DEVELOPMENT OF MANAGEMENT OPTIONS FOR OPTIMIZING WATER AND NITROGEN UTILIZATION FOR MAIZE PRODUCTION IN MALAWI

JOHN MTHANDI

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE.

MOROGORO, TANZANIA.

2015

EXTENDED ABSTRACT

Nitrogen and water management practices are key components in Crop production. Plants cannot grow in soil without water, so too when soil is saturated with water. Plants lacking N show stunted growth and yellowish leaves. Too much N can have negative environmental impacts such as contamination of water, pollution, and eutrophication. Leaching is the main vehicle through which applied nitrogen can contaminate groundwater. Identifying the most economic application rate of N fertilizer is most important in high N demanding crops such as maize. Understanding of N movement through soil profile is also essential for more N efficient and minimizing N leaching. The aims of this study were to evaluate the agronomic response of maize to different water and N application regimes; to determine the lateral and vertical movement of nitrogen under different irrigation regimes; and to model the distribution pattern of nitrogen in the maize root zone. The research study was conducted in two irrigation growing seasons from 1st June to 8th September 2012, and from 10th September to 15th December, 2012 at Nkango Irrigation Scheme in Kasungu, Malawi. The factors under study were water and nitrogen with four levels each. A V-notch flume was used to measure volume of applied water to the plots.

Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia), which has ability to monitor the direction and movement of nitrogen in the soil at instant time of inserting monitoring probe in the soil, was used to measure total nitrogen concentration at lateral distances. The measurement of the sensor is in Volumetric Ion Concentration (VIC), but using standazation equation the concentration of total nitrogen on each point was calculated. The lateral distances at which measurements were taken were at point of

application (represented by 0 cm), at 5 cm away from the plant (represented by -5 cm), at 5 cm towards the plant, 10 cm towards the plant (this point was maize planting station), and 15 cm (this point was 5 cm after planting station in the direction opposite from where N was applied). The lateral distances were taken based on spreading and elongation pattern of lateral roots of maize plants. The lateral readings of nitrogen were respecively taken at five soil depths of 20, 40, 60, 80, and 100 cm. The R version 3.2.2, open source statistical software (R Core Team, 2015) was used to run ANOVA statistical analysis on yield data, separate treatment effect means and plot various graphical plots such as box and whisker and interaction effects.

The following conclusions were drawn from the study:

- The study has concluded that statistically interactive effect of 60% of FWRR and 92 N Kg/ha gave optimum yields compared to other combination of treatments. The interactive effect of nitrogen and water on maize yield has indicated that it is only a combination of 100% FWRR: 92 Kgs N/Ha – 60% FWRR: 92 Kgs N/Ha that has no significant difference on maize yield (*p-values* <0.1). The irrigated smallholder farmers can therefore be advised to apply 60%FWRR to their maize fields to save water.
- The study has identified that vertical movement of nitrogen is influenced by water flux, and the direction of flow is greatly influenced by absorption rate of plants roots due to gradient created by absorption. When supply of nitrogen is low due to high absorption of plants roots especially during the period when plants require large quantities of nitrogen, the lateral movement of nitrogen towards plant roots is greatly influenced by pulling effect by plant roots, caused by negative gradient due to water uptake known as diffusion.

- The study has also shown that the factors that influence movement patterns, direction, and distribution of nitrogen concentration are: evaporation of water from the soil surfaces, pulling effects by plant roots, deep percolation through gravitational force, and ability of plant roots to create environment that is conducive to diffusion of nitrogen.
- The study has inferred that the soil moisture redistribution in the root zone is directly related to the amount of applied irