-403.

APPENDICES

Appendix I. Weather data for maize grown over two seasons in Embu (April 2012 – March 2013)

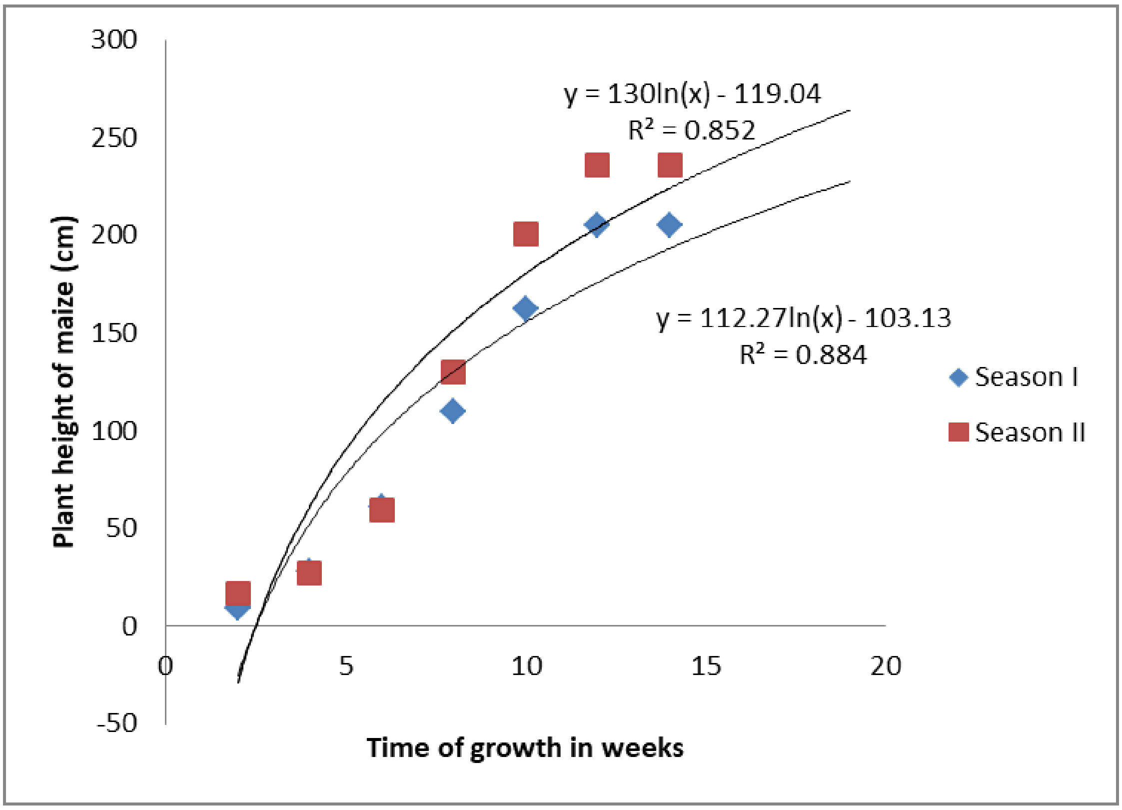
Month of the year	Rainfall (mm)	Min. Temp. (°C)	Max. Temp. (°C)	Mean Temp. (°C)	Wind run (km/day)	Rad. (MJm^{-2})	RH (%) [06Z]	RH (%) [12Z]	RH (%) Mean
Season I									
Apr	271.4	15.8	25.8	20.8	97.2	17.48	80	57	68.5
May	164.4	15.3	24.2	19.8	74.3	17.34	78	63	70.5
Jun	39.2	13.9	22.3	18.1	53.3	13.57	80	62	71.0
Jul	30.7	13.0	23.3	18.2	45.9	10.08	85	68	71.5
Aug	28.0	12.9	20.1	16.5	59.2	15.10	78	53	65.5
Sep	8.7	13.5	25.4	19.5	76.4	18.57	75	49	62.0
Season II									
Oct	123.5	15.2	26.2	20.7	102.3	21.20	75	52	63.5
Nov	280.1	15.0	25.1	20.1	111.1	19.87	78	58	68.0
Dec	187.1	14.1	24.1	19.1	105.8	18.76	76	62	69.0
Jan	17.1	13.7	25.6	19.7	118.7	22.97	68	55	61.5
Feb	4.7	13.3	27.6	20.5	156.4	25.19	62	41	51.5
Mar	0.3	15.4	29.0	22.2	112.0	21.46	78	49	63.5

Source: Kenya Meteorological Department, Embu Station (2012-2013)

Appendix II. Total moisture received from rainfall and irrigation application during the growth of DK8031 maize

Season	Source of water	Phased time (Days after sowing)							Total
		0 - 14	15 - 42	43 - 70	71 - 98	99 - 126	127 - 140	141 - 168	
I	Rainfall (mm)	271.4	164.4	39.2	28.4	22.3	12.9	3.8	542.4
	Irrigation (mm)	119	119	119	119	0	0	0	476
	Total water received (mm)	390.4	283.4	158.2	143.4	22.3	12.9	3.8	*1018.4*
II	Rainfall (mm)	272.6	230.7	188.2	66.9	21.3	0.3	0	*780.0*
	Irrigation (mm)	119	119	119	119	0	0	0	476
	Total water received (mm)	391.6	349.7	307.2	185.9	21.3	0.3	0	*1256*

Appendix III. Plant height of DK8031 maize grown at the University of Embu Demonstration Farm in Embu (2012-2013)



Appendix IV. SAS Output for grain and biomass yields of DK8031 maize grown in two in the two seasons

```
                          The SAS System        16:49 Thursday, April 8, 2016   1
                           The GLM Procedure
                         Class Level Information
                     Class        Levels    Values
                     Block           3    1 2 3
                     Irrign          4    1 2 3 4
                     Nitrgn          5    1 2 3 4 5
                       Number of observations    60
                            The SAS System        16:49 Thursday, April 8, 2016   2
                           The GLM Procedure
Dependent Variable: Grain1   Grain1
                              Sum of
   Source              DF        Squares     Mean Square   F Value    Pr > F
   Model               27    57564619.89      2132022.96     11.77    <.0001
   Error               32     5798588.83       181205.90
   Corrected Total     59    63363208.72
          R-Square    Coeff Var     Root MSE    Grain1 Mean
          0.908487     11.59594     425.6829       3670.965
   Source              DF    Type III SS     Mean Square   F Value    Pr > F
   Block                2     1888275.33       944137.66      5.21    0.0110
   Irrign               3     7366859.23      2455619.74     13.55    <.0001
   Block*Irrign         6     1218470.86       203078.48      1.12    0.3725
   Nitrgn               4    43969543.18     10992385.79     60.66    <.0001
   Irrign*Nitrgn       12     3121471.30       260122.61      1.44    0.2010
     Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
   Source              DF    Type III SS     Mean Square   F Value    Pr > F
   Irrign               3    7366859.225     2455619.742     12.09    0.0059
                            The SAS System        16:49 Thursday, April 8, 2016   3
                           The GLM Procedure
Dependent Variable: Grain2   Grain2
                              Sum of
   Source              DF        Squares     Mean Square   F Value    Pr > F
   Model               27    30018424.12      1111793.49      8.56    <.0001
   Error               32     4155460.29       129858.13
   Corrected Total     59    34173884.41
          R-Square    Coeff Var     Root MSE    Grain2 Mean
          0.878402     8.636151     360.3583       4172.673
   Source              DF    Type III SS     Mean Square   F Value    Pr > F
   Block                2      735008.19       367504.10      2.83    0.0738
   Irrign               3     2948757.17       982919.06      7.57    0.0006
   Block*Irrign         6     1129140.75       188190.13      1.45    0.2271
   Nitrgn               4    23965452.84      5991363.21     46.14    <.0001
   Irrign*Nitrgn       12     1240065.17       103338.76      0.80    0.6516
     Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
   Source              DF    Type III SS     Mean Square   F Value    Pr > F
   Irrign               3    2948757.167      982919.056      5.22    0.0413
                            The SAS System        16:49 Thursday, April 8, 2016   4
                           The GLM Procedure
```

```
Dependent Variable: Biomass1   Biomass1
                                    Sum of
     Source                  DF        Squares     Mean Square   F Value    Pr > F
     Model                    27    309692392.1      11470088.6       5.67    <.0001
     Error                   32     64742252.2      2023195.4
     Corrected Total            59    374434644.3
                R-Square    Coeff Var     Root MSE    Biomass1 Mean
                0.827093     20.40555     1422.391        6970.608
     Source                  DF     Type III SS     Mean Square    F Value    Pr > F
     Block                    2       1095789.1        547894.5       0.27    0.7645
     Irrign                  3     90082724.6     30027574.9      14.84    <.0001
     Block*Irrign              6      14036124.5       2339354.1       1.16    0.3537
     Nitrgn                   4     196246267.2      49061566.8      24.25    <.0001
     Irrign*Nitrgn            12       8231486.9        685957.2       0.34    0.9750
        Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
     Source                  DF     Type III SS     Mean Square    F Value    Pr > F
     Irrign                  3     90082724.55     30027574.85      12.84    0.0051
                                 The SAS System          16:49 Thursday, April 8, 2016   5
                               The GLM Procedure
Dependent Variable: Biomass2   Biomass2
                                    Sum of
     Source                  DF        Squares     Mean Square   F Value    Pr > F
     Model                    27    464666031.3      17209853.0      18.77    <.0001
     Error                   32     29346000.0       917062.5
     Corrected Total            59    494012031.3
                R-Square    Coeff Var     Root MSE    Biomass2 Mean
                0.940597     7.902084     957.6338        12118.75
     Source                  DF     Type III SS     Mean Square    F Value    Pr > F
     Block                    2         95312.5         47656.2       0.05    0.9494
     Irrign                  3    163114781.2     54371593.7      59.29    <.0001
     Block*Irrign              6       7759937.5       1293322.9       1.41    0.2411
     Nitrgn                   4     279930000.0      69982500.0      76.31    <.0001
     Irrign*Nitrgn            12      13766000.0       1147166.7       1.25    0.2938
        Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
     Source                  DF     Type III SS     Mean Square    F Value    Pr > F
     Irrign                  3    163114781.2     54371593.7      42.04    0.0002
                                 The SAS System          16:49 Thursday, April 8, 2016   6
                               The GLM Procedure
Dependent Variable: WUE1g   WUE1g
                                    Sum of
     Source                  DF        Squares     Mean Square   F Value    Pr > F
     Model                    27    103.0247105       3.8157300      12.30    <.0001
     Error                   32      9.9280548      0.3102517
     Corrected Total            59    112.9527654
                 R-Square    Coeff Var     Root MSE    WUE1g Mean
                 0.912104     12.67575     0.557002     4.394236
     Source                  DF     Type III SS     Mean Square    F Value    Pr > F
     Block                    2      3.02404111      1.51202056       4.87    0.0142
     Irrign                  3     20.24620014     6.74873338      21.75    <.0001
     Block*Irrign              6      8.85142826      1.47523804       4.75    0.0014
```

```
    Nitrgn                  4    64.80236699    16.20059175     52.22   <.0001
    Irrign*Nitrgn          12     6.10067405     0.50838950      1.64    0.1300
       Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
    Source                 DF     Type III SS    Mean Square    F Value    Pr > F
    Irrign                  3    20.24620014     6.74873338      4.57    0.0541
                             The SAS System        16:49 Thursday, April 8, 2016   7
                           The GLM Procedure
Dependent Variable: WUE2g   WUE2g
                                Sum of
    Source                 DF        Squares    Mean Square    F Value    Pr > F
    Model                  27    48.65202117     1.80192671      8.87    <.0001
    Error                  32     6.49788645     0.20305895
    Corrected Total        59    55.14990762
               R-Square     Coeff Var      Root MSE    WUE2g Mean
               0.882178      9.873787      0.450621      4.563808
    Source                 DF     Type III SS    Mean Square    F Value    Pr > F
    Block                   2     1.09281113     0.54640556      2.69    0.0831
    Irrign                  3    13.59319180     4.53106393     22.31    <.0001
    Block*Irrign            6     2.05197350     0.34199558      1.68    0.1570
    Nitrgn                  4    29.94074400     7.48518600     36.86    <.0001
    Irrign*Nitrgn          12     1.97330074     0.16444173      0.81    0.6387
       Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
    Source                 DF     Type III SS    Mean Square    F Value    Pr > F
    Irrign                  3    13.59319180     4.53106393     13.25    0.0047
                             The SAS System        16:49 Thursday, April 8, 2016   8
                           The GLM Procedure
Dependent Variable: WUE1b   WUE1b
                                Sum of
    Source                 DF        Squares    Mean Square    F Value    Pr > F
    Model                  27    338.4229870    12.5341847      4.08     0.0001
    Error                  32     98.3864578     3.0745768
    Corrected Total        59    436.8094448
               R-Square     Coeff Var      Root MSE    WUE1b Mean
               0.774761      21.49827      1.753447      8.156223
    Source                 DF     Type III SS    Mean Square    F Value    Pr > F
    Block                   2      3.0612158      1.5306079      0.50    0.6125
    Irrign                  3      4.7863242      1.5954414      0.52    0.6723
    Block*Irrign            6     19.8594972      3.3099162      1.08    0.3970
    Nitrgn                  4    288.6538198     72.1634550     23.47    <.0001
    Irrign*Nitrgn          12     22.0621299      1.8385108      0.60    0.8275
       Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
    Source                 DF     Type III SS    Mean Square    F Value    Pr > F
    Irrign                  3     4.78632422     1.59544141      0.48    0.7068
                             The SAS System        16:49 Thursday, April 8, 2016   9
                           The GLM Procedure
Dependent Variable: WUE2b   WUE2b
                                Sum of
    Source                 DF        Squares    Mean Square    F Value    Pr > F
    Model                  27    500.8601772    18.5503769     18.94    <.0001
    Error                  32     31.3497727     0.9796804
```

```
        Corrected Total           59     532.2099500
                      R-Square     Coeff Var     Root MSE    WUE2b Mean
                      0.941095      7.525550      0.989788      13.15237
        Source                    DF      Type III SS      Mean Square     F Value     Pr > F
        Block                      2       0.0914292        0.0457146       0.05    0.9545
        Irrign                     3      46.4553704       15.4851235      15.81    <.0001
        Block*Irrign               6      98.9785226       16.4964204      16.84    <.0001
        Nitrgn                     4     334.0833616       83.5208404      85.25    <.0001
        Irrign*Nitrgn             12      21.2514934        1.7709578       1.81    0.0896
          Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
        Source                    DF      Type III SS      Mean Square     F Value     Pr > F
        Irrign                     3     46.45537042     15.48512347       0.94    0.4784
                                  The SAS System         16:49 Thursday, April 8, 2016  10
                                 The GLM Procedure
                               Class Level Information
                            Class         Levels    Values
                            Block              3    1 2 3
                            Irrign             4    1 2 3 4
                            Nitrgn             5    1 2 3 4 5
                              Number of observations    60
                                  The SAS System         16:49 Thursday, April 8, 2016  11
                                 The GLM Procedure
    Dependent Variable: Grain1   Grain1
                                     Sum of
        Source                    DF        Squares     Mean Square    F Value    Pr > F
        Model                     27    57564619.89      2132022.96      11.77    <.0001
        Error                     32     5798588.83       181205.90
        Corrected Total           59    63363208.72
                     R-Square     Coeff Var      Root MSE    Grain1 Mean
                     0.908487      11.59594      425.6829      3670.965
        Source                    DF      Type III SS      Mean Square     F Value     Pr > F
        Block                      2      1888275.33        944137.66       5.21    0.0110
        Irrign                     3      7366859.23       2455619.74      13.55    <.0001
        Block*Irrign               6      1218470.86        203078.48       1.12    0.3725
        Nitrgn                     4     43969543.18      10992385.79      60.66    <.0001
        Irrign*Nitrgn             12      3121471.30        260122.61       1.44    0.2010
          Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
        Source                    DF      Type III SS      Mean Square     F Value     Pr > F
        Irrign                     3     7366859.225      2455619.742      12.09    0.0059
                                  The SAS System         16:49 Thursday, April 8, 2016  12
                                 The GLM Procedure
    Dependent Variable: Grain2   Grain2
                                     Sum of
        Source                    DF        Squares     Mean Square    F Value    Pr > F
        Model                     27    30018424.12      1111793.49       8.56    <.0001
        Error                     32     4155460.29       129858.13
        Corrected Total           59    34173884.41
                     R-Square     Coeff Var      Root MSE    Grain2 Mean
                     0.878402      8.636151      360.3583      4172.673
        Source                    DF      Type III SS      Mean Square     F Value     Pr > F
```

```
     Block                 2     735008.19      367504.10      2.83    0.0738
     Irrign               3     2948757.17      982919.06      7.57    0.0006
     Block*Irrign             6     1129140.75      188190.13      1.45    0.2271
     Nitrgn                4     23965452.84     5991363.21     46.14    <.0001
     Irrign*Nitrgn           12     1240065.17      103338.76      0.80    0.6516
        Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
     Source               DF     Type III SS     Mean Square    F Value    Pr > F
     Irrign               3    2948757.167     982919.056      5.22    0.0413
                            The SAS System        16:49 Thursday, April 8, 2016  13
                          The GLM Procedure
Dependent Variable: Biomass1   Biomass1
                                 Sum of
     Source               DF         Squares     Mean Square    F Value    Pr > F
     Model                27     309692392.1      11470088.6      5.67    <.0001
     Error               32      64742252.2      2023195.4
     Corrected Total           59     374434644.3
                R-Square     Coeff Var      Root MSE    Biomass1 Mean
                0.827093      20.40555      1422.391        6970.608
     Source               DF     Type III SS     Mean Square    F Value    Pr > F
     Block                 2      1095789.1       547894.5      0.27    0.7645
     Irrign               3     90082724.6     30027574.9     14.84    <.0001
     Block*Irrign             6      14036124.5      2339354.1      1.16    0.3537
     Nitrgn                4     196246267.2     49061566.8     24.25    <.0001
     Irrign*Nitrgn           12       8231486.9       685957.2      0.34    0.9750
        Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
     Source               DF     Type III SS     Mean Square    F Value    Pr > F
     Irrign               3    90082724.55    30027574.85     12.84    0.0051
                            The SAS System        16:49 Thursday, April 8, 2016  14
                          The GLM Procedure
Dependent Variable: Biomass2   Biomass2
                                 Sum of
     Source               DF         Squares     Mean Square    F Value    Pr > F
     Model                27     464666031.3      17209853.0     18.77    <.0001
     Error               32      29346000.0       917062.5
     Corrected Total           59     494012031.3
                R-Square     Coeff Var      Root MSE    Biomass2 Mean
                0.940597      7.902084      957.6338        12118.75
     Source               DF     Type III SS     Mean Square    F Value    Pr > F
     Block                 2        95312.5        47656.2      0.05    0.9494
     Irrign               3    163114781.2     54371593.7     59.29    <.0001
     Block*Irrign             6       7759937.5      1293322.9      1.41    0.2411
     Nitrgn                4     279930000.0     69982500.0     76.31    <.0001
     Irrign*Nitrgn           12      13766000.0      1147166.7      1.25    0.2938
        Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
     Source               DF     Type III SS     Mean Square    F Value    Pr > F
     Irrign               3    163114781.2     54371593.7     42.04    0.0002
                            The SAS System        16:49 Thursday, April 8, 2016  15
                          The GLM Procedure
Dependent Variable: WUE1g   WUE1g
                                 Sum of
```

```
    Source                DF        Squares     Mean Square   F Value    Pr > F
    Model                 27     103.0247105       3.8157300     12.30   <.0001
    Error                32       9.9280548       0.3102517
    Corrected Total           59     112.9527654
              R-Square     Coeff Var      Root MSE    WUE1g Mean
              0.912104      12.67575      0.557002      4.394236
    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    Block                  2      3.02404111      1.51202056      4.87    0.0142
    Irrign                3     20.24620014      6.74873338     21.75    <.0001
    Block*Irrign              6      8.85142826      1.47523804      4.75    0.0014
    Nitrgn                 4     64.80236699     16.20059175     52.22    <.0001
    Irrign*Nitrgn            12      6.10067405      0.50838950      1.64    0.1300
       Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    Irrign                3     20.24620014      6.74873338      4.57    0.0541
                          The SAS System         16:49 Thursday, April 8, 2016  16
                         The GLM Procedure
Dependent Variable: WUE2g   WUE2g
                              Sum of
    Source                DF        Squares     Mean Square   F Value    Pr > F
    Model                 27     48.65202117      1.80192671      8.87   <.0001
    Error                32      6.49788645      0.20305895
    Corrected Total           59     55.14990762
              R-Square     Coeff Var      Root MSE    WUE2g Mean
              0.882178      9.873787      0.450621      4.563808
    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    Block                  2      1.09281113      0.54640556      2.69    0.0831
    Irrign                3     13.59319180      4.53106393     22.31    <.0001
    Block*Irrign              6      2.05197350      0.34199558      1.68    0.1570
    Nitrgn                 4     29.94074400      7.48518600     36.86    <.0001
    Irrign*Nitrgn            12      1.97330074      0.16444173      0.81    0.6387
       Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    Irrign                3     13.59319180      4.53106393     13.25    0.0047
                          The SAS System         16:49 Thursday, April 8, 2016  17
                         The GLM Procedure
Dependent Variable: WUE1b   WUE1b
                              Sum of
    Source                DF        Squares     Mean Square   F Value    Pr > F
    Model                 27     338.4229870      12.5341847      4.08    0.0001
    Error                32      98.3864578       3.0745768
    Corrected Total           59     436.8094448
              R-Square     Coeff Var      Root MSE    WUE1b Mean
              0.774761      21.49827      1.753447      8.156223
    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    Block                  2       3.0612158       1.5306079      0.50    0.6125
    Irrign                3       4.7863242       1.5954414      0.52    0.6723
    Block*Irrign              6      19.8594972       3.3099162      1.08    0.3970
    Nitrgn                 4     288.6538198      72.1634550     23.47    <.0001
    Irrign*Nitrgn            12      22.0621299       1.8385108      0.60    0.8275
```

```
   Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
Source               DF     Type III SS     Mean Square    F Value    Pr > F
Irrign                3     4.78632422      1.59544141       0.48    0.7068
                          The SAS System         16:49 Thursday, April 8, 2016  18
                         The GLM Procedure
Dependent Variable: WUE2b   WUE2b
                              Sum of
Source               DF        Squares     Mean Square   F Value    Pr > F
Model                27     500.8601772      18.5503769     18.94    <.0001
Error                32      31.3497727       0.9796804
Corrected Total      59     532.2099500
          R-Square     Coeff Var      Root MSE    WUE2b Mean
          0.941095      7.525550      0.989788      13.15237
Source               DF     Type III SS     Mean Square    F Value    Pr > F
Block                 2      0.0914292       0.0457146       0.05    0.9545
Irrign                3     46.4553704      15.4851235      15.81    <.0001
Block*Irrign          6     98.9785226      16.4964204      16.84    <.0001
Nitrgn                4    334.0833616      83.5208404      85.25    <.0001
Irrign*Nitrgn        12     21.2514934       1.7709578       1.81    0.0896
   Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term
Source               DF     Type III SS     Mean Square    F Value    Pr > F
Irrign                3    46.45537042     15.48512347       0.94    0.4784
                          The SAS System         16:49 Thursday, April 8, 2016  19
                         The GLM Procedure
                        Least Squares Means
              Grain1       Standard              LSMEAN
   Irrign       LSMEAN          Error    Pr > |t|     Number
   1        3223.74200     109.91084     <.0001          1
   2        3448.88911     109.91084     <.0001          2
   3        3911.23022     109.91084     <.0001          3
   4        4099.99933     109.91084     <.0001          4
             Least Squares Means for effect Irrign
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                 Dependent Variable: Grain1
   i/j          1          2          3          4
     1                0.1572     0.0001     <.0001
     2     0.1572                0.0055     0.0002
     3     0.0001     0.0055                0.2335
     4     <.0001     0.0002     0.2335
              Grain2       Standard              LSMEAN
   Irrign       LSMEAN          Error    Pr > |t|     Number
   1        3815.00000      93.04412     <.0001          1
   2        4221.65533      93.04412     <.0001          2
   3        4230.55578      93.04412     <.0001          3
   4        4423.48000      93.04412     <.0001          4
             Least Squares Means for effect Irrign
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                 Dependent Variable: Grain2
   i/j          1          2          3          4
     1                0.0041     0.0035     <.0001
```

```
   2      0.0041              0.9465      0.1349
   3      0.0035      0.9465              0.1524
   4      <.0001      0.1349      0.1524
          Biomass1       Standard             LSMEAN
Irrign       LSMEAN         Error   Pr > |t|     Number
1        5513.30848      367.25971     <.0001          1
2        6117.75266      367.25971     <.0001          2
3        7632.72334      367.25971     <.0001          3
                 The SAS System         16:49 Thursday, April 8, 2016  20
                The GLM Procedure
               Least Squares Means
          Biomass1       Standard             LSMEAN
Irrign       LSMEAN         Error   Pr > |t|     Number
4        8618.64748      367.25971     <.0001          4
         Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
             Dependent Variable: Biomass1
 i/j          1           2           3           4
   1                  0.2531      0.0003      <.0001
   2      0.2531                  0.0064      <.0001
   3      0.0003      0.0064                  0.0667
   4      <.0001      <.0001      0.0667
          Biomass2       Standard             LSMEAN
Irrign       LSMEAN         Error   Pr > |t|     Number
1         9470.0000      247.2600    <.0001          1
2        12100.0000       247.2600    <.0001          2
3        13065.0000       247.2600    <.0001          3
4        13840.0000       247.2600    <.0001          4
         Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
             Dependent Variable: Biomass2
 i/j          1           2           3           4
   1                  <.0001      <.0001      <.0001
   2      <.0001                  0.0095      <.0001
   3      <.0001      0.0095                  0.0339
   4      <.0001      <.0001      0.0339
                     Standard             LSMEAN
Irrign   WUE1g LSMEAN          Error   Pr > |t|     Number
1        5.30177687     0.14381741     <.0001          1
2        4.48478794     0.14381741     <.0001          2
3        3.79563356     0.14381741     <.0001          3
4        3.99474669     0.14381741     <.0001          4
                 The SAS System         16:49 Thursday, April 8, 2016  21
                The GLM Procedure
               Least Squares Means
         Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
              Dependent Variable: WUE1g
 i/j          1           2           3           4
   1                  0.0003      <.0001      <.0001
```

```
    2      0.0003                 0.0019     0.0219
    3      <.0001      0.0019                0.3349
    4      <.0001      0.0219     0.3349
                    Standard              LSMEAN
Irrign    WUE2g LSMEAN        Error    Pr > |t|     Number
1         5.09272530     0.11634975    <.0001        1
2         4.89385907     0.11634975    <.0001        2
3         4.40691341     0.11634975    <.0001        3
4         3.86173275     0.11634975    <.0001        4
          Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
              Dependent Variable: WUE2g
 i/j          1          2          3          4
    1                 0.2357     0.0002     <.0001
    2      0.2357                0.0058     <.0001
    3      0.0002      0.0058                0.0023
    4      <.0001      <.0001     0.0023
                    Standard              LSMEAN
Irrign    WUE1b LSMEAN        Error    Pr > |t|     Number
1         8.16383867     0.45273810    <.0001        1
2         7.69288908     0.45273810    <.0001        2
3         8.36807352     0.45273810    <.0001        3
4         8.40009041     0.45273810    <.0001        4
                 The SAS System        16:49 Thursday, April 8, 2016  22
                 The GLM Procedure
                Least Squares Means
          Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
              Dependent Variable: WUE1b
 i/j          1          2          3          4
    1                 0.4674     0.7518     0.7146
    2      0.4674                0.2995     0.2776
    3      0.7518      0.2995                0.9604
    4      0.7146      0.2776     0.9604
                    Standard              LSMEAN
Irrign    WUE2b LSMEAN        Error    Pr > |t|     Number
1         13.7339001      0.2555622    <.0001        1
2         13.2662459      0.2555622    <.0001        2
3         13.9236094      0.2555622    <.0001        3
4         11.6857175      0.2555622    <.0001        4
          Least Squares Means for effect Irrign
          Pr > |t| for H0: LSMean(i)=LSMean(j)
              Dependent Variable: WUE2b
 i/j          1          2          3          4
    1                 0.2049     0.6033     <.0001
    2      0.2049                0.0783     0.0001
    3      0.6033      0.0783                <.0001
    4      <.0001      0.0001     <.0001
NOTE: To ensure overall protection level, only probabilities associated with pre-planned
      comparisons should be used.
```

```
              Grain1      Standard              LSMEAN
   Nitrgn        LSMEAN          Error   Pr > |t|     Number
   1         2213.16000     122.88406     <.0001          1
   2         3304.16639     122.88406     <.0001          2
   3         3923.61083     122.88406     <.0001          3
   4         4227.77722     122.88406     <.0001          4
   5         4686.11139     122.88406     <.0001          5
                    The SAS System         16:49 Thursday, April 8, 2016  23
                    The GLM Procedure
                   Least Squares Means
              Least Squares Means for effect Nitrgn
               Pr > |t| for H0: LSMean(i)=LSMean(j)
                  Dependent Variable: Grain1
i/j          1          2          3          4          5
  1                 <.0001     <.0001     <.0001     <.0001
  2      <.0001                0.0012     <.0001     <.0001
  3      <.0001     0.0012                0.0897     0.0001
  4      <.0001     <.0001     0.0897                0.0128
  5      <.0001     <.0001     0.0001     0.0128
              Grain2      Standard              LSMEAN
   Nitrgn        LSMEAN          Error   Pr > |t|     Number
   1         3224.30556     104.02649     <.0001          1
   2         3734.37500     104.02649     <.0001          2
   3         4236.47500     104.02649     <.0001          3
   4         4718.86083     104.02649     <.0001          4
   5         4949.34750     104.02649     <.0001          5
              Least Squares Means for effect Nitrgn
               Pr > |t| for H0: LSMean(i)=LSMean(j)
                  Dependent Variable: Grain2
i/j          1          2          3          4          5
  1                 0.0015     <.0001     <.0001     <.0001
  2      0.0015                0.0018     <.0001     <.0001
  3      <.0001     0.0018                0.0025     <.0001
  4      <.0001     <.0001     0.0025                0.1270
  5      <.0001     <.0001     <.0001     0.1270
             Biomass1      Standard              LSMEAN
   Nitrgn        LSMEAN          Error   Pr > |t|     Number
   1         4336.66274     410.60883     <.0001          1
   2         5665.32639     410.60883     <.0001          2
   3         7272.98603     410.60883     <.0001          3
   4         8079.22227     410.60883     <.0001          4
   5         9498.84252     410.60883     <.0001          5
                    The SAS System         16:49 Thursday, April 8, 2016  24
                    The GLM Procedure
                   Least Squares Means
              Least Squares Means for effect Nitrgn
               Pr > |t| for H0: LSMean(i)=LSMean(j)
                 Dependent Variable: Biomass1
i/j          1          2          3          4          5
  1                 0.0289     <.0001     <.0001     <.0001
```

```
  2      0.0289              0.0093      0.0002      <.0001
  3      <.0001     0.0093               0.1746      0.0006
  4      <.0001     0.0002      0.1746               0.0202
  5      <.0001     <.0001      0.0006      0.0202
              Biomass2      Standard             LSMEAN
   Nitrgn         LSMEAN          Error    Pr > |t|     Number
   1          8954.1667       276.4451     <.0001         1
   2         10606.2500       276.4451     <.0001         2
   3         12179.1667       276.4451     <.0001         3
   4         14000.0000       276.4451     <.0001         4
   5         14854.1667       276.4451     <.0001         5
            Least Squares Means for effect Nitrgn
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                Dependent Variable: Biomass2
i/j          1          2          3          4          5
  1                 0.0002      <.0001      <.0001      <.0001
  2      0.0002              0.0003      <.0001      <.0001
  3      <.0001     0.0003               <.0001      <.0001
  4      <.0001     <.0001      <.0001               0.0363
  5      <.0001     <.0001      <.0001      0.0363
                       Standard              LSMEAN
   Nitrgn    WUE1g LSMEAN          Error    Pr > |t|     Number
   1         2.60819562     0.16079275     <.0001         1
   2         3.96374176     0.16079275     <.0001         2
   3         4.77410128     0.16079275     <.0001         3
   4         5.00115957     0.16079275     <.0001         4
   5         5.62398308     0.16079275     <.0001         5
                    The SAS System        16:49 Thursday, April 8, 2016  25
                   The GLM Procedure
                   Least Squares Means
            Least Squares Means for effect Nitrgn
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                 Dependent Variable: WUE1g
i/j          1          2          3          4          5
  1                 <.0001      <.0001      <.0001      <.0001
  2      <.0001              0.0012      <.0001      <.0001
  3      <.0001     0.0012               0.3255      0.0007
  4      <.0001     <.0001      0.3255               0.0100
  5      <.0001     <.0001      0.0007      0.0100
                       Standard              LSMEAN
   Nitrgn    WUE2g LSMEAN          Error    Pr > |t|     Number
   1         3.50178051     0.13008297     <.0001         1
   2         4.07007373     0.13008297     <.0001         2
   3         4.64240814     0.13008297     <.0001         3
   4         5.18791610     0.13008297     <.0001         4
   5         5.41685969     0.13008297     <.0001         5
            Least Squares Means for effect Nitrgn
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                 Dependent Variable: WUE2g
i/j          1          2          3          4          5
```

```
   1            0.0041     <.0001     <.0001     <.0001
   2     0.0041            0.0039     <.0001     <.0001
   3     <.0001     0.0039            0.0057     0.0002
   4     <.0001     <.0001     0.0057            0.2224
   5     <.0001     <.0001     0.0002     0.2224
                         Standard             LSMEAN
     Nitrgn    WUE1b LSMEAN         Error    Pr > |t|     Number
     1        4.9391254      0.5061766     <.0001         1
     2        6.5879870      0.5061766     <.0001         2
     3        8.5755567      0.5061766     <.0001         3
     4        9.4621291      0.5061766     <.0001         4
     5        11.2163165      0.5061766     <.0001         5
                    The SAS System        16:49 Thursday, April 8, 2016  26
                    The GLM Procedure
                   Least Squares Means
            Least Squares Means for effect Nitrgn
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                  Dependent Variable: WUE1b
 i/j         1          2          3          4          5
   1            0.0279     <.0001     <.0001     <.0001
   2     0.0279            0.0091     0.0003     <.0001
   3     <.0001     0.0091            0.2245     0.0008
   4     <.0001     0.0003     0.2245            0.0199
   5     <.0001     <.0001     0.0008     0.0199
                         Standard             LSMEAN
     Nitrgn    WUE2b LSMEAN         Error    Pr > |t|     Number
     1        9.7012280      0.2857272     <.0001         1
     2        11.5179436      0.2857272     <.0001         2
     3        13.1754218      0.2857272     <.0001         3
     4        15.2127064      0.2857272     <.0001         4
     5        16.1545413      0.2857272     <.0001         5
            Least Squares Means for effect Nitrgn
             Pr > |t| for H0: LSMean(i)=LSMean(j)
                  Dependent Variable: WUE2b
 i/j         1          2          3          4          5
   1            <.0001     <.0001     <.0001     <.0001
   2     <.0001            0.0003     <.0001     <.0001
   3     <.0001     0.0003            <.0001     <.0001
   4     <.0001     <.0001     <.0001            0.0262
   5     <.0001     <.0001     <.0001     0.0262
NOTE: To ensure overall protection level, only probabilities associated with pre-planned
      comparisons should be used.
                   Grain1       Standard              LSMEAN
 Irrign    Nitrgn          LSMEAN         Error    Pr > |t|     Number
 1       1         1868.70889      245.76812     <.0001          1
 1       2         2500.00111      245.76812     <.0001          2
 1       3         3500.00000      245.76812     <.0001          3
 1       4         3805.55444      245.76812     <.0001          4
 1       5         4444.44556      245.76812     <.0001          5
                    The SAS System        16:49 Thursday, April 8, 2016  27
```

```
                         The GLM Procedure
                        Least Squares Means
                        Grain1      Standard            LSMEAN
         Irrign   Nitrgn      LSMEAN          Error   Pr > |t|      Number
         2        1        1988.88889      245.76812    <.0001          6
         2        2        3133.33333      245.76812    <.0001          7
         2        3        3611.11111      245.76812    <.0001          8
         2        4        4066.66667      245.76812    <.0001          9
         2        5        4444.44556      245.76812    <.0001         10
         3        1        1867.26444      245.76812    <.0001         11
         3        2        3805.55444      245.76812    <.0001         12
         3        3        4361.11111      245.76812    <.0001         13
         3        4        4666.66556      245.76812    <.0001         14
         3        5        4855.55556      245.76812    <.0001         15
         4        1        3127.77778      245.76812    <.0001         16
         4        2        3777.77667      245.76812    <.0001         17
         4        3        4222.22111      245.76812    <.0001         18
         4        4        4372.22222      245.76812    <.0001         19
         4        5        4999.99889      245.76812    <.0001         20
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: Grain1
i/j      1       2       3       4       5       6       7       8       9       10
  1           0.0787  <.0001  <.0001  <.0001  0.7318  0.0010  <.0001  <.0001  <.0001
  2  0.0787           0.0071  0.0007  <.0001  0.1512  0.0778  0.0031  <.0001  <.0001
  3  <.0001  0.0071           0.3859  0.0105  0.0001  0.2993  0.7513  0.1128  0.0105
  4  <.0001  0.0007  0.3859           0.0753  <.0001  0.0620  0.5798  0.4580  0.0753
  5  <.0001  <.0001  0.0105  0.0753           <.0001  0.0007  0.0225  0.2852  1.0000
  6  0.7318  0.1512  0.0001  <.0001  <.0001           0.0024  <.0001  <.0001  <.0001
  7  0.0010  0.0778  0.2993  0.0620  0.0007  0.0024           0.1788  0.0114  0.0007
  8  <.0001  0.0031  0.7513  0.5798  0.0225  <.0001  0.1788           0.1993  0.0225
  9  <.0001  <.0001  0.1128  0.4580  0.2852  <.0001  0.0114  0.1993          0.2852
 10  <.0001  <.0001  0.0105  0.0753  1.0000  <.0001  0.0007  0.0225  0.2852
 11  0.9967  0.0781  <.0001  <.0001  <.0001  0.7287  0.0009  <.0001  <.0001  <.0001
 12  <.0001  0.0007  0.3859  1.0000  0.0753  <.0001  0.0620  0.5798  0.4580  0.0753
 13  <.0001  <.0001  0.0187  0.1198  0.8120  <.0001  0.0013  0.0386  0.4032  0.8120
 14  <.0001  <.0001  0.0020  0.0187  0.5271  <.0001  0.0001  0.0047  0.0939  0.5271
 15  <.0001  <.0001  0.0005  0.0049  0.2456  <.0001  <.0001  0.0011  0.0301  0.2456
 16  0.0010  0.0803  0.2922  0.0600  0.0006  0.0025  0.9873  0.1739  0.0110  0.0006
 17  <.0001  0.0009  0.4301  0.9368  0.0641  <.0001  0.0730  0.6348  0.4120  0.0641
 18  <.0001  <.0001  0.0458  0.2394  0.5271  <.0001  0.0037  0.0883  0.6575  0.5271
 19  <.0001  <.0001  0.0173  0.1128  0.8367  <.0001  0.0012  0.0359  0.3859  0.8367
 20  <.0001  <.0001  0.0001  0.0017  0.1198  <.0001  <.0001  0.0004  0.0114  0.1198
                          The SAS System        16:49 Thursday, April 8, 2016  28
                         The GLM Procedure
                        Least Squares Means
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: Grain1
i/j      11      12      13      14      15      16      17      18      19      20
```

```
 1  0.9967  <.0001  <.0001  <.0001  <.0001  0.0010  <.0001  <.0001  <.0001  <.0001
 2  0.0781  0.0007  <.0001  <.0001  <.0001  0.0803  0.0009  <.0001  <.0001  <.0001
 3  <.0001  0.3859  0.0187  0.0020  0.0005  0.2922  0.4301  0.0458  0.0173  0.0001
 4  <.0001  1.0000  0.1198  0.0187  0.0049  0.0600  0.9368  0.2394  0.1128  0.0017
 5  <.0001  0.0753  0.8120  0.5271  0.2456  0.0006  0.0641  0.5271  0.8367  0.1198
 6  0.7287  <.0001  <.0001  <.0001  <.0001  0.0025  <.0001  <.0001  <.0001  <.0001
 7  0.0009  0.0620  0.0013  0.0001  <.0001  0.9873  0.0730  0.0037  0.0012  <.0001
 8  <.0001  0.5798  0.0386  0.0047  0.0011  0.1739  0.6348  0.0883  0.0359  0.0004
 9  <.0001  0.4580  0.4032  0.0939  0.0301  0.0110  0.4120  0.6575  0.3859  0.0114
10  <.0001  0.0753  0.8120  0.5271  0.2456  0.0006  0.0641  0.5271  0.8367  0.1198
11          <.0001  <.0001  <.0001  <.0001  0.0010  <.0001  <.0001  <.0001  <.0001
12  <.0001          0.1198  0.0187  0.0049  0.0600  0.9368  0.2394  0.1128  0.0017
13  <.0001  0.1198          0.3859  0.1645  0.0012  0.1030  0.6921  0.9747  0.0753
14  <.0001  0.0187  0.3859          0.5906  0.0001  0.0155  0.2102  0.4032  0.3447
15  <.0001  0.0049  0.1645  0.5906          <.0001  0.0040  0.0778  0.1739  0.6805
16  0.0010  0.0600  0.0012  0.0001  <.0001          0.0706  0.0035  0.0011  <.0001
17  <.0001  0.9368  0.1030  0.0155  0.0040  0.0706          0.2102  0.0969  0.0013
18  <.0001  0.2394  0.6921  0.2102  0.0778  0.0035  0.2102          0.6689  0.0323
19  <.0001  0.1128  0.9747  0.4032  0.1739  0.0011  0.0969  0.6689          0.0803
20  <.0001  0.0017  0.0753  0.3447  0.6805  <.0001  0.0013  0.0323  0.0803
                         Grain2       Standard              LSMEAN
      Irrign   Nitrgn        LSMEAN          Error    Pr > |t|      Number
      1        1          2743.05556     208.05299    <.0001          1
      1        2          3305.55556     208.05299    <.0001          2
      1        3          3834.72222     208.05299    <.0001          3
      1        4          4431.94444     208.05299    <.0001          4
      1        5          4759.72222     208.05299    <.0001          5
      2        1          3083.33333     208.05299    <.0001          6
      2        2          3583.33333     208.05299    <.0001          7
      2        3          4479.16556     208.05299    <.0001          8
      2        4          4876.33333     208.05299    <.0001          9
      2        5          5086.11111     208.05299    <.0001         10
      3        1          3534.72222     208.05299    <.0001         11
      3        2          3993.05667     208.05299    <.0001         12
      3        3          4236.11111     208.05299    <.0001         13
      3        4          4527.77778     208.05299    <.0001         14
      3        5          4861.11111     208.05299    <.0001         15
      4        1          3536.11111     208.05299    <.0001         16
      4        2          4055.55444     208.05299    <.0001         17
      4        3          4395.90111     208.05299    <.0001         18
                          The SAS System         16:49 Thursday, April 8, 2016  29
                         The GLM Procedure
                         Least Squares Means
                         Grain2       Standard              LSMEAN
      Irrign   Nitrgn        LSMEAN          Error    Pr > |t|      Number
      4        4          5039.38778     208.05299    <.0001         19
      4        5          5090.44556     208.05299    <.0001         20
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: Grain2
```

```
i/j      1       2       3       4       5       6       7       8       9      10
  1          0.0649  0.0008  <.0001  <.0001  0.2560  0.0075  <.0001  <.0001  <.0001
  2  0.0649          0.0815  0.0006  <.0001  0.4556  0.3522  0.0004  <.0001  <.0001
  3  0.0008  0.0815          0.0508  0.0036  0.0156  0.3992  0.0359  0.0012  0.0002
  4  <.0001  0.0006  0.0508          0.2736  <.0001  0.0070  0.8735  0.1408  0.0334
  5  <.0001  <.0001  0.0036  0.2736          <.0001  0.0004  0.3475  0.6945  0.2756
  6  0.2560  0.4556  0.0156  <.0001  <.0001          0.0990  <.0001  <.0001  <.0001
  7  0.0075  0.3522  0.3992  0.0070  0.0004  0.0990          0.0046  0.0001  <.0001
  8  <.0001  0.0004  0.0359  0.8735  0.3475  <.0001  0.0046          0.1865  0.0473
  9  <.0001  <.0001  0.0012  0.1408  0.6945  <.0001  0.0001  0.1865          0.4810
 10  <.0001  <.0001  0.0002  0.0334  0.2756  <.0001  <.0001  0.0473  0.4810
 11  0.0112  0.4418  0.3156  0.0046  0.0002  0.1348  0.8698  0.0030  <.0001  <.0001
 12  0.0002  0.0259  0.5942  0.1456  0.0138  0.0041  0.1734  0.1083  0.0052  0.0008
 13  <.0001  0.0034  0.1820  0.5105  0.0846  0.0004  0.0337  0.4149  0.0371  0.0069
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: Grain2
i/j     11      12      13      14      15      16      17      18      19      20
  1  0.0112  0.0002  <.0001  <.0001  <.0001  0.0111  <.0001  <.0001  <.0001  <.0001
  2  0.4418  0.0259  0.0034  0.0002  <.0001  0.4390  0.0158  0.0008  <.0001  <.0001
  3  0.3156  0.5942  0.1820  0.0248  0.0014  0.3178  0.4584  0.0655  0.0003  0.0002
  4  0.0046  0.1456  0.5105  0.7468  0.1544  0.0046  0.2100  0.9033  0.0472  0.0323
  5  0.0002  0.0138  0.0846  0.4363  0.7327  0.0002  0.0227  0.2253  0.3490  0.2694
  6  0.1348  0.0041  0.0004  <.0001  <.0001  0.1337  0.0024  <.0001  <.0001  <.0001
  7  0.8698  0.1734  0.0337  0.0030  0.0001  0.8735  0.1183  0.0094  <.0001  <.0001
  8  0.0030  0.1083  0.4149  0.8698  0.2035  0.0031  0.1597  0.7790  0.0659  0.0459
  9  <.0001  0.0052  0.0371  0.2449  0.9591  <.0001  0.0088  0.1123  0.5833  0.4721
 10  <.0001  0.0008  0.0069  0.0668  0.4501  <.0001  0.0014  0.0253  0.8748  0.9883
 11          0.1291  0.0232  0.0019  <.0001  0.9963  0.0862  0.0063  <.0001  <.0001
 12  0.1291          0.4149  0.0785  0.0059  0.1303  0.8331  0.1805  0.0012  0.0007
 13  0.0232  0.4149          0.3290  0.0415  0.0235  0.5438  0.5908  0.0102  0.0066
                         The SAS System       16:49 Thursday, April 8, 2016  30
                         The GLM Procedure
                         Least Squares Means
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: Grain2
i/j      1       2       3       4       5       6       7       8       9      10
 14  <.0001  0.0002  0.0248  0.7468  0.4363  <.0001  0.0030  0.8698  0.2449  0.0668
 15  <.0001  <.0001  0.0014  0.1544  0.7327  <.0001  0.0001  0.2035  0.9591  0.4501
 16  0.0111  0.4390  0.3178  0.0046  0.0002  0.1337  0.8735  0.0031  <.0001  <.0001
 17  <.0001  0.0158  0.4584  0.2100  0.0227  0.0024  0.1183  0.1597  0.0088  0.0014
 18  <.0001  0.0008  0.0655  0.9033  0.2253  <.0001  0.0094  0.7790  0.1123  0.0253
 19  <.0001  <.0001  0.0003  0.0472  0.3490  <.0001  <.0001  0.0659  0.5833  0.8748
 20  <.0001  <.0001  0.0002  0.0323  0.2694  <.0001  <.0001  0.0459  0.4721  0.9883
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: Grain2
i/j     11      12      13      14      15      16      17      18      19      20
 14  0.0019  0.0785  0.3290          0.2657  0.0020  0.1183  0.6570  0.0917  0.0648
```

```
 15  <.0001  0.0059  0.0415  0.2657          <.0001  0.0100  0.1237  0.5489  0.4414
 16  0.9963  0.1303  0.0235  0.0020  <.0001          0.0870  0.0063  <.0001  <.0001
 17  0.0862  0.8331  0.5438  0.1183  0.0100  0.0870          0.2559  0.0021  0.0013
 18  0.0063  0.1805  0.5908  0.6570  0.1237  0.0063  0.2559          0.0362  0.0245
 19  <.0001  0.0012  0.0102  0.0917  0.5489  <.0001  0.0021  0.0362          0.8633
 20  <.0001  0.0007  0.0066  0.0648  0.4414  <.0001  0.0013  0.0245  0.8633
                       Biomass1      Standard              LSMEAN
      Irrign   Nitrgn       LSMEAN         Error   Pr > |t|     Number
      1        1         2609.1493      821.2177     0.0033          1
      1        2         4858.3065      821.2177     <.0001          2
      1        3         5784.6252      821.2177     <.0001          3
      1        4         6522.2389      821.2177     <.0001          4
      1        5         7792.2225      821.2177     <.0001          5
      2        1         3073.2401      821.2177     0.0007          6
      2        2         4345.8358      821.2177     <.0001          7
      2        3         6255.8008      821.2177     <.0001          8
      2        4         7259.6167      821.2177     <.0001          9
      2        5         9654.2699      821.2177     <.0001         10
      3        1         5412.2348      821.2177     <.0001         11
      3        2         6260.6624      821.2177     <.0001         12
      3        3         8003.9146      821.2177     <.0001         13
      3        4         8944.5971      821.2177     <.0001         14
      3        5         9542.2078      821.2177     <.0001         15
      4        1         6252.0267      821.2177     <.0001         16
                         The SAS System        16:49 Thursday, April 8, 2016  31
                        The GLM Procedure
                        Least Squares Means
                       Biomass1      Standard              LSMEAN
      Irrign   Nitrgn       LSMEAN         Error   Pr > |t|     Number
      4        2         7196.5008      821.2177     <.0001         17
      4        3         9047.6034      821.2177     <.0001         18
      4        4         9590.4365      821.2177     <.0001         19
      4        5        11006.6700       821.2177     <.0001         20
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                        Dependent Variable: Biomass1
i/j      1       2       3       4       5       6       7       8       9      10
  1          0.0617  0.0101  0.0020  <.0001  0.6921  0.1446  0.0036  0.0003  <.0001
  2  0.0617          0.4310  0.1616  0.0167  0.1341  0.6620  0.2377  0.0468  0.0002
  3  0.0101  0.4310          0.5299  0.0935  0.0260  0.2244  0.6877  0.2132  0.0022
  4  0.0020  0.1616  0.5299          0.2823  0.0056  0.0701  0.8200  0.5300  0.0111
  5  <.0001  0.0167  0.0935  0.2823          0.0003  0.0056  0.1952  0.6496  0.1187
  6  0.6921  0.1341  0.0260  0.0056  0.0003          0.2814  0.0100  0.0010  <.0001
  7  0.1446  0.6620  0.2244  0.0701  0.0056  0.2814          0.1098  0.0174  <.0001
  8  0.0036  0.2377  0.6877  0.8200  0.1952  0.0100  0.1098          0.3938  0.0063
  9  0.0003  0.0468  0.2132  0.5300  0.6496  0.0010  0.0174  0.3938          0.0474
 10  <.0001  0.0002  0.0022  0.0111  0.1187  <.0001  <.0001  0.0063  0.0474
 11  0.0217  0.6366  0.7506  0.3464  0.0487  0.0525  0.3654  0.4729  0.1215  0.0009
 12  0.0036  0.2361  0.6846  0.8232  0.1966  0.0099  0.1090  0.9967  0.3961  0.0063
                  Least Squares Means for effect Irrign*Nitrgn
```

```
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: Biomass1
i/j      11      12      13      14      15      16      17      18      19      20
  1  0.0217  0.0036  <.0001  <.0001  <.0001  0.0037  0.0004  <.0001  <.0001  <.0001
  2  0.6366  0.2361  0.0108  0.0013  0.0003  0.2389  0.0526  0.0010  0.0003  <.0001
  3  0.7506  0.6846  0.0650  0.0104  0.0028  0.6900  0.2330  0.0084  0.0025  <.0001
  4  0.3464  0.8232  0.2112  0.0451  0.0140  0.8175  0.5656  0.0372  0.0127  0.0005
  5  0.0487  0.1966  0.8565  0.3285  0.1417  0.1942  0.6115  0.2878  0.1314  0.0093
  6  0.0525  0.0099  0.0002  <.0001  <.0001  0.0100  0.0012  <.0001  <.0001  <.0001
  7  0.3654  0.1090  0.0035  0.0004  <.0001  0.1105  0.0197  0.0003  <.0001  <.0001
  8  0.4729  0.9967  0.1421  0.0272  0.0080  0.9974  0.4239  0.0222  0.0072  0.0003
  9  0.1215  0.3961  0.5262  0.1566  0.0581  0.3921  0.9570  0.1335  0.0533  0.0029
 10  0.0009  0.0063  0.1650  0.5455  0.9237  0.0062  0.0422  0.6050  0.9565  0.2528
 11          0.4704  0.0328  0.0047  0.0012  0.4749  0.1343  0.0037  0.0011  <.0001
 12  0.4704          0.1432  0.0274  0.0081  0.9941  0.4263  0.0224  0.0073  0.0003
                         The SAS System       16:49 Thursday, April 8, 2016  32
                          The GLM Procedure
                          Least Squares Means
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: Biomass1
i/j       1       2       3       4       5       6       7       8       9      10
 13  <.0001  0.0108  0.0650  0.2112  0.8565  0.0002  0.0035  0.1421  0.5262  0.1650
 14  <.0001  0.0013  0.0104  0.0451  0.3285  <.0001  0.0004  0.0272  0.1566  0.5455
 15  <.0001  0.0003  0.0028  0.0140  0.1417  <.0001  <.0001  0.0080  0.0581  0.9237
 16  0.0037  0.2389  0.6900  0.8175  0.1942  0.0100  0.1105  0.9974  0.3921  0.0062
 17  0.0004  0.0526  0.2330  0.5656  0.6115  0.0012  0.0197  0.4239  0.9570  0.0422
 18  <.0001  0.0010  0.0084  0.0372  0.2878  <.0001  0.0003  0.0222  0.1335  0.6050
 19  <.0001  0.0003  0.0025  0.0127  0.1314  <.0001  <.0001  0.0072  0.0533  0.9565
 20  <.0001  <.0001  <.0001  0.0005  0.0093  <.0001  <.0001  0.0003  0.0029  0.2528
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: Biomass1
i/j      11      12      13      14      15      16      17      18      19      20
 13  0.0328  0.1432          0.4239  0.1947  0.1412  0.4919  0.3755  0.1814  0.0145
 14  0.0047  0.0274  0.4239          0.6104  0.0270  0.1421  0.9299  0.5820  0.0853
 15  0.0012  0.0081  0.1947  0.6104          0.0079  0.0518  0.6730  0.9671  0.2164
 16  0.4749  0.9941  0.1412  0.0270  0.0079          0.4221  0.0220  0.0071  0.0003
 17  0.1343  0.4263  0.4919  0.1421  0.0518  0.4221          0.1208  0.0475  0.0025
 18  0.0037  0.0224  0.3755  0.9299  0.6730  0.0220  0.1208          0.6434  0.1014
 19  0.0011  0.0073  0.1814  0.5820  0.9671  0.0071  0.0475  0.6434          0.2316
 20  <.0001  0.0003  0.0145  0.0853  0.2164  0.0003  0.0025  0.1014  0.2316
                     Biomass2      Standard           LSMEAN
       Irrign   Nitrgn      LSMEAN        Error   Pr > |t|     Number
       1        1        6966.6667     552.8901    <.0001          1
       1        2        7666.6667     552.8901    <.0001          2
       1        3        9383.3333     552.8901    <.0001          3
       1        4       10833.3333     552.8901    <.0001          4
       1        5       12500.0000     552.8901    <.0001          5
       2        1        9416.6667     552.8901    <.0001          6
```

```
        2      2        11250.0000      552.8901     <.0001        7
        2      3        11833.3333      552.8901     <.0001        8
        2      4        13916.6667      552.8901     <.0001        9
        2      5        14083.3333      552.8901     <.0001       10
        3      1         9316.6667      552.8901     <.0001       11
        3      2        11508.3333      552.8901     <.0001       12
        3      3        13833.3333      552.8901     <.0001       13
        3      4        15250.0000      552.8901     <.0001       14
                             The SAS System        16:49 Thursday, April 8, 2016  33
                            The GLM Procedure
                           Least Squares Means
                         Biomass2       Standard              LSMEAN
       Irrign   Nitrgn          LSMEAN          Error   Pr > |t|     Number
        3      5        15416.6667      552.8901     <.0001       15
        4      1        10116.6667      552.8901     <.0001       16
        4      2        12000.0000      552.8901     <.0001       17
        4      3        13666.6667      552.8901     <.0001       18
        4      4        16000.0000      552.8901     <.0001       19
        4      5        17416.6667      552.8901     <.0001       20
                  Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)
                          Dependent Variable: Biomass2
 i/j      1       2       3       4       5       6       7       8       9      10
   1         0.3773  0.0041  <.0001  <.0001  0.0037  <.0001  <.0001  <.0001  <.0001
   2  0.3773         0.0355  0.0003  <.0001  0.0323  <.0001  <.0001  <.0001  <.0001
   3  0.0041  0.0355         0.0729  0.0004  0.9663  0.0230  0.0037  <.0001  <.0001
   4  <.0001  0.0003  0.0729         0.0408  0.0794  0.5978  0.2101  0.0004  0.0002
   5  <.0001  <.0001  0.0004  0.0408         0.0004  0.1197  0.4002  0.0794  0.0513
   6  0.0037  0.0323  0.9663  0.0794  0.0004         0.0254  0.0041  <.0001  <.0001
   7  <.0001  <.0001  0.0230  0.5978  0.1197  0.0254         0.4611  0.0018  0.0010
   8  <.0001  <.0001  0.0037  0.2101  0.4002  0.0041  0.4611         0.0120  0.0071
   9  <.0001  <.0001  <.0001  0.0004  0.0794  <.0001  0.0018  0.0120         0.8326
  10  <.0001  <.0001  <.0001  0.0002  0.0513  <.0001  0.0010  0.0071  0.8326
  11  0.0051  0.0427  0.9326  0.0613  0.0003  0.8990  0.0189  0.0029  <.0001  <.0001
                  Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)
                          Dependent Variable: Biomass2
 i/j     11      12      13      14      15      16      17      18      19      20
   1  0.0051  <.0001  <.0001  <.0001  <.0001  0.0003  <.0001  <.0001  <.0001  <.0001
   2  0.0427  <.0001  <.0001  <.0001  <.0001  0.0037  <.0001  <.0001  <.0001  <.0001
   3  0.9326  0.0105  <.0001  <.0001  <.0001  0.3553  0.0021  <.0001  <.0001  <.0001
   4  0.0613  0.3944  0.0006  <.0001  <.0001  0.3662  0.1455  0.0010  <.0001  <.0001
   5  0.0003  0.2139  0.0978  0.0013  0.0007  0.0046  0.5271  0.1455  <.0001  <.0001
   6  0.8990  0.0117  <.0001  <.0001  <.0001  0.3773  0.0024  <.0001  <.0001  <.0001
   7  0.0189  0.7433  0.0024  <.0001  <.0001  0.1569  0.3447  0.0041  <.0001  <.0001
   8  0.0029  0.6804  0.0155  0.0001  <.0001  0.0355  0.8326  0.0254  <.0001  <.0001
   9  <.0001  0.0042  0.9158  0.0978  0.0640  <.0001  0.0199  0.7512  0.0120  <.0001
  10  <.0001  0.0024  0.7512  0.1455  0.0978  <.0001  0.0120  0.5978  0.0199  0.0002
  11          0.0085  <.0001  <.0001  <.0001  0.3139  0.0017  <.0001  <.0001  <.0001
                             The SAS System        16:49 Thursday, April 8, 2016  34
```

```
                         The GLM Procedure
                         Least Squares Means
                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)
                      Dependent Variable: Biomass2
i/j      1       2       3       4       5       6       7       8       9      10
 12  <.0001  <.0001  0.0105  0.3944  0.2139  0.0117  0.7433  0.6804  0.0042  0.0024
 13  <.0001  <.0001  <.0001  0.0006  0.0978  <.0001  0.0024  0.0155  0.9158  0.7512
 14  <.0001  <.0001  <.0001  <.0001  0.0013  <.0001  <.0001  0.0001  0.0978  0.1455
 15  <.0001  <.0001  <.0001  <.0001  0.0007  <.0001  <.0001  <.0001  0.0640  0.0978
 16  0.0003  0.0037  0.3553  0.3662  0.0046  0.3773  0.1569  0.0355  <.0001  <.0001
 17  <.0001  <.0001  0.0021  0.1455  0.5271  0.0024  0.3447  0.8326  0.0199  0.0120
 18  <.0001  <.0001  <.0001  0.0010  0.1455  <.0001  0.0041  0.0254  0.7512  0.5978
 19  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  0.0120  0.0199
 20  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  0.0002
                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)
                      Dependent Variable: Biomass2
i/j     11      12      13      14      15      16      17      18      19      20
 12  0.0085          0.0056  <.0001  <.0001  0.0846  0.5339  0.0095  <.0001  <.0001
 13  <.0001  0.0056          0.0794  0.0513  <.0001  0.0254  0.8326  0.0092  <.0001
 14  <.0001  <.0001  0.0794          0.8326  <.0001  0.0002  0.0513  0.3447  0.0092
 15  <.0001  <.0001  0.0513  0.8326          <.0001  0.0001  0.0323  0.4611  0.0155
 16  0.3139  0.0846  <.0001  <.0001  <.0001          0.0219  <.0001  <.0001  <.0001
 17  0.0017  0.5339  0.0254  0.0002  0.0001  0.0219          0.0408  <.0001  <.0001
 18  <.0001  0.0095  0.8326  0.0513  0.0323  <.0001  0.0408          0.0054  <.0001
 19  <.0001  <.0001  0.0092  0.3447  0.4611  <.0001  <.0001  0.0054          0.0794
 20  <.0001  <.0001  <.0001  0.0092  0.0155  <.0001  <.0001  <.0001  0.0794
                                   Standard            LSMEAN
      Irrign   Nitrgn   WUE1g LSMEAN        Error   Pr > |t|     Number
      1        1        3.27787058     0.32158551     <.0001          1
      1        2        4.69429269     0.32158551     <.0001          2
      1        3        5.68164098     0.32158551     <.0001          3
      1        4        5.86098094     0.32158551     <.0001          4
      1        5        6.99409914     0.32158551     <.0001          5
      2        1        2.01592163     0.32158551     <.0001          6
      2        2        4.32547058     0.32158551     <.0001          7
      2        3        5.09877321     0.32158551     <.0001          8
      2        4        5.23561833     0.32158551     <.0001          9
      2        5        5.74815598     0.32158551     <.0001          10
      3        1        2.11450126     0.32158551     <.0001          11
      3        2        3.16587442     0.32158551     <.0001          12
                          The SAS System        16:49 Thursday, April 8, 2016  35
                         The GLM Procedure
                         Least Squares Means
                                   Standard            LSMEAN
      Irrign   Nitrgn   WUE1g LSMEAN        Error   Pr > |t|     Number
      3        3        4.16470085     0.32158551     <.0001          13
      3        4        4.66342357     0.32158551     <.0001          14
      3        5        4.86966768     0.32158551     <.0001          15
```

```
        4      1       3.02448903    0.32158551    <.0001      16
        4      2       3.66932936    0.32158551    <.0001      17
        4      3       4.15129007    0.32158551    <.0001      18
        4      4       4.24461543    0.32158551    <.0001      19
        4      5       4.88400954    0.32158551    <.0001      20
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: WUE1g
i/j      1       2       3       4       5       6       7       8       9       10
 1          0.0039  <.0001  <.0001  <.0001  0.0091  0.0279  0.0003  0.0001  <.0001
 2  0.0039          0.0375  0.0152  <.0001  <.0001  0.4234  0.3804  0.2427  0.0270
 3  <.0001  0.0375          0.6959  0.0069  <.0001  0.0054  0.2092  0.3341  0.8846
 4  <.0001  0.0152  0.6959          0.0181  <.0001  0.0019  0.1035  0.1787  0.8057
 5  <.0001  <.0001  0.0069  0.0181          <.0001  <.0001  0.0002  0.0005  0.0100
 6  0.0091  <.0001  <.0001  <.0001  <.0001          <.0001  <.0001  <.0001  <.0001
 7  0.0279  0.4234  0.0054  0.0019  <.0001  <.0001          0.0988  0.0539  0.0037
 8  0.0003  0.3804  0.2092  0.1035  0.0002  <.0001  0.0988          0.7654  0.1630
 9  0.0001  0.2427  0.3341  0.1787  0.0005  <.0001  0.0539  0.7654          0.2681
10  <.0001  0.0270  0.8846  0.8057  0.0100  <.0001  0.0037  0.1630  0.2681
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: WUE1g
i/j     11      12      13      14      15      16      17      18      19      20
 1  0.0155  0.8071  0.0600  0.0046  0.0014  0.5813  0.3958  0.0637  0.0413  0.0013
 2  <.0001  0.0020  0.2528  0.9463  0.7023  0.0009  0.0312  0.2413  0.3302  0.6794
 3  <.0001  <.0001  0.0022  0.0322  0.0837  <.0001  0.0001  0.0020  0.0034  0.0890
 4  <.0001  <.0001  0.0007  0.0129  0.0367  <.0001  <.0001  0.0007  0.0012  0.0394
 5  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001  <.0001
 6  0.8298  0.0166  <.0001  <.0001  <.0001  0.0338  0.0010  <.0001  <.0001  <.0001
 7  <.0001  0.0158  0.7260  0.4628  0.2403  0.0074  0.1588  0.7043  0.8600  0.2284
 8  <.0001  0.0002  0.0482  0.3456  0.6179  <.0001  0.0036  0.0453  0.0695  0.6400
 9  <.0001  <.0001  0.0248  0.2174  0.4270  <.0001  0.0016  0.0232  0.0368  0.4451
10  <.0001  <.0001  0.0015  0.0232  0.0623  <.0001  <.0001  0.0014  0.0023  0.0665
                          The SAS System       16:49 Thursday, April 8, 2016  36
                          The GLM Procedure
                          Least Squares Means
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                         Dependent Variable: WUE1g
i/j      1       2       3       4       5       6       7       8       9       10
11  0.0155  <.0001  <.0001  <.0001  <.0001  0.8298  <.0001  <.0001  <.0001  <.0001
12  0.8071  0.0020  <.0001  <.0001  <.0001  0.0166  0.0158  0.0002  <.0001  <.0001
13  0.0600  0.2528  0.0022  0.0007  <.0001  <.0001  0.7260  0.0482  0.0248  0.0015
14  0.0046  0.9463  0.0322  0.0129  <.0001  <.0001  0.4628  0.3456  0.2174  0.0232
15  0.0014  0.7023  0.0837  0.0367  <.0001  <.0001  0.2403  0.6179  0.4270  0.0623
16  0.5813  0.0009  <.0001  <.0001  <.0001  0.0338  0.0074  <.0001  <.0001  <.0001
17  0.3958  0.0312  0.0001  <.0001  <.0001  0.0010  0.1588  0.0036  0.0016  <.0001
18  0.0637  0.2413  0.0020  0.0007  <.0001  <.0001  0.7043  0.0453  0.0232  0.0014
19  0.0413  0.3302  0.0034  0.0012  <.0001  <.0001  0.8600  0.0695  0.0368  0.0023
20  0.0013  0.6794  0.0890  0.0394  <.0001  <.0001  0.2284  0.6400  0.4451  0.0665
```

```
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                        Dependent Variable: WUE1g
i/j      11      12      13      14      15      16      17      18      19      20
 11          0.0274  <.0001  <.0001  <.0001  0.0539  0.0017  <.0001  <.0001  <.0001
 12  0.0274          0.0354  0.0024  0.0007  0.7579  0.2765  0.0378  0.0239  0.0007
 13  <.0001  0.0354          0.2810  0.1310  0.0174  0.2842  0.9767  0.8616  0.1236
 14  <.0001  0.0024  0.2810          0.6533  0.0011  0.0363  0.2685  0.3640  0.6310
 15  <.0001  0.0007  0.1310  0.6533          0.0003  0.0127  0.1240  0.1789  0.9750
 16  0.0539  0.7579  0.0174  0.0011  0.0003          0.1659  0.0187  0.0115  0.0003
 17  0.0017  0.2765  0.2842  0.0363  0.0127  0.1659          0.2972  0.2150  0.0118
 18  <.0001  0.0378  0.9767  0.2685  0.1240  0.0187  0.2972          0.8387  0.1170
 19  <.0001  0.0239  0.8616  0.3640  0.1789  0.0115  0.2150  0.8387          0.1694
 20  <.0001  0.0007  0.1236  0.6310  0.9750  0.0003  0.0118  0.1170  0.1694
                                    Standard              LSMEAN
        Irrign   Nitrgn   WUE2g LSMEAN         Error   Pr > |t|     Number
        1        1        3.65163406     0.26016594     <.0001        1
        1        2        4.39818859     0.26016594     <.0001        2
        1        3        5.15271030     0.26016594     <.0001        3
        1        4        5.93924592     0.26016594     <.0001        4
        1        5        6.32184766     0.26016594     <.0001        5
        2        1        3.78321298     0.26016594     <.0001        6
        2        2        4.46108375     0.26016594     <.0001        7
        2        3        5.11865399     0.26016594     <.0001        8
        2        4        5.48580068     0.26016594     <.0001        9
        2        5        5.62054393     0.26016594     <.0001        10
                          The SAS System         16:49 Thursday, April 8, 2016  37
                          The GLM Procedure
                          Least Squares Means
                                    Standard              LSMEAN
        Irrign   Nitrgn   WUE2g LSMEAN         Error   Pr > |t|     Number
        3        1        3.57624823     0.26016594     <.0001        11
        3        2        3.99647490     0.26016594     <.0001        12
        3        3        4.37700112     0.26016594     <.0001        13
        3        4        5.07905699     0.26016594     <.0001        14
        3        5        5.00578582     0.26016594     <.0001        15
        4        1        2.99602676     0.26016594     <.0001        16
        4        2        3.42454769     0.26016594     <.0001        17
        4        3        3.92126715     0.26016594     <.0001        18
        4        4        4.24756081     0.26016594     <.0001        19
        4        5        4.71926135     0.26016594     <.0001        20
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                        Dependent Variable: WUE2g
i/j      1       2       3       4       5       6       7       8       9       10
  1          0.0508  0.0003  <.0001  <.0001  0.7230  0.0351  0.0004  <.0001  <.0001
  2  0.0508          0.0486  0.0002  <.0001  0.1044  0.8653  0.0590  0.0058  0.0022
  3  0.0003  0.0486          0.0403  0.0033  0.0008  0.0693  0.9268  0.3721  0.2127
  4  <.0001  0.0002  0.0403          0.3062  <.0001  0.0003  0.0329  0.2268  0.3928
  5  <.0001  <.0001  0.0033  0.3062          <.0001  <.0001  0.0026  0.0299  0.0657
```

```
  6  0.7230  0.1044  0.0008  <.0001  <.0001          0.0747  0.0010  <.0001  <.0001
  7  0.0351  0.8653  0.0693  0.0003  <.0001  0.0747          0.0834  0.0089  0.0035
  8  0.0004  0.0590  0.9268  0.0329  0.0026  0.0010  0.0834          0.3258  0.1821
  9  <.0001  0.0058  0.3721  0.2268  0.0299  <.0001  0.0089  0.3258          0.7166
 10  <.0001  0.0022  0.2127  0.3928  0.0657  <.0001  0.0035  0.1821  0.7166
 11  0.8390  0.0326  0.0002  <.0001  <.0001  0.5777  0.0221  0.0002  <.0001  <.0001
 12  0.3557  0.2831  0.0036  <.0001  <.0001  0.5662  0.2158  0.0046  0.0003  0.0001
 13  0.0574  0.9544  0.0429  0.0002  <.0001  0.1164  0.8207  0.0523  0.0050  0.0019
 14  0.0005  0.0735  0.8426  0.0258  0.0019  0.0013  0.1028  0.9150  0.2772  0.1509
 15  0.0009  0.1084  0.6923  0.0163  0.0011  0.0022  0.1485  0.7610  0.2013  0.1045
 16  0.0843  0.0006  <.0001  <.0001  <.0001  0.0401  0.0004  <.0001  <.0001  <.0001
 17  0.5415  0.0125  <.0001  <.0001  <.0001  0.3370  0.0082  <.0001  <.0001  <.0001
 18  0.4690  0.2042  0.0021  <.0001  <.0001  0.7100  0.1521  0.0027  0.0002  <.0001
 19  0.1151  0.6850  0.0195  <.0001  <.0001  0.2161  0.5658  0.0241  0.0020  0.0007
 20  0.0067  0.3894  0.2475  0.0023  0.0001  0.0160  0.4879  0.2858  0.0453  0.0200
                        The SAS System        16:49 Thursday, April 8, 2016  38
                       The GLM Procedure
                      Least Squares Means
              Least Squares Means for effect Irrign*Nitrgn
                 Pr > |t| for H0: LSMean(i)=LSMean(j)
                    Dependent Variable: WUE2g
i/j      11      12      13      14      15      16      17      18      19      20
  1  0.8390  0.3557  0.0574  0.0005  0.0009  0.0843  0.5415  0.4690  0.1151  0.0067
  2  0.0326  0.2831  0.9544  0.0735  0.1084  0.0006  0.0125  0.2042  0.6850  0.3894
  3  0.0002  0.0036  0.0429  0.8426  0.6923  <.0001  <.0001  0.0021  0.0195  0.2475
  4  <.0001  <.0001  0.0002  0.0258  0.0163  <.0001  <.0001  <.0001  <.0001  0.0023
  5  <.0001  <.0001  <.0001  0.0019  0.0011  <.0001  <.0001  <.0001  <.0001  0.0001
  6  0.5777  0.5662  0.1164  0.0013  0.0022  0.0401  0.3370  0.7100  0.2161  0.0160
  7  0.0221  0.2158  0.8207  0.1028  0.1485  0.0004  0.0082  0.1521  0.5658  0.4879
  8  0.0002  0.0046  0.0523  0.9150  0.7610  <.0001  <.0001  0.0027  0.0241  0.2858
  9  <.0001  0.0003  0.0050  0.2772  0.2013  <.0001  <.0001  0.0002  0.0020  0.0453
 10  <.0001  0.0001  0.0019  0.1509  0.1045  <.0001  <.0001  <.0001  0.0007  0.0200
 11          0.2619  0.0370  0.0003  0.0005  0.1246  0.6829  0.3554  0.0774  0.0039
 12  0.2619          0.3088  0.0060  0.0099  0.0105  0.1299  0.8393  0.4999  0.0582
 13  0.0370  0.3088          0.0654  0.0971  0.0007  0.0144  0.2245  0.7273  0.3592
 14  0.0003  0.0060  0.0654          0.8434  <.0001  <.0001  0.0036  0.0308  0.3355
 15  0.0005  0.0099  0.0971  0.8434          <.0001  0.0002  0.0059  0.0475  0.4418
 16  0.1246  0.0105  0.0007  <.0001  <.0001          0.2528  0.0171  0.0018  <.0001
 17  0.6829  0.1299  0.0144  <.0001  0.0002  0.2528          0.1865  0.0324  0.0013
 18  0.3554  0.8393  0.2245  0.0036  0.0059  0.0171  0.1865          0.3818  0.0376
 19  0.0774  0.4999  0.7273  0.0308  0.0475  0.0018  0.0324  0.3818          0.2090
 20  0.0039  0.0582  0.3592  0.3355  0.4418  <.0001  0.0013  0.0376  0.2090
                                 Standard          LSMEAN
      Irrign   Nitrgn   WUE1b LSMEAN       Error   Pr > |t|      Number
      1        1         3.8666270     1.0123532    0.0006          1
      1        2         7.1399927     1.0123532    <.0001          2
      1        3         8.6485912     1.0123532    <.0001          3
      1        4         9.6227725     1.0123532    <.0001          4
      1        5        11.5412099     1.0123532    <.0001          5
      2        1         3.8922036     1.0123532    0.0005          6
```

```
      2     2       5.4123398     1.0123532    <.0001       7
      2     3       7.9281900     1.0123532    <.0001       8
      2     4       9.1196541     1.0123532    <.0001       9
      2     5      12.1120579     1.0123532    <.0001      10
      3     1       5.9541271     1.0123532    <.0001      11
      3     2       6.8116102     1.0123532    <.0001      12
      3     3       8.8287437     1.0123532    <.0001      13
      3     4       9.7866193     1.0123532    <.0001      14
      3     5      10.4592673     1.0123532    <.0001      15
      4     1       6.0435437     1.0123532    <.0001      16
      4     2       6.9880053     1.0123532    <.0001      17
      4     3       8.8967019     1.0123532    <.0001      18
                         The SAS System      16:49 Thursday, April 8, 2016  39
                        The GLM Procedure
                       Least Squares Means
                              Standard            LSMEAN
      Irrign   Nitrgn   WUE1b LSMEAN        Error   Pr > |t|     Number
      4     4       9.3194704     1.0123532    <.0001      19
      4     5      10.7527308     1.0123532    <.0001      20
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                        Dependent Variable: WUE1b
i/j      1       2       3       4       5       6       7       8       9      10
  1          0.0290  0.0021  0.0003  <.0001  0.9859  0.2884  0.0078  0.0009  <.0001
  2  0.0290          0.2999  0.0925  0.0043  0.0302  0.2364  0.5858  0.1763  0.0015
  3  0.0021  0.2999          0.5011  0.0518  0.0022  0.0307  0.6183  0.7443  0.0214
  4  0.0003  0.0925  0.5011          0.1897  0.0003  0.0060  0.2453  0.7276  0.0917
  5  <.0001  0.0043  0.0518  0.1897          <.0001  0.0002  0.0168  0.1005  0.6927
  6  0.9859  0.0302  0.0022  0.0003  <.0001          0.2963  0.0082  0.0009  <.0001
  7  0.2884  0.2364  0.0307  0.0060  0.0002  0.2963          0.0884  0.0143  <.0001
  8  0.0078  0.5858  0.6183  0.2453  0.0168  0.0082  0.0884          0.4115  0.0063
  9  0.0009  0.1763  0.7443  0.7276  0.1005  0.0009  0.0143  0.4115          0.0446
 10  <.0001  0.0015  0.0214  0.0917  0.6927  <.0001  <.0001  0.0063  0.0446
 11  0.1546  0.4136  0.0690  0.0153  0.0005  0.1595  0.7076  0.1775  0.0343  0.0001
 12  0.0479  0.8200  0.2087  0.0583  0.0024  0.0498  0.3357  0.4412  0.1168  0.0008
 13  0.0015  0.2469  0.9007  0.5830  0.0672  0.0016  0.0231  0.5338  0.8403  0.0285
                  Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)
                        Dependent Variable: WUE1b
i/j     11      12      13      14      15      16      17      18      19      20
  1  0.1546  0.0479  0.0015  0.0002  <.0001  0.1382  0.0367  0.0013  0.0006  <.0001
  2  0.4136  0.8200  0.2469  0.0738  0.0270  0.4494  0.9161  0.2288  0.1378  0.0168
  3  0.0690  0.2087  0.9007  0.4325  0.2151  0.0782  0.2547  0.8635  0.6425  0.1514
  4  0.0153  0.0583  0.5830  0.9096  0.5631  0.0177  0.0750  0.6155  0.8336  0.4358
  5  0.0005  0.0024  0.0672  0.2293  0.4553  0.0005  0.0033  0.0740  0.1305  0.5856
  6  0.1595  0.0498  0.0016  0.0003  <.0001  0.1427  0.0382  0.0014  0.0006  <.0001
  7  0.7076  0.3357  0.0231  0.0045  0.0013  0.6623  0.2793  0.0207  0.0102  0.0007
  8  0.1775  0.4412  0.5338  0.2035  0.0866  0.1974  0.5161  0.5036  0.3384  0.0572
  9  0.0343  0.1168  0.8403  0.6445  0.3564  0.0393  0.1463  0.8772  0.8899  0.2625
 10  0.0001  0.0008  0.0285  0.1141  0.2569  0.0002  0.0011  0.0317  0.0599  0.3495
```

```
  11          0.5534  0.0532  0.0116  0.0036  0.9506  0.4755  0.0481  0.0251  0.0021
  12  0.5534          0.1685  0.0458  0.0158  0.5953  0.9027  0.1550  0.0894  0.0097
  13  0.0532  0.1685          0.5083  0.2632  0.0606  0.2078  0.9624  0.7340  0.1884
                          The SAS System        16:49 Thursday, April 8, 2016  40
                         The GLM Procedure
                        Least Squares Means
                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: WUE1b
i/j      1       2       3       4       5       6       7       8       9      10
  14  0.0002  0.0738  0.4325  0.9096  0.2293  0.0003  0.0045  0.2035  0.6445  0.1141
  15  <.0001  0.0270  0.2151  0.5631  0.4553  <.0001  0.0013  0.0866  0.3564  0.2569
  16  0.1382  0.4494  0.0782  0.0177  0.0005  0.1427  0.6623  0.1974  0.0393  0.0002
  17  0.0367  0.9161  0.2547  0.0750  0.0033  0.0382  0.2793  0.5161  0.1463  0.0011
  18  0.0013  0.2288  0.8635  0.6155  0.0740  0.0014  0.0207  0.5036  0.8772  0.0317
  19  0.0006  0.1378  0.6425  0.8336  0.1305  0.0006  0.0102  0.3384  0.8899  0.0599
  20  <.0001  0.0168  0.1514  0.4358  0.5856  <.0001  0.0007  0.0572  0.2625  0.3495
                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: WUE1b
i/j     11      12      13      14      15      16      17      18      19      20
  14  0.0116  0.0458  0.5083          0.6417  0.0135  0.0594  0.5386  0.7463  0.5046
  15  0.0036  0.0158  0.2632  0.6417          0.0042  0.0211  0.2832  0.4318  0.8389
  16  0.9506  0.5953  0.0606  0.0135  0.0042          0.5142  0.0549  0.0289  0.0024
  17  0.4755  0.9027  0.2078  0.0594  0.0211  0.5142          0.1919  0.1132  0.0130
  18  0.0481  0.1550  0.9624  0.5386  0.2832  0.0549  0.1919          0.7697  0.2041
  19  0.0251  0.0894  0.7340  0.7463  0.4318  0.0289  0.1132  0.7697          0.3243
  20  0.0021  0.0097  0.1884  0.5046  0.8389  0.0024  0.0130  0.2041  0.3243
                               Standard           LSMEAN
       Irrign  Nitrgn   WUE2b LSMEAN        Error   Pr > |t|     Number
       1       1        10.7070269     0.5714544     <.0001         1
       1       2        12.7570200     0.5714544     <.0001         2
       1       3        12.6052325     0.5714544     <.0001         3
       1       4        15.2037771     0.5714544     <.0001         4
       1       5        17.3964439     0.5714544     <.0001         5
       2       1         9.4426588     0.5714544     <.0001         6
       2       2        10.9897822     0.5714544     <.0001         7
       2       3        13.8070486     0.5714544     <.0001         8
       2       4        15.7608500     0.5714544     <.0001         9
       2       5        16.3308896     0.5714544     <.0001        10
       3       1         9.4596734     0.5714544     <.0001        11
       3       2        12.1440215     0.5714544     <.0001        12
       3       3        14.6937205     0.5714544     <.0001        13
       3       4        16.5032195     0.5714544     <.0001        14
       3       5        16.8174123     0.5714544     <.0001        15
       4       1         9.1955530     0.5714544     <.0001        16
                          The SAS System        16:49 Thursday, April 8, 2016  41
                         The GLM Procedure
                        Least Squares Means
                               Standard           LSMEAN
```

```
    Irrign   Nitrgn   WUE2b LSMEAN         Error    Pr > |t|    Number
      4        2        10.1809508      0.5714544    <.0001        17
      4        3        11.5956857      0.5714544    <.0001        18
      4        4        13.3829789      0.5714544    <.0001        19
      4        5        14.0734191      0.5714544    <.0001        20
                      Least Squares Means for effect Irrign*Nitrgn
                          Pr > |t| for H0: LSMean(i)=LSMean(j)
                              Dependent Variable: WUE2b
i/j      1       2       3       4       5       6       7       8       9      10
  1           0.0163  0.0252  <.0001  <.0001  0.1275  0.7287  0.0006  <.0001  <.0001
  2  0.0163           0.8522  0.0048  <.0001  0.0003  0.0362  0.2031  0.0008  0.0001
  3  0.0252  0.8522           0.0030  <.0001  0.0004  0.0542  0.1468  0.0005  <.0001
  4  <.0001  0.0048  0.0030           0.0106  <.0001  <.0001  0.0936  0.4956  0.1727
  5  <.0001  <.0001  <.0001  0.0106          <.0001  <.0001  <.0001  0.0514  0.1967
  6  0.1275  0.0003  0.0004  <.0001  <.0001           0.0645  <.0001  <.0001  <.0001
  7  0.7287  0.0362  0.0542  <.0001  <.0001  0.0645          0.0014  <.0001  <.0001
  8  0.0006  0.2031  0.1468  0.0936  <.0001  <.0001  0.0014          0.0215  0.0038
  9  <.0001  0.0008  0.0005  0.4956  0.0514  <.0001  <.0001  0.0215          0.4857
 10  <.0001  0.0001  <.0001  0.1727  0.1967  <.0001  <.0001  0.0038  0.4857
 11  0.1326  0.0003  0.0005  <.0001  <.0001  0.9833  0.0674  <.0001  <.0001  <.0001
 12  0.0849  0.4537  0.5722  0.0006  <.0001  0.0021  0.1629  0.0478  <.0001  <.0001
                      Least Squares Means for effect Irrign*Nitrgn
                          Pr > |t| for H0: LSMean(i)=LSMean(j)
                              Dependent Variable: WUE2b
i/j     11      12      13      14      15      16      17      18      19      20
  1  0.1326  0.0849  <.0001  <.0001  <.0001  0.0706  0.5197  0.2797  0.0023  0.0002
  2  0.0003  0.4537  0.0226  <.0001  <.0001  0.0001  0.0032  0.1604  0.4443  0.1131
  3  0.0005  0.5722  0.0145  <.0001  <.0001  0.0002  0.0052  0.2207  0.3431  0.0786
  4  <.0001  0.0006  0.5324  0.1177  0.0544  <.0001  <.0001  <.0001  0.0312  0.1715
  5  <.0001  <.0001  0.0021  0.2773  0.4789  <.0001  <.0001  <.0001  <.0001  0.0003
  6  0.9833  0.0021  <.0001  <.0001  <.0001  0.7618  0.3678  0.0120  <.0001  <.0001
  7  0.0674  0.1629  <.0001  <.0001  <.0001  0.0336  0.3244  0.4589  0.0057  0.0006
  8  <.0001  0.0478  0.2808  0.0022  0.0008  <.0001  <.0001  0.0101  0.6034  0.7438
  9  <.0001  <.0001  0.1961  0.3652  0.2004  <.0001  <.0001  <.0001  0.0060  0.0448
 10  <.0001  <.0001  0.0512  0.8325  0.5514  <.0001  <.0001  <.0001  0.0009  0.0087
 11          0.0022  <.0001  <.0001  <.0001  0.7459  0.3788  0.0126  <.0001  <.0001
 12  0.0022          0.0035  <.0001  <.0001  0.0009  0.0209  0.5023  0.1351  0.0230
                              The SAS System        16:49 Thursday, April 8, 2016  42
                              The GLM Procedure
                              Least Squares Means
                      Least Squares Means for effect Irrign*Nitrgn
                          Pr > |t| for H0: LSMean(i)=LSMean(j)
                              Dependent Variable: WUE2b
i/j      1       2       3       4       5       6       7       8       9      10
 13  <.0001  0.0226  0.0145  0.5324  0.0021  <.0001  <.0001  0.2808  0.1961  0.0512
 14  <.0001  <.0001  <.0001  0.1177  0.2773  <.0001  <.0001  0.0022  0.3652  0.8325
 15  <.0001  <.0001  <.0001  0.0544  0.4789  <.0001  <.0001  0.0008  0.2004  0.5514
 16  0.0706  0.0001  0.0002  <.0001  <.0001  0.7618  0.0336  <.0001  <.0001  <.0001
 17  0.5197  0.0032  0.0052  <.0001  <.0001  0.3678  0.3244  <.0001  <.0001  <.0001
 18  0.2797  0.1604  0.2207  <.0001  <.0001  0.0120  0.4589  0.0101  <.0001  <.0001
```

```
  19  0.0023  0.4443  0.3431  0.0312  <.0001  <.0001  0.0057  0.6034  0.0060  0.0009
  20  0.0002  0.1131  0.0786  0.1715  0.0003  <.0001  0.0006  0.7438  0.0448  0.0087
                 Least Squares Means for effect Irrign*Nitrgn
                    Pr > |t| for H0: LSMean(i)=LSMean(j)
                       Dependent Variable: WUE2b
 i/j      11       12       13       14       15       16       17       18       19       20
  13  <.0001  0.0035          0.0322  0.0131  <.0001  <.0001  0.0006  0.1146  0.4484
  14  <.0001  <.0001  0.0322          0.7000  <.0001  <.0001  <.0001  0.0005  0.0051
  15  <.0001  <.0001  0.0131  0.7000          <.0001  <.0001  <.0001  0.0002  0.0018
  16  0.7459  0.0009  <.0001  <.0001  <.0001          0.2316  0.0056  <.0001  <.0001
  17  0.3788  0.0209  <.0001  <.0001  <.0001  0.2316          0.0896  0.0004  <.0001
  18  0.0126  0.5023  0.0006  <.0001  <.0001  0.0056  0.0896          0.0343  0.0044
  19  <.0001  0.1351  0.1146  0.0005  0.0002  <.0001  0.0004  0.0343          0.3993
  20  <.0001  0.0230  0.4484  0.0051  0.0018  <.0001  <.0001  0.0044  0.3993
NOTE: To ensure overall protection level, only probabilities associated with pre-planned
    comparisons should be used.
                          The SAS System        16:49 Thursday, April 8, 2016  43
                         The GLM Procedure
                       t Tests (LSD) for Grain1
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                       0.05
                    Error Degrees of Freedom          32
                    Error Mean Square           181205.9
                    Critical Value of t          2.03693
                    Least Significant Difference   316.62
            Means with the same letter are not significantly different.
               t Grouping          Mean      N    Irrign
                      A        4100.0     15    4
                      A        3911.2     15    3
                      B        3448.9     15    2
                      B        3223.7     15    1
                          The SAS System        16:49 Thursday, April 8, 2016  44
                         The GLM Procedure
                       t Tests (LSD) for Grain2
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                       0.05
                    Error Degrees of Freedom          32
                    Error Mean Square           129858.1
                    Critical Value of t          2.03693
                    Least Significant Difference   268.03
            Means with the same letter are not significantly different.
               t Grouping          Mean      N    Irrign
                      A        4423.5     15    4
                      A        4230.6     15    3
                      A        4221.7     15    2
                      B        3815.0     15    1
                          The SAS System        16:49 Thursday, April 8, 2016  45
                         The GLM Procedure
```

```
                    t Tests (LSD) for Biomass1
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                 Alpha                       0.05
                 Error Degrees of Freedom          32
                 Error Mean Square           2023195
                 Critical Value of t         2.03693
                 Least Significant Difference   1057.9
             Means with the same letter are not significantly different.
               t Grouping          Mean      N    Irrign
                    A        8618.6     15    4
                    A        7632.7     15    3
                    B        6117.8     15    2
                    B        5513.3     15    1
                        The SAS System          16:49 Thursday, April 8, 2016  46
                       The GLM Procedure
                    t Tests (LSD) for Biomass2
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                 Alpha                       0.05
                 Error Degrees of Freedom          32
                 Error Mean Square           917062.5
                 Critical Value of t         2.03693
                 Least Significant Difference   712.27
             Means with the same letter are not significantly different.
               t Grouping          Mean      N    Irrign
                    A       13840.0     15    4
                    B       13065.0     15    3
                    C       12100.0     15    2
                    D        9470.0     15    1
                        The SAS System          16:49 Thursday, April 8, 2016  47
                       The GLM Procedure
                    t Tests (LSD) for WUE1g
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                 Alpha                       0.05
                 Error Degrees of Freedom          32
                 Error Mean Square           0.310252
                 Critical Value of t         2.03693
                 Least Significant Difference   0.4143
             Means with the same letter are not significantly different.
               t Grouping          Mean      N    Irrign
                    A        5.3018     15    1
                    B        4.4848     15    2
                    C        3.9947     15    4
                    C        3.7956     15    3
                        The SAS System          16:49 Thursday, April 8, 2016  48
                       The GLM Procedure
                    t Tests (LSD) for WUE2g
```

```
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                         Alpha                       0.05
                         Error Degrees of Freedom          32
                         Error Mean Square           0.203059
                         Critical Value of t         2.03693
                         Least Significant Difference   0.3352
                 Means with the same letter are not significantly different.
                    t Grouping          Mean      N    Irrign
                           A       5.0927     15    1
                           A       4.8939     15    2
                           B       4.4069     15    3
                           C       3.8617     15    4
                                   The SAS System        16:49 Thursday, April 8, 2016  49
                                  The GLM Procedure
                               t Tests (LSD) for WUE1b
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                         Alpha                       0.05
                         Error Degrees of Freedom          32
                         Error Mean Square           3.074577
                         Critical Value of t         2.03693
                         Least Significant Difference   1.3042
                 Means with the same letter are not significantly different.
                    t Grouping          Mean      N    Irrign
                           A       8.4001     15    4
                           A       8.3681     15    3
                           A       8.1638     15    1
                           A       7.6929     15    2
                                   The SAS System        16:49 Thursday, April 8, 2016  50
                                  The GLM Procedure
                               t Tests (LSD) for WUE2b
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                         Alpha                       0.05
                         Error Degrees of Freedom          32
                         Error Mean Square           0.97968
                         Critical Value of t         2.03693
                         Least Significant Difference   0.7362
                 Means with the same letter are not significantly different.
                    t Grouping          Mean      N    Irrign
                           A       13.9236     15    3
                           A       13.7339     15    1
                           A       13.2662     15    2
                           B       11.6857     15    4
                                   The SAS System        16:49 Thursday, April 8, 2016  51
                                  The GLM Procedure
                               t Tests (LSD) for Grain1
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
```

```
                    Alpha                       0.05
                    Error Degrees of Freedom          32
                    Error Mean Square           181205.9
                    Critical Value of t         2.03693
                    Least Significant Difference   353.99
            Means with the same letter are not significantly different.
              t Grouping          Mean      N    Nitrgn
                    A       4686.1     12    5
                    B       4227.8     12    4
                    B       3923.6     12    3
                    C       3304.2     12    2
                    D       2213.2     12    1
                            The SAS System         16:49 Thursday, April 8, 2016  52
                          The GLM Procedure
                        t Tests (LSD) for Grain2
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                       0.05
                    Error Degrees of Freedom          32
                    Error Mean Square           129858.1
                    Critical Value of t         2.03693
                    Least Significant Difference   299.66
            Means with the same letter are not significantly different.
              t Grouping          Mean      N    Nitrgn
                    A       4949.3     12    5
                    A       4718.9     12    4
                    B       4236.5     12    3
                    C       3734.4     12    2
                    D       3224.3     12    1
                            The SAS System         16:49 Thursday, April 8, 2016  53
                          The GLM Procedure
                       t Tests (LSD) for Biomass1
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                       0.05
                    Error Degrees of Freedom          32
                    Error Mean Square            2023195
                    Critical Value of t         2.03693
                    Least Significant Difference   1182.8
            Means with the same letter are not significantly different.
              t Grouping          Mean      N    Nitrgn
                    A       9498.8     12    5
                    B       8079.2     12    4
                    B       7273.0     12    3
                    C       5665.3     12    2
                    D       4336.7     12    1
                            The SAS System         16:49 Thursday, April 8, 2016  54
                          The GLM Procedure
                       t Tests (LSD) for Biomass2
```

```
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                    0.05
                    Error Degrees of Freedom          32
                    Error Mean Square          917062.5
                    Critical Value of t          2.03693
                    Least Significant Difference   796.34
             Means with the same letter are not significantly different.
                t Grouping          Mean      N    Nitrgn
                      A       14854.2     12    5
                      B       14000.0     12    4
                      C       12179.2     12    3
                      D       10606.3     12    2
                      E        8954.2    12    1
                          The SAS System        16:49 Thursday, April 8, 2016  55
                          The GLM Procedure
                        t Tests (LSD) for WUE1g
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                    0.05
                    Error Degrees of Freedom          32
                    Error Mean Square          0.310252
                    Critical Value of t          2.03693
                    Least Significant Difference   0.4632
             Means with the same letter are not significantly different.
                t Grouping          Mean      N    Nitrgn
                      A        5.6240     12    5
                      B        5.0012     12    4
                      B        4.7741     12    3
                      C        3.9637     12    2
                      D        2.6082     12    1
                          The SAS System        16:49 Thursday, April 8, 2016  56
                          The GLM Procedure
                        t Tests (LSD) for WUE2g
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                    0.05
                    Error Degrees of Freedom          32
                    Error Mean Square          0.203059
                    Critical Value of t          2.03693
                    Least Significant Difference   0.3747
             Means with the same letter are not significantly different.
                t Grouping          Mean      N    Nitrgn
                      A        5.4169     12    5
                      A        5.1879     12    4
                      B        4.6424     12    3
                      C        4.0701     12    2
                      D        3.5018     12    1
                          The SAS System        16:49 Thursday, April 8, 2016  57
                          The GLM Procedure
```

```
                         t Tests (LSD) for WUE1b
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                    0.05
                    Error Degrees of Freedom          32
                    Error Mean Square           3.074577
                    Critical Value of t          2.03693
                    Least Significant Difference   1.4581
              Means with the same letter are not significantly different.
                t Grouping          Mean       N    Nitrgn
                     A        11.2163      12    5
                     B         9.4621      12    4
                     B         8.5756      12    3
                     C         6.5880      12    2
                     D         4.9391      12    1
                              The SAS System         16:49 Thursday, April 8, 2016  58
                             The GLM Procedure
                         t Tests (LSD) for WUE2b
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                    0.05
                    Error Degrees of Freedom          32
                    Error Mean Square            0.97968
                    Critical Value of t          2.03693
                    Least Significant Difference   0.8231
              Means with the same letter are not significantly different.
                t Grouping          Mean       N    Nitrgn
                     A        16.1545      12    5
                     B        15.2127      12    4
                     C        13.1754      12    3
                     D        11.5179      12    2
                     E         9.7012     12    1
                              The SAS System         16:49 Thursday, April 8, 2016  59
                             The GLM Procedure
Level of Level of   ----------Grain1--------- ----------Grain2--------- ---------Biomass1--------
Irrign   Nitrgn   N        Mean       Std Dev         Mean       Std Dev         Mean       Std Dev
1       1       3   1868.70889   195.142908   2743.05556   469.713516   2609.1493
248.61293
1       2       3   2500.00111   416.668333   3305.55556   294.873246   4858.3065
1316.07832
1       3       3   3500.00000   220.479276   3834.72222   552.304725   5784.6252
1732.49265
1       4       3   3805.55444   502.311048   4431.94444   666.410541   6522.2389
1205.90291
1       5       3   4444.44556   240.560688   4759.72222   533.745500   7792.2225
1074.25827
2       1       3   1988.88889   655.390751   3083.33333   688.446318   3073.2401
233.36858
2       2       3   3133.33333   541.858940   3583.33333   425.428705   4345.8358
846.18798
```

```
2      3      3   3611.11111   481.125224   4479.16556   275.600355    6255.8008
2263.68407
2      4      3   4066.66667   451.230232   4876.33333   129.611278    7259.6167
2937.75867
2      5      3   4444.44556   240.560688   5086.11111   257.739012    9654.2699
1813.91800
3      1      3   1867.26444   964.871359   3534.72222   409.486750    5412.2348
955.35272
3      2      3   3805.55444   427.635294   3993.05667   159.115757    6260.6624
124.09001
3      3      3   4361.11111   209.717623   4236.11111   159.117212    8003.9146
1066.40963
3      4      3   4666.66556   144.338530   4527.77778   229.482106    8944.5971
1847.14185
3      5      3   4855.55556   486.007926   4861.11111   365.821311    9542.2078
1405.55007
4      1      3   3127.77778   208.388881   3536.11111   370.466423    6252.0267
1381.61768
4      2      3   3777.77667   585.312515   4055.55444   372.871087    7196.5008
500.47450
4      3      3   4222.22111   625.461829   4395.90111   145.760743    9047.6034
1702.16168
4      4      3   4372.22222   548.060554   5039.38778   236.586100    9590.4365
1310.16383
4      5      3   4999.99889   416.668333   5090.44556   309.457098   11006.6700
701.36110
Level of Level of   ---------Biomass2-------- ----------WUE1g---------- ----------WUE2g---------
-
Irrign   Nitrgn   N        Mean        Std Dev         Mean        Std Dev         Mean       Std Dev
1      1      3    6966.6667    644.85140   3.27787058   0.93799787   3.65163406
0.64791918
1      2      3    7666.6667   1010.36297   4.69429269   1.27354096   4.39818859
0.39475931
1      3      3    9383.3333   1020.21240   5.68164098   0.72463369   5.15271030
0.76632304
1      4      3   10833.3333   1040.83300   5.86098094   1.13347137   5.93924592
0.86876138
1      5      3   12500.0000   1561.24950   6.99409914   0.92163660   6.32184766
0.66909338
2      1      3    9416.6667    629.15287   2.01592163   1.02105422   3.78321298
0.91664441
2      2      3   11250.0000   1089.72474   4.32547058   0.78090587   4.46108375
0.63562935
2      3      3   11833.3333   1154.70054   5.09877321   0.82105941   5.11865399
0.32798997
2      4      3   13916.6667    520.41650   5.23561833   0.52437065   5.48580068
0.39742184
2      5      3   14083.3333    946.48472   5.74815598   0.04596373   5.62054393
0.53122150
```

```
3    1    3   9316.6667    513.16014   2.11450126   0.30356165   3.57624823
0.36567858
3    2    3  11508.3333    425.97926   3.16587442   1.00831898   3.99647490
0.33047902
3    3    3  13833.3333   1040.83300   4.16470085   0.74864550   4.37700112
0.24772375
3    4    3  15250.0000    901.38782   4.66342357   0.41964292   5.07905699
0.23904283
3    5    3  15416.6667    946.48472   4.86966768   0.28341277   5.00578582
0.20835609
4    1    3  10116.6667    340.34296   3.02448903   0.18233562   2.99602676
0.34516961
4    2    3  12000.0000    750.00000   3.66932936   0.58648420   3.42454769
0.29149316
4    3    3  13666.6667   1258.30574   4.15129007   0.63570922   3.92126715
0.06685634
4    4    3  16000.0000   1322.87566   4.24461543   0.50989261   4.24756081
0.21868706
4    5    3  17416.6667   1127.31244   4.88400954   0.41242218   4.71926135
0.05269246
                         The SAS System         16:49 Thursday, April 8, 2016  60
                        The GLM Procedure
    Level of Level of   ------------WUE1b------------    ------------WUE2b------------
    Irrign  Nitrgn  N        Mean         Std Dev          Mean         Std Dev
    1       1       3   3.8666270     0.36521041      10.7070269     1.67110936
    1       2       3   7.1399927     1.93590969      12.7570200     3.50564345
    1       3       3   8.6485912     2.62436450      12.6052325     1.39421147
    1       4       3   9.6227725     1.75813733      15.2037771     2.62941794
    1       5       3  11.5412099     1.55995981      17.3964439     2.86632124
    2       1       3   3.8922036     0.31516134       9.4426588     2.04596456
    2       2       3   5.4123398     1.02960499      10.9897822     2.89299879
    2       3       3   7.9281900     2.90130867      13.8070486     1.61491376
    2       4       3   9.1196541     3.68554787      15.7608500     1.71041995
    2       5       3  12.1120579     2.19180911      16.3308896     1.23282315
    3       1       3   5.9541271     1.05055561       9.4596734     0.60496610
    3       2       3   6.8116102     0.06241366      12.1440215     0.72624667
    3       3       3   8.8287437     1.17716039      14.6937205     0.86997067
    3       4       3   9.7866193     2.01762397      16.5032195     1.38377214
    3       5       3  10.4592673     1.60248779      16.8174123     1.96050327
    4       1       3   6.0435437     1.31313149       9.1955530     0.28492398
    4       2       3   6.9880053     0.52244391      10.1809508     0.72979222
    4       3       3   8.8967019     1.72164293      11.5956857     0.57576115
    4       4       3   9.3194704     1.32671094      13.3829789     0.84815882
    4       5       3  10.7527308     0.73677235      14.0734191     2.09097848
```

Appendix V. SAA Output for plant height of maize grown at University of Embu Farm in two seasons (2012 – 2013)

```
        The SAS System       13:24 Wednesday, August 25, 2018   1

                       The GLM Procedure

                     Class Level Information

                   Class        Levels    Values

                   Block           3    1 2 3

                   Irrign         4    1 2 3 4

                   Nitrgn          5    1 2 3 4 5


                     Number of observations    68

NOTE: All dependent variables are consistent with respect to the presence or absence of
missing
   values.  However only 60 observations can be used in this analysis.
      The SAS System       13:24 Wednesday, August 25, 2018   2
                       The GLM Procedure

Dependent Variable: HT04   HT04

                          Sum of
   Source               DF        Squares     Mean Square   F Value   Pr > F

   Model                 27      939.056500       34.779870       1.67    0.0826

   Error               32      666.653333       20.832917

   Corrected Total           59     1605.709833


           R-Square     Coeff Var      Root MSE     HT04 Mean

           0.584823      16.96874      4.564309      26.89833


   Source               DF     Type III SS     Mean Square    F Value    Pr > F

   Block                 2     115.2563333      57.6281667       2.77    0.0780
   Irrign               3     126.6725000     42.2241667       2.03    0.1299
   Block*Irrign              6     143.5570000     23.9261667       1.15    0.3577
   Nitrgn               4    449.6440000    112.4110000      5.40    0.0019
   Irrign*Nitrgn             12     103.9266667       8.6605556       0.42    0.9461
```

```
    Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

Source                      DF     Type III SS     Mean Square    F Value    Pr > F

Irrign                     3     126.6725000      42.2241667       1.76    0.2535
The SAS System          13:24 Wednesday, August 25, 2018   3
                            The GLM Procedure

Dependent Variable: HT06   HT06

                                   Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        27     11079.39667       410.34802       2.66    0.0043

Error                      32      4927.97067       153.99908

Corrected Total              59     16007.36733


               R-Square     Coeff Var      Root MSE     HT06 Mean

               0.692144      20.89985      12.40964      59.37667


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

Block                        2      593.224333      296.612167       1.93    0.1622
Irrign                     3     1417.283333      472.427778       3.07    0.0418
Block*Irrign                 6      858.311667      143.051944       0.93    0.4877
Nitrgn                       4     6260.170667     1565.042667      10.16    <.0001
Irrign*Nitrgn               12     1950.406667      162.533889       1.06    0.4267


    Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

Source                      DF     Type III SS     Mean Square    F Value    Pr > F

Irrign                     3     1417.283333      472.427778       3.30    0.0993
 The SAS System          13:24 Wednesday, August 25, 2018   4
                            The GLM Procedure

Dependent Variable: HT08   HT08

                                   Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        27     55479.38717      2054.79212       1.72    0.0710
```

```
          Error                 32     38222.88533      1194.46517

          Corrected Total            59     93702.27250


                    R-Square     Coeff Var      Root MSE     HT08 Mean

                    0.592082      26.53948      34.56104      130.2250


          Source                  DF     Type III SS     Mean Square    F Value    Pr > F

          Block                    2      4639.79100      2319.89550       1.94    0.1599
          Irrign                  3      2434.54583       811.51528       0.68    0.5711
          Block*Irrign               6     13823.24367      2303.87394       1.93    0.1063
          Nitrgn                   4     19595.89167      4898.97292       4.10    0.0085
          Irrign*Nitrgn               12     14985.91500      1248.82625       1.05    0.4344


             Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

          Source                  DF     Type III SS     Mean Square    F Value    Pr > F

          Irrign                  3     2434.545833      811.515278       0.35    0.7896
              The SAS System       13:24 Wednesday, August 25, 2018   5
                                   The GLM Procedure

     Dependent Variable: HT10   HT10

                                     Sum of
          Source                  DF         Squares     Mean Square    F Value    Pr > F

          Model                    27     44222.87517      1637.88427       2.90    0.0022

          Error                 32     18050.59467       564.08108

          Corrected Total            59     62273.46983


                    R-Square     Coeff Var      Root MSE     HT10 Mean

                    0.710140      11.84155      23.75039      200.5683


          Source                  DF     Type III SS     Mean Square    F Value    Pr > F

          Block                    2      6691.94433      3345.97217       5.93    0.0064
          Irrign                  3      4206.72450      1402.24150       2.49    0.0784
          Block*Irrign               6      6992.28100      1165.38017       2.07    0.0853
```

```
Nitrgn              4    22189.03733     5547.25933      9.83   <.0001
Irrign*Nitrgn          12    4142.88800      345.24067      0.61    0.8160


  Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

Source              DF    Type III SS    Mean Square   F Value    Pr > F

Irrign             3    4206.724500    1402.241500      1.20    0.3859
  The SAS System      13:24 Wednesday, August 25, 2018   6
                    The GLM Procedure

                    Class Level Information

                Class       Levels    Values

                Block           3    1 2 3

                Irrign          4    1 2 3 4

                Nitrgn          5    1 2 3 4 5

                  Number of observations    68

NOTE: All dependent variables are consistent with respect to the presence or absence of
missing
      values.  However only 60 observations can be used in this analysis.
         The SAS System       13:24 Wednesday, August 25, 2018   7
                    The GLM Procedure

Dependent Variable: HT04   HT04

                             Sum of
Source              DF        Squares     Mean Square   F Value    Pr > F

Model                27      939.056500       34.779870      1.67    0.0826

Error              32      666.653333       20.832917

Corrected Total           59     1605.709833

          R-Square     Coeff Var      Root MSE     HT04 Mean

          0.584823      16.96874      4.564309      26.89833


Source              DF     Type III SS     Mean Square    F Value    Pr > F

Block               2     115.2563333      57.6281667       2.77    0.0780
Irrign             3    126.6725000      42.2241667      2.03    0.1299
```

```
          Block*Irrign             6     143.5570000      23.9261667       1.15    0.3577
          Nitrgn                 4    449.6440000    112.4110000       5.40    0.0019
          Irrign*Nitrgn            12     103.9266667       8.6605556       0.42    0.9461


             Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

          Source                 DF     Type III SS     Mean Square    F Value    Pr > F

          Irrign                 3     126.6725000      42.2241667       1.76    0.2535
              The SAS System       13:24 Wednesday, August 25, 2018   8
                                 The GLM Procedure

    Dependent Variable: HT06   HT06

                                      Sum of
          Source                 DF        Squares     Mean Square    F Value    Pr > F

          Model                  27     11079.39667       410.34802       2.66    0.0043

          Error                 32      4927.97067       153.99908

          Corrected Total           59     16007.36733


                       R-Square     Coeff Var      Root MSE     HT06 Mean

                       0.692144      20.89985      12.40964      59.37667


          Source                 DF     Type III SS     Mean Square    F Value    Pr > F

          Block                  2      593.224333      296.612167       1.93    0.1622
          Irrign                 3     1417.283333      472.427778       3.07    0.0418
          Block*Irrign             6      858.311667      143.051944       0.93    0.4877
          Nitrgn                 4     6260.170667     1565.042667      10.16    <.0001
          Irrign*Nitrgn            12     1950.406667      162.533889       1.06    0.4267


             Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

          Source                 DF     Type III SS     Mean Square    F Value    Pr > F

          Irrign                 3     1417.283333      472.427778       3.30    0.0993
              The SAS System       13:24 Wednesday, August 25, 2018   9
                                 The GLM Procedure

    Dependent Variable: HT08   HT08

                                      Sum of
```

```
Source                     DF        Squares     Mean Square    F Value    Pr > F

Model                       27     55479.38717      2054.79212       1.72    0.0710

Error                      32     38222.88533      1194.46517

Corrected Total             59     93702.27250


            R-Square     Coeff Var      Root MSE     HT08 Mean

            0.592082      26.53948      34.56104      130.2250


Source                     DF     Type III SS     Mean Square    F Value    Pr > F

Block                       2      4639.79100      2319.89550       1.94    0.1599
Irrign                     3      2434.54583       811.51528       0.68    0.5711
Block*Irrign                 6      13823.24367      2303.87394       1.93    0.1063
Nitrgn                      4      19595.89167      4898.97292       4.10    0.0085
Irrign*Nitrgn                12      14985.91500      1248.82625       1.05    0.4344


   Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

Source                     DF     Type III SS     Mean Square    F Value    Pr > F

Irrign                     3     2434.545833     811.515278       0.35    0.7896
     The SAS System       13:24 Wednesday, August 25, 2018  10
                          The GLM Procedure

Dependent Variable: HT10   HT10

                             Sum of
Source                     DF        Squares     Mean Square    F Value    Pr > F

Model                       27     44222.87517      1637.88427       2.90    0.0022

Error                      32     18050.59467       564.08108

Corrected Total             59     62273.46983


            R-Square     Coeff Var      Root MSE     HT10 Mean

            0.710140      11.84155      23.75039      200.5683


Source                     DF     Type III SS     Mean Square    F Value    Pr > F
```

```
Block               2     6691.94433     3345.97217      5.93    0.0064
Irrign             3     4206.72450     1402.24150      2.49    0.0784
Block*Irrign            6     6992.28100     1165.38017      2.07    0.0853
Nitrgn              4    22189.03733     5547.25933      9.83    <.0001
Irrign*Nitrgn          12     4142.88800      345.24067      0.61    0.8160


   Tests of Hypotheses Using the Type III MS for Block*Irrign as an Error Term

Source              DF     Type III SS     Mean Square    F Value    Pr > F

Irrign              3    4206.724500    1402.241500      1.20    0.3859

     The SAS System       13:24 Wednesday, August 25, 2018  11

                     The GLM Procedure
                    Least Squares Means

                        Standard              LSMEAN
        Irrign    HT04 LSMEAN         Error    Pr > |t|     Number

        1         28.5800000      1.1784995     <.0001         1
        2         28.0200000      1.1784995     <.0001         2
        3         25.9600000      1.1784995     <.0001         3
        4         25.0333333      1.1784995     <.0001         4


               Least Squares Means for effect Irrign
                Pr > |t| for H0: LSMean(i)=LSMean(j)

                   Dependent Variable: HT04

        i/j          1           2           3           4

          1                    0.7391      0.1258      0.0411
          2       0.7391                   0.2255      0.0826
          3       0.1258      0.2255                   0.5821
          4       0.0411      0.0826      0.5821


                        Standard              LSMEAN
        Irrign    HT06 LSMEAN         Error    Pr > |t|     Number

        1         66.2466667      3.2041544     <.0001         1
        2         61.6733333      3.2041544     <.0001         2
        3         54.7866667      3.2041544     <.0001         3
        4         54.8000000      3.2041544     <.0001         4


               Least Squares Means for effect Irrign
```

```
            Pr > |t| for H0: LSMean(i)=LSMean(j)

                Dependent Variable: HT06

   i/j          1          2          3          4

    1                  0.3204     0.0166     0.0167
    2       0.3204                0.1384     0.1391
    3       0.0166     0.1384                0.9977
    4       0.0167     0.1391     0.9977


The SAS System      13:24 Wednesday, August 25, 2018  12
                  The GLM Procedure
                 Least Squares Means

                    Standard              LSMEAN
  Irrign    HT08 LSMEAN         Error    Pr > |t|     Number

  1         128.866667      8.923621     <.0001         1
  2         132.700000      8.923621     <.0001         2
  3         120.900000      8.923621     <.0001         3
  4         138.433333      8.923621     <.0001         4

           Least Squares Means for effect Irrign
            Pr > |t| for H0: LSMean(i)=LSMean(j)

                Dependent Variable: HT08

   i/j          1          2          3          4

    1                  0.7633     0.5323     0.4540
    2       0.7633                0.3568     0.6527
    3       0.5323     0.3568                0.1743
    4       0.4540     0.6527     0.1743

                    Standard              LSMEAN
  Irrign    HT10 LSMEAN         Error    Pr > |t|     Number

  1         209.040000      6.132325     <.0001         1
  2         208.260000      6.132325     <.0001         2
  3         195.560000      6.132325     <.0001         3
  4         189.413333      6.132325     <.0001         4


           Least Squares Means for effect Irrign
            Pr > |t| for H0: LSMean(i)=LSMean(j)

                Dependent Variable: HT10
```

```
        i/j          1          2          3          4

          1                  0.9289     0.1299     0.0305
          2       0.9289                0.1528     0.0373
          3       0.1299     0.1528                0.4836
          4       0.0305     0.0373     0.4836

NOTE: To ensure overall protection level, only probabilities associated with pre-planned
      comparisons should be used.
The SAS System      13:24 Wednesday, August 25, 2018  13

                          The GLM Procedure
                         Least Squares Means

                              Standard                LSMEAN
        Nitrgn    HT04 LSMEAN         Error    Pr > |t|      Number

        1         22.4250000      1.3176025     <.0001          1
        2         29.4583333      1.3176025     <.0001          2
        3         26.3583333      1.3176025     <.0001          3
        4         26.1750000      1.3176025     <.0001          4
        5         30.0750000      1.3176025     <.0001          5


                  Least Squares Means for effect Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)

                        Dependent Variable: HT04

    i/j          1          2          3          4          5

      1                  0.0007     0.0427     0.0526     0.0003
      2       0.0007                0.1059     0.0876     0.7428
      3       0.0427     0.1059                0.9222     0.0547
      4       0.0526     0.0876     0.9222                0.0444
      5       0.0003     0.7428     0.0547     0.0444


                              Standard                LSMEAN
        Nitrgn    HT06 LSMEAN         Error    Pr > |t|      Number

        1         41.3916667      3.5823535     <.0001          1
        2         60.8916667      3.5823535     <.0001          2
        3         61.7583333      3.5823535     <.0001          3
        4         59.6750000      3.5823535     <.0001          4
        5         73.1666667      3.5823535     <.0001          5


                  Least Squares Means for effect Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)
```

```
                   Dependent Variable: HT06

    i/j          1          2          3          4          5

      1                  0.0005     0.0003     0.0010     <.0001
      2       0.0005                0.8652     0.8117     0.0212
      3       0.0003     0.8652                0.6837     0.0313
      4       0.0010     0.8117     0.6837                0.0120
      5       <.0001     0.0212     0.0313     0.0120
The SAS System      13:24 Wednesday, August 25, 2018  14

                      The GLM Procedure
                     Least Squares Means

                           Standard              LSMEAN
        Nitrgn    HT08 LSMEAN          Error    Pr > |t|     Number

          1        99.416667      9.976912     <.0001         1
          2       123.716667      9.976912     <.0001         2
          3       134.558333      9.976912     <.0001         3
          4       152.991667      9.976912     <.0001         4
          5       140.441667      9.976912     <.0001         5


               Least Squares Means for effect Nitrgn
                Pr > |t| for H0: LSMean(i)=LSMean(j)

                   Dependent Variable: HT08

    i/j          1          2          3          4          5

      1                  0.0947     0.0181     0.0006     0.0066
      2       0.0947                0.4479     0.0461     0.2446
      3       0.0181     0.4479                0.2007     0.6795
      4       0.0006     0.0461     0.2007                0.3804
      5       0.0066     0.2446     0.6795     0.3804


                           Standard              LSMEAN
        Nitrgn    HT10 LSMEAN          Error    Pr > |t|     Number

          1       164.366667      6.856147     <.0001         1
          2       199.783333      6.856147     <.0001         2
          3       207.866667      6.856147     <.0001         3
          4       210.725000      6.856147     <.0001         4
          5       220.100000      6.856147     <.0001         5


               Least Squares Means for effect Nitrgn
```

```
              Pr > |t| for H0: LSMean(i)=LSMean(j)

                    Dependent Variable: HT10

      i/j         1          2          3          4          5

       1                  0.0009     <.0001     <.0001     <.0001
       2      0.0009                 0.4106     0.2675     0.0441
       3      <.0001     0.4106                 0.7701     0.2162
       4      <.0001     0.2675     0.7701                 0.3409
       5      <.0001     0.0441     0.2162     0.3409


      The SAS System      13:24 Wednesday, August 25, 2018  15
                        The GLM Procedure
                       Least Squares Means

NOTE: To ensure overall protection level, only probabilities associated with pre-planned
   comparisons should be used.

                               Standard            LSMEAN
      Irrign   Nitrgn    HT04 LSMEAN          Error    Pr > |t|     Number

      1        1        26.9000000     2.6352050    <.0001          1
      1        2        30.6333333     2.6352050    <.0001          2
      1        3        26.3333333     2.6352050    <.0001          3
      1        4        28.0333333     2.6352050    <.0001          4
      1        5        31.0000000     2.6352050    <.0001          5
      2        1        22.5666667     2.6352050    <.0001          6
      2        2        30.1000000     2.6352050    <.0001          7
      2        3        28.3333333     2.6352050    <.0001          8
      2        4        27.8000000     2.6352050    <.0001          9
      2        5        31.3000000     2.6352050    <.0001          10
      3        1        19.1333333     2.6352050    <.0001          11
      3        2        31.2333333     2.6352050    <.0001          12
      3        3        25.6666667     2.6352050    <.0001          13
      3        4        23.6666667     2.6352050    <.0001          14
      3        5        30.1000000     2.6352050    <.0001          15
      4        1        21.1000000     2.6352050    <.0001          16
      4        2        25.8666667     2.6352050    <.0001          17
      4        3        25.1000000     2.6352050    <.0001          18
      4        4        25.2000000     2.6352050    <.0001          19
      4        5        27.9000000     2.6352050    <.0001          20


           Least Squares Means for effect Irrign*Nitrgn
              Pr > |t| for H0: LSMean(i)=LSMean(j)

                    Dependent Variable: HT04
```

```
i/j       1        2        3        4        5        6        7        8        9       10
  1           0.3240   0.8801   0.7630   0.2795   0.2535   0.3969   0.7031   0.8107   0.2464
  2  0.3240            0.2571   0.4904   0.9222   0.0380   0.8871   0.5415   0.4527   0.8592
  3  0.8801   0.2571            0.6514   0.2196   0.3197   0.3197   0.5952   0.6965   0.1920
  4  0.7630   0.4904   0.6514            0.4319   0.1522   0.5831   0.9363   0.9505   0.3873
  5  0.2795   0.9222   0.2196   0.4319            0.0306   0.8107   0.4795   0.3969   0.9363
  6  0.2535   0.0380   0.3197   0.1522   0.0306            0.0517   0.1316   0.1699   0.0255
  7  0.3969   0.8871   0.3197   0.5831   0.8107   0.0517            0.6387   0.5415   0.7495
  8  0.7031   0.5415   0.5952   0.9363   0.4795   0.1316   0.6387            0.8871   0.4319
  9  0.8107   0.4527   0.6965   0.9505   0.3969   0.1699   0.5415   0.8871            0.3547
 10   0.2464   0.8592   0.1920   0.3873   0.9363   0.0255   0.7495   0.4319   0.3547
 11   0.0452   0.0042   0.0623   0.0230   0.0032   0.3638   0.0060   0.0191   0.0265   0.0026
 12   0.2535   0.8731   0.1979   0.3969   0.9505   0.0265   0.7630   0.4422   0.3638   0.9858
            The SAS System        13:24 Wednesday, August 25, 2018  16
                              The GLM Procedure
                             Least Squares Means

                  Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)

                          Dependent Variable: HT04

i/j       1        2        3        4        5        6        7        8        9       10

 13   0.7428   0.1920   0.8592   0.5299   0.1621   0.4117   0.2430   0.4795   0.5710   0.1404
 14   0.3921   0.0707   0.4795   0.2500   0.0578   0.7698   0.0939   0.2196   0.2757   0.0488
 15   0.3969   0.8871   0.3197   0.5831   0.8107   0.0517   1.0000   0.6387   0.5415   0.7495
 16   0.1295   0.0155   0.1699   0.0720   0.0122   0.6965   0.0216   0.0611   0.0816   0.0100
 17   0.7834   0.2101   0.9011   0.5651   0.1779   0.3825   0.2644   0.5128   0.6075   0.1546
 18   0.6324   0.1474   0.7428   0.4370   0.1232   0.5015   0.1892   0.3921   0.4740   0.1059
 19   0.6514   0.1546   0.7630   0.4527   0.1295   0.4849   0.1979   0.4067   0.4904   0.1115
 20   0.7902   0.4686   0.6770   0.9717   0.4117   0.1621   0.5591   0.9082   0.9788   0.3684

                  Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)

                          Dependent Variable: HT04

i/j      11       12       13       14       15       16       17       18       19       20
  1  0.0452   0.2535   0.7428   0.3921   0.3969   0.1295   0.7834   0.6324   0.6514   0.7902
  2  0.0042   0.8731   0.1920   0.0707   0.8871   0.0155   0.2101   0.1474   0.1546   0.4686
  3  0.0623   0.1979   0.8592   0.4795   0.3197   0.1699   0.9011   0.7428   0.7630   0.6770
  4  0.0230   0.3969   0.5299   0.2500   0.5831   0.0720   0.5651   0.4370   0.4527   0.9717
  5  0.0032   0.9505   0.1621   0.0578   0.8107   0.0122   0.1779   0.1232   0.1295   0.4117
  6  0.3638   0.0265   0.4117   0.7698   0.0517   0.6965   0.3825   0.5015   0.4849   0.1621
  7  0.0060   0.7630   0.2430   0.0939   1.0000   0.0216   0.2644   0.1892   0.1979   0.5591
  8  0.0191   0.4422   0.4795   0.2196   0.6387   0.0611   0.5128   0.3921   0.4067   0.9082
  9  0.0265   0.3638   0.5710   0.2757   0.5415   0.0816   0.6075   0.4740   0.4904   0.9788
 10   0.0026   0.9858   0.1404   0.0488   0.7495   0.0100   0.1546   0.1059   0.1115   0.3684
 11           0.0027   0.0892   0.2327   0.0060   0.6013   0.0802   0.1192   0.1134   0.0250
```

```
12  0.0027          0.1450  0.0507  0.7630  0.0105  0.1596  0.1096  0.1153  0.3778
13  0.0892  0.1450          0.5952  0.2430  0.2294  0.9575  0.8801  0.9011  0.5532
14  0.2327  0.0507  0.5952          0.0939  0.4960  0.5591  0.7031  0.6835  0.2644
15  0.0060  0.7630  0.2430  0.0939          0.0216  0.2644  0.1892  0.1979  0.5591
16  0.6013  0.0105  0.2294  0.4960  0.0216          0.2101  0.2912  0.2795  0.0774
17  0.0802  0.1596  0.9575  0.5591  0.2644  0.2101          0.8383  0.8592  0.5891
18  0.1192  0.1096  0.8801  0.7031  0.1892  0.2912  0.8383          0.9788  0.4579
19  0.1134  0.1153  0.9011  0.6835  0.1979  0.2795  0.8592  0.9788          0.4740
20  0.0250  0.3778  0.5532  0.2644  0.5591  0.0774  0.5891  0.4579  0.4740
```

```
         The SAS System      13:24 Wednesday, August 25, 2018  17
                         The GLM Procedure
                        Least Squares Means

                                  Standard             LSMEAN
      Irrign   Nitrgn    HT06 LSMEAN        Error    Pr > |t|     Number

       1        1        49.3000000     7.1647071     <.0001         1
       1        2        61.0000000     7.1647071     <.0001         2
       1        3        57.9000000     7.1647071     <.0001         3
       1        4        67.8000000     7.1647071     <.0001         4
       1        5        95.2333333     7.1647071     <.0001         5
       2        1        42.1333333     7.1647071     <.0001         6
       2        2        62.8000000     7.1647071     <.0001         7
       2        3        73.2333333     7.1647071     <.0001         8
       2        4        58.2333333     7.1647071     <.0001         9
       2        5        71.9666667     7.1647071     <.0001        10
       3        1        35.2666667     7.1647071     <.0001        11
       3        2        63.8666667     7.1647071     <.0001        12
       3        3        56.4666667     7.1647071     <.0001        13
       3        4        55.4333333     7.1647071     <.0001        14
       3        5        62.9000000     7.1647071     <.0001        15
       4        1        38.8666667     7.1647071     <.0001        16
       4        2        55.9000000     7.1647071     <.0001        17
       4        3        59.4333333     7.1647071     <.0001        18
       4        4        57.2333333     7.1647071     <.0001        19
       4        5        62.5666667     7.1647071     <.0001        20

              Least Squares Means for effect Irrign*Nitrgn
                 Pr > |t| for H0: LSMean(i)=LSMean(j)

                      Dependent Variable: HT06

i/j      1       2       3       4       5       6       7       8       9      10
  1          0.2568  0.4023  0.0772  <.0001  0.4845  0.1922  0.0244  0.3845  0.0324
  2  0.2568          0.7616  0.5070  0.0019  0.0718  0.8601  0.2361  0.7866  0.2872
  3  0.4023  0.7616          0.3359  0.0008  0.1295  0.6320  0.1400  0.9740  0.1746
  4  0.0772  0.5070  0.3359          0.0108  0.0164  0.6251  0.5955  0.3522  0.6837
  5  <.0001  0.0019  0.0008  0.0108          <.0001  0.0031  0.0374  0.0009  0.0284
```

```
  6  0.4845  0.0718  0.1295  0.0164  <.0001          0.0497  0.0043  0.1219  0.0060
  7  0.1922  0.8601  0.6320  0.6251  0.0031  0.0497          0.3109  0.6552  0.3724
  8  0.0244  0.2361  0.1400  0.5955  0.0374  0.0043  0.3109          0.1485  0.9013
  9  0.3845  0.7866  0.9740  0.3522  0.0009  0.1219  0.6552  0.1485          0.1848
 10  0.0324  0.2872  0.1746  0.6837  0.0284  0.0060  0.3724  0.9013  0.1848
 11  0.1756  0.0162  0.0326  0.0030  <.0001  0.5028  0.0105  0.0007  0.0303  0.0010
 12  0.1602  0.7791  0.5601  0.7004  0.0041  0.0397  0.9168  0.3622  0.5821  0.4299
 13  0.4845  0.6576  0.8884  0.2717  0.0006  0.1668  0.5364  0.1078  0.8627  0.1359
 14  0.5492  0.5866  0.8092  0.2312  0.0004  0.1986  0.4725  0.0885  0.7841  0.1125
 15  0.1890  0.8524  0.6251  0.6320  0.0032  0.0487  0.9922  0.3155  0.6482  0.3776
 16  0.3109  0.0364  0.0695  0.0075  <.0001  0.7492  0.0244  0.0019  0.0650  0.0026
           The SAS System       13:24 Wednesday, August 25, 2018  18

                          The GLM Procedure
                         Least Squares Means

                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)

                        Dependent Variable: HT06

i/j      1       2       3       4       5       6       7       8       9      10
 17  0.5195  0.6182  0.8448  0.2489  0.0005  0.1838  0.5008  0.0968  0.8193  0.1226
 18  0.3248  0.8781  0.8807  0.4151  0.0013  0.0974  0.7419  0.1827  0.9065  0.2251
 19  0.4394  0.7125  0.9480  0.3048  0.0007  0.1459  0.5866  0.1242  0.9220  0.1557
 20  0.1997  0.8781  0.6482  0.6091  0.0029  0.0522  0.9818  0.3004  0.6718  0.3605

                Least Squares Means for effect Irrign*Nitrgn
                   Pr > |t| for H0: LSMean(i)=LSMean(j)

                        Dependent Variable: HT06

i/j     11      12      13      14      15      16      17      18      19      20
  1  0.1756  0.1602  0.4845  0.5492  0.1890  0.3109  0.5195  0.3248  0.4394  0.1997
  2  0.0162  0.7791  0.6576  0.5866  0.8524  0.0364  0.6182  0.8781  0.7125  0.8781
  3  0.0326  0.5601  0.8884  0.8092  0.6251  0.0695  0.8448  0.8807  0.9480  0.6482
  4  0.0030  0.7004  0.2717  0.2312  0.6320  0.0075  0.2489  0.4151  0.3048  0.6091
  5  <.0001  0.0041  0.0006  0.0004  0.0032  <.0001  0.0005  0.0013  0.0007  0.0029
  6  0.5028  0.0397  0.1668  0.1986  0.0487  0.7492  0.1838  0.0974  0.1459  0.0522
  7  0.0105  0.9168  0.5364  0.4725  0.9922  0.0244  0.5008  0.7419  0.5866  0.9818
  8  0.0007  0.3622  0.1078  0.0885  0.3155  0.0019  0.0968  0.1827  0.1242  0.3004
  9  0.0303  0.5821  0.8627  0.7841  0.6482  0.0650  0.8193  0.9065  0.9220  0.6718
 10  0.0010  0.4299  0.1359  0.1125  0.3776  0.0026  0.1226  0.2251  0.1557  0.3605
 11          0.0081  0.0444  0.0552  0.0103  0.7247  0.0501  0.0232  0.0377  0.0111
 12  0.0081          0.4705  0.4114  0.9246  0.0191  0.4375  0.6647  0.5174  0.8987
 13  0.0444  0.4705          0.9194  0.5300  0.0920  0.9557  0.7716  0.9402  0.5514
 14  0.0552  0.4114  0.9194          0.4665  0.1118  0.9636  0.6956  0.8601  0.4865
 15  0.0103  0.9246  0.5300  0.4665          0.0239  0.4946  0.7345  0.5799  0.9740
 16  0.7247  0.0191  0.0920  0.1118  0.0239          0.1025  0.0508  0.0793  0.0257
 17  0.0501  0.4375  0.9557  0.9636  0.4946  0.1025          0.7296  0.8961  0.5153
```

```
 18  0.0232  0.6647  0.7716  0.6956  0.7345  0.0508  0.7296          0.8295  0.7591
 19  0.0377  0.5174  0.9402  0.8601  0.5799  0.0793  0.8961  0.8295          0.6023
 20  0.0111  0.8987  0.5514  0.4865  0.9740  0.0257  0.5153  0.7591  0.6023


                           Standard           LSMEAN
   Irrign  Nitrgn   HT08 LSMEAN        Error   Pr > |t|     Number

   1       1        108.800000      19.953823     <.0001        1
   1       2        120.100000      19.953823     <.0001        2
   1       3        132.133333      19.953823     <.0001        3
   1       4        144.100000      19.953823     <.0001        4

   The SAS System      13:24 Wednesday, August 25, 2018  19
                        The GLM Procedure
                       Least Squares Means
                           Standard           LSMEAN
   Irrign  Nitrgn   HT08 LSMEAN        Error   Pr > |t|     Number

   1       5        139.200000      19.953823     <.0001        5
   2       1        108.800000      19.953823     <.0001        6
   2       2        128.333333      19.953823     <.0001        7
   2       3        140.800000      19.953823     <.0001        8
   2       4        135.900000      19.953823     <.0001        9
   2       5        149.666667      19.953823     <.0001        10
   3       1         89.433333     19.953823     <.0001        11
   3       2        127.200000      19.953823     <.0001        12
   3       3        131.666667      19.953823     <.0001        13
   3       4        118.533333      19.953823     <.0001        14
   3       5        137.666667      19.953823     <.0001        15
   4       1         90.633333     19.953823     <.0001        16
   4       2        119.233333      19.953823     <.0001        17
   4       3        133.633333      19.953823     <.0001        18
   4       4        213.433333      19.953823     <.0001        19
   4       5        135.233333      19.953823     <.0001        20


              Least Squares Means for effect Irrign*Nitrgn
                Pr > |t| for H0: LSMean(i)=LSMean(j)

                     Dependent Variable: HT08

i/j      1       2       3       4       5       6       7       8       9      10
 1          0.6915  0.4144  0.2200  0.2894  1.0000  0.4938  0.2652  0.3441  0.1573
 2  0.6915          0.6727  0.4014  0.5034  0.6915  0.7723  0.4686  0.5794  0.3026
 3  0.4144  0.6727          0.6744  0.8039  0.4144  0.8937  0.7607  0.8946  0.5388
 4  0.2200  0.4014  0.6744          0.8632  0.2200  0.5802  0.9076  0.7732  0.8449
 5  0.2894  0.5034  0.8039  0.8632          0.2894  0.7027  0.9551  0.9076  0.7131
 6  1.0000  0.6915  0.4144  0.2200  0.2894          0.4938  0.2652  0.3441  0.1573
 7  0.4938  0.7723  0.8937  0.5802  0.7027  0.4938          0.6616  0.7903  0.4552
```

```
  8  0.2652  0.4686  0.7607  0.9076  0.9551  0.2652  0.6616          0.8632  0.7554
  9  0.3441  0.5794  0.8946  0.7732  0.9076  0.3441  0.7903  0.8632          0.6290
 10  0.1573  0.3026  0.5388  0.8449  0.7131  0.1573  0.4552  0.7554  0.6290
 11  0.4975  0.2853  0.1401  0.0616  0.0873  0.4975  0.1776  0.0781  0.1094  0.0406
 12  0.5190  0.8030  0.8623  0.5535  0.6735  0.5190  0.9682  0.6331  0.7598  0.4318
 13  0.4237  0.6846  0.9869  0.6625  0.7912  0.4237  0.9067  0.7483  0.8817  0.5281
 14  0.7324  0.9561  0.6331  0.3717  0.4693  0.7324  0.7307  0.4359  0.5426  0.2781
 15  0.3140  0.5380  0.8458  0.8211  0.9570  0.3140  0.7430  0.9123  0.9505  0.6735
 16  0.5243  0.3042  0.1512  0.0672  0.0949  0.5243  0.1910  0.0849  0.1185  0.0445
 17  0.7140  0.9757  0.6507  0.3848  0.4843  0.7140  0.7492  0.4503  0.5589  0.2889
 18  0.3854  0.6348  0.9579  0.7131  0.8449  0.3854  0.8522  0.8011  0.9365  0.5739
 19  0.0008  0.0023  0.0070  0.0196  0.0130  0.0008  0.0050  0.0149  0.0098  0.0308
 20  0.3559  0.5955  0.9132  0.7554  0.8891  0.3559  0.8084  0.8449  0.9813  0.6125
          The SAS System       13:24 Wednesday, August 25, 2018  20
                            The GLM Procedure
                           Least Squares Means

                 Least Squares Means for effect Irrign*Nitrgn
                     Pr > |t| for H0: LSMean(i)=LSMean(j)

                          Dependent Variable: HT08

i/j      11      12      13      14      15      16      17      18      19      20
  1  0.4975  0.5190  0.4237  0.7324  0.3140  0.5243  0.7140  0.3854  0.0008  0.3559
  2  0.2853  0.8030  0.6846  0.9561  0.5380  0.3042  0.9757  0.6348  0.0023  0.5955
  3  0.1401  0.8623  0.9869  0.6331  0.8458  0.1512  0.6507  0.9579  0.0070  0.9132
  4  0.0616  0.5535  0.6625  0.3717  0.8211  0.0672  0.3848  0.7131  0.0196  0.7554
  5  0.0873  0.6735  0.7912  0.4693  0.9570  0.0949  0.4843  0.8449  0.0130  0.8891
  6  0.4975  0.5190  0.4237  0.7324  0.3140  0.5243  0.7140  0.3854  0.0008  0.3559
  7  0.1776  0.9682  0.9067  0.7307  0.7430  0.1910  0.7492  0.8522  0.0050  0.8084
  8  0.0781  0.6331  0.7483  0.4359  0.9123  0.0849  0.4503  0.8011  0.0149  0.8449
  9  0.1094  0.7598  0.8817  0.5426  0.9505  0.1185  0.5589  0.9365  0.0098  0.9813
 10  0.0406  0.4318  0.5281  0.2781  0.6735  0.0445  0.2889  0.5739  0.0308  0.6125
 11          0.1902  0.1443  0.3102  0.0971  0.9663  0.2989  0.1271  0.0001  0.1144
 12  0.1902          0.8752  0.7607  0.7131  0.2043  0.7795  0.8211  0.0045  0.7777
 13  0.1443  0.8752          0.6448  0.8330  0.1557  0.6625  0.9449  0.0067  0.9002
 14  0.3102  0.7607  0.6448          0.5026  0.3302  0.9804  0.5963  0.0020  0.5581
 15  0.0971  0.7131  0.8330  0.5026          0.1053  0.5183  0.8872  0.0114  0.9318
 16  0.9663  0.2043  0.1557  0.3302  0.1053          0.3184  0.1374  0.0001  0.1238
 17  0.2989  0.7795  0.6625  0.9804  0.5183  0.3184          0.6133  0.0021  0.5747
 18  0.1271  0.8211  0.9449  0.5963  0.8872  0.1374  0.6133          0.0080  0.9551
 19  0.0001  0.0045  0.0067  0.0020  0.0114  0.0001  0.0021  0.0080          0.0092
 20  0.1144  0.7777  0.9002  0.5581  0.9318  0.1238  0.5747  0.9551  0.0092

                                  Standard           LSMEAN
    Irrign   Nitrgn    HT10 LSMEAN         Error   Pr > |t|     Number

    1        1        175.566667      13.712295     <.0001        1
    1        2        201.566667      13.712295     <.0001        2
    1        3        210.000000      13.712295     <.0001        3
```

```
        1      4       234.966667     13.712295     <.0001        4
        1      5       223.100000     13.712295     <.0001        5
        2      1       177.433333     13.712295     <.0001        6
        2      2       196.666667     13.712295     <.0001        7
        2      3       212.333333     13.712295     <.0001        8
        2      4       210.433333     13.712295     <.0001        9
        2      5       244.433333     13.712295     <.0001       10
        3      1       153.466667     13.712295     <.0001       11
        3      2       211.466667     13.712295     <.0001       12
        3      3       208.233333     13.712295     <.0001       13
        3      4       196.866667     13.712295     <.0001       14
        3      5       207.766667     13.712295     <.0001       15
        4      1       151.000000     13.712295     <.0001       16
         The SAS System      13:24 Wednesday, August 25, 2018  21

                           The GLM Procedure
                          Least Squares Means
                                 Standard             LSMEAN
       Irrign   Nitrgn    HT10 LSMEAN          Error    Pr > |t|      Number

        4      2       189.433333     13.712295     <.0001       17
        4      3       200.900000     13.712295     <.0001       18
        4      4       200.633333     13.712295     <.0001       19
        4      5       205.100000     13.712295     <.0001       20


                   Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)

                          Dependent Variable: HT10

i/j      1       2       3       4       5       6       7       8       9      10
  1         0.1894  0.0853  0.0044  0.0199  0.9239  0.2847  0.0670  0.0816  0.0012
  2  0.1894         0.6666  0.0947  0.2751  0.2224  0.8021  0.5826  0.6506  0.0343
  3  0.0853  0.6666         0.2072  0.5042  0.1028  0.4967  0.9050  0.9823  0.0853
  4  0.0044  0.0947  0.2072         0.5449  0.0057  0.0569  0.2518  0.2150  0.6288
  5  0.0199  0.2751  0.5042  0.5449         0.0248  0.1824  0.5826  0.5183  0.2795
  6  0.9239  0.2224  0.1028  0.0057  0.0248         0.3287  0.0813  0.0985  0.0016
  7  0.2847  0.8021  0.4967  0.0569  0.1824  0.3287         0.4251  0.4829  0.0193
  8  0.0670  0.5826  0.9050  0.2518  0.5826  0.0813  0.4251         0.9226  0.1076
  9  0.0816  0.6506  0.9823  0.2150  0.5183  0.0985  0.4829  0.9226         0.0891
 10  0.0012  0.0343  0.0853  0.6288  0.2795  0.0016  0.0193  0.1076  0.0891
 11  0.2629  0.0186  0.0064  0.0002  0.0011  0.2255  0.0331  0.0047  0.0061  <.0001

                   Least Squares Means for effect Irrign*Nitrgn
                      Pr > |t| for H0: LSMean(i)=LSMean(j)

                          Dependent Variable: HT10

i/j      11      12      13      14      15      16      17      18      19      20
```

```
  1  0.2629  0.0734  0.1018  0.2802  0.1066  0.2144  0.4798  0.2007  0.2054  0.1376
  2  0.0186  0.6132  0.7333  0.8100  0.7513  0.0137  0.5360  0.9728  0.9619  0.8566
  3  0.0064  0.9402  0.9280  0.5031  0.9090  0.0047  0.2968  0.6421  0.6324  0.8021
  4  0.0002  0.2344  0.1776  0.0582  0.1704  0.0001  0.0252  0.0885  0.0862  0.1334
  5  0.0011  0.5528  0.4489  0.1856  0.4349  0.0008  0.0922  0.2608  0.2552  0.3602
  6  0.2255  0.0888  0.1221  0.3238  0.1276  0.1824  0.5404  0.2351  0.2403  0.1634
  7  0.0331  0.4509  0.5551  0.9918  0.5711  0.0248  0.7116  0.8286  0.8392  0.6666
  8  0.0047  0.9646  0.8339  0.4310  0.8153  0.0034  0.2463  0.5596  0.5505  0.7116
  9  0.0061  0.9578  0.9104  0.4892  0.8915  0.0044  0.2869  0.6264  0.6168  0.7851
 10  <.0001  0.0988  0.0711  0.0198  0.0677  <.0001  0.0079  0.0318  0.0309  0.0509
 11          0.0053  0.0081  0.0323  0.0086  0.8996  0.0729  0.0201  0.0208  0.0120
       The SAS System       13:24 Wednesday, August 25, 2018  22

                          The GLM Procedure
                         Least Squares Means

              Least Squares Means for effect Irrign*Nitrgn
                 Pr > |t| for H0: LSMean(i)=LSMean(j)

                     Dependent Variable: HT10

i/j       1       2       3       4       5       6       7       8       9      10
 12  0.0734  0.6132  0.9402  0.2344  0.5528  0.0888  0.4509  0.9646  0.9578  0.0988
 13  0.1018  0.7333  0.9280  0.1776  0.4489  0.1221  0.5551  0.8339  0.9104  0.0711
 14  0.2802  0.8100  0.5031  0.0582  0.1856  0.3238  0.9918  0.4310  0.4892  0.0198
 15  0.1066  0.7513  0.9090  0.1704  0.4349  0.1276  0.5711  0.8153  0.8915  0.0677
 16  0.2144  0.0137  0.0047  0.0001  0.0008  0.1824  0.0248  0.0034  0.0044  <.0001
 17  0.4798  0.5360  0.2968  0.0252  0.0922  0.5404  0.7116  0.2463  0.2869  0.0079
 18  0.2007  0.9728  0.6421  0.0885  0.2608  0.2351  0.8286  0.5596  0.6264  0.0318
 19  0.2054  0.9619  0.6324  0.0862  0.2552  0.2403  0.8392  0.5505  0.6168  0.0309
 20  0.1376  0.8566  0.8021  0.1334  0.3602  0.1634  0.6666  0.7116  0.7851  0.0509

              Least Squares Means for effect Irrign*Nitrgn
                 Pr > |t| for H0: LSMean(i)=LSMean(j)

                     Dependent Variable: HT10

i/j      11      12      13      14      15      16      17      18      19      20

 12  0.0053          0.8686  0.4570  0.8499  0.0038  0.2643  0.5896  0.5803  0.7448
 13  0.0081  0.8686          0.5619  0.9810  0.0059  0.3396  0.7078  0.6977  0.8727
 14  0.0323  0.4570  0.5619          0.5780  0.0242  0.7040  0.8366  0.8472  0.6740
 15  0.0086  0.8499  0.9810  0.5780          0.0062  0.3515  0.7256  0.7154  0.8915
 16  0.8996  0.0038  0.0059  0.0242  0.0062          0.0561  0.0149  0.0154  0.0088
 17  0.0729  0.2643  0.3396  0.7040  0.3515  0.0561          0.5585  0.5676  0.4251
 18  0.0201  0.5896  0.7078  0.8366  0.7256  0.0149  0.5585          0.9891  0.8299
 19  0.0208  0.5803  0.6977  0.8472  0.7154  0.0154  0.5676  0.9891          0.8193
 20  0.0120  0.7448  0.8727  0.6740  0.8915  0.0088  0.4251  0.8299  0.8193

NOTE: To ensure overall protection level, only probabilities associated with pre-planned
```

```
comparisons should be used.
  The SAS System       13:24 Wednesday, August 25, 2018  23

                         The GLM Procedure

                        t Tests (LSD) for HT04

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                 Alpha                       0.05
                 Error Degrees of Freedom           32
                 Error Mean Square           20.83292
                 Critical Value of t         2.03693
                 Least Significant Difference   3.3949

             Means with the same letter are not significantly different.

               t Grouping          Mean      N    Irrign

                   A       28.580     15    1
                   A
                 B   A       28.020     15    2
                 B   A
                 B   A       25.960     15    3
                 B
                 B         25.033     15    4
 The SAS System       13:24 Wednesday, August 25, 2018  24

                         The GLM Procedure

                        t Tests (LSD) for HT06

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.

                 Alpha                       0.05
                 Error Degrees of Freedom           32
                 Error Mean Square           153.9991
                 Critical Value of t         2.03693
                 Least Significant Difference   9.2301

             Means with the same letter are not significantly different.


               t Grouping          Mean      N    Irrign

                   A       66.247     15    1
                   A
                 B   A       61.673     15    2
                 B
```

```
                    B           54.800     15    4
                    B
                    B           54.787     15    3
     The SAS System       13:24 Wednesday, August 25, 2018  25

                              The GLM Procedure

                            t Tests (LSD) for HT08

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.
                    Alpha                         0.05
                    Error Degrees of Freedom           32
                    Error Mean Square           1194.465
                    Critical Value of t          2.03693
                    Least Significant Difference   25.706

               Means with the same letter are not significantly different.

                 t Grouping          Mean      N    Irrign

                     A       138.43     15    4
                     A
                     A       132.70     15    2
                     A
                     A       128.87     15    1
                     A
                     A       120.90     15    3
    The SAS System       13:24 Wednesday, August 25, 2018  26

                              The GLM Procedure

                            t Tests (LSD) for HT10

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.


                    Alpha                         0.05
                    Error Degrees of Freedom           32
                    Error Mean Square            564.0811
                    Critical Value of t          2.03693
                    Least Significant Difference   17.665


               Means with the same letter are not significantly different.


                  t Grouping          Mean      N    Irrign
```

```
             A      209.040    15   1
             A
             A      208.260    15   2
             A
          B  A       195.560    15   3
          B
          B         189.413    15   4
    The SAS System      13:24 Wednesday, August 25, 2018  27

                       The GLM Procedure

                     t Tests (LSD) for HT04

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.

          Alpha                    0.05
          Error Degrees of Freedom          32
          Error Mean Square           20.83292
          Critical Value of t         2.03693
          Least Significant Difference   3.7956

     Means with the same letter are not significantly different.


        t Grouping         Mean      N    Nitrgn

             A       30.075     12    5
             A
          B   A       29.458     12    2
          B   A
          B   A       26.358     12    3
          B
          B   C       26.175     12    4
             C
             C       22.425     12    1
   The SAS System      13:24 Wednesday, August 25, 2018  28

                       The GLM Procedure

                     t Tests (LSD) for HT06

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.

          Alpha                    0.05
          Error Degrees of Freedom          32
          Error Mean Square           153.9991
          Critical Value of t         2.03693
          Least Significant Difference    10.32
```

```
              Means with the same letter are not significantly different.


                t Grouping          Mean      N    Nitrgn

                       A        73.167     12    5

                       B        61.758     12    3
                       B
                       B        60.892     12    2
                       B
                       B        59.675     12    4

                       C        41.392     12    1
          The SAS System       13:24 Wednesday, August 25, 2018  29

                              The GLM Procedure

                            t Tests (LSD) for HT08

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.

                      Alpha                        0.05
                      Error Degrees of Freedom           32
                      Error Mean Square            1194.465
                      Critical Value of t          2.03693
                      Least Significant Difference    28.74

              Means with the same letter are not significantly different.


                 t Grouping          Mean      N    Nitrgn

                        A       152.99     12    4
                        A
                      B   A      140.44     12    5
                      B   A
                      B   A      134.56     12    3
                      B
                      B   C      123.72     12    2
                        C
                        C       99.42     12    1

           The SAS System       13:24 Wednesday, August 25, 2018  30

                              The GLM Procedure

                            t Tests (LSD) for HT10
```

```
 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
rate.

                         Alpha                      0.05
                         Error Degrees of Freedom          32
                         Error Mean Square           564.0811
                         Critical Value of t          2.03693
                         Least Significant Difference    19.75

                    Means with the same letter are not significantly different.

                       t Grouping          Mean      N    Nitrgn

                           A       220.100     12    5
                           A
                         B    A       210.725     12    4
                         B    A
                         B    A       207.867     12    3
                         B
                         B          199.783     12    2

                           C       164.367     12    1

              The SAS System        13:24 Wednesday, August 25, 2018  31

                              The GLM Procedure

 Level of Level of   -----------HT04---------- -----------HT06---------- -----------HT08----------
 Irrign   Nitrgn  N        Mean        Std Dev          Mean        Std Dev          Mean        Std Dev

 1        1       3  26.9000000   4.16173041   49.3000000   12.1280666   108.800000
8.702299
 1        2       3  30.6333333   1.15470054  61.0000000    3.6055513   120.100000
13.509996
 1        3       3  26.3333333   5.20800666  57.9000000   12.5391387   132.133333
23.444900
 1        4       3  28.0333333   1.52752523  67.8000000    1.8520259   144.100000
3.862642
 1        5       3  31.0000000   5.81291665  95.2333333   39.2079499   139.200000
27.639284
 2        1       3  22.5666667   2.37977590  42.1333333    0.7505553   108.800000
18.529166
 2        2       3  30.1000000   4.23320210  62.8000000    7.8504777   128.333333
17.919914
 2        3       3  28.3333333   5.50757055  73.2333333   10.7267578   140.800000
9.681426
 2        4       3  27.8000000   9.61925153  58.2333333   11.7202105   135.900000
20.780520
```

```
 2      5     3  31.3000000  2.00000000  71.9666667   3.2145503  149.666667
8.386497
 3      1     3  19.1333333  7.65919926  35.2666667  15.6174048   89.433333
24.080144
 3      2     3  31.2333333  4.61121820  63.8666667   8.2923660  127.200000
6.717887
 3      3     3  25.6666667  4.10162569  56.4666667  10.6800437  131.666667
15.928695
 3      4     3  23.6666667  4.04145188  55.4333333   4.1186567  118.533333
8.256109
 3      5     3  30.1000000  5.52449093  62.9000000  12.0797351  137.666667
27.862579
 4      1     3  21.1000000  4.25793377  38.8666667  11.6345749   90.633333
24.214321
 4      2     3  25.8666667  3.85529938  55.9000000   7.2332565  119.233333
8.078572
 4      3     3  25.1000000  4.74657771  59.4333333   5.5193599  133.633333
8.962886
 4      4     3  25.2000000  3.38082830  57.2333333   8.5125398  213.433333
149.403023
 4      5     3  27.9000000  4.45308882  62.5666667  11.2500370  135.233333
26.822814

                         Level of Level of  -------------HT10------------
                         Irrign   Nitrgn  N        Mean          Std Dev

                         1        1       3  175.566667       27.0157978
                         1        2       3  201.566667       10.0281271
                         1        3       3  210.000000       29.0325679
                         1        4       3  234.966667        0.4618802
                         1        5       3  223.100000       24.5016326
                         2        1       3  177.433333       26.9861693
                         2        2       3  196.666667       14.4368741
                         2        3       3  212.333333       12.3216611
                         2        4       3  210.433333       20.3681942
                         2        5       3  244.433333       35.4056963
                         3        1       3  153.466667       41.9435732
                         3        2       3  211.466667       37.0454226
                         3        3       3  208.233333       31.3394852
                         3        4       3  196.866667       18.5704963
                         3        5       3  207.766667       45.8982934
                         4        1       3  151.000000       21.9724828
                         4        2       3  189.433333       24.0117332
                         4        3       3  200.900000       20.5358224
                         4        4       3  200.633333       32.1299445
                         4        5       3  205.100000       41.9275566
```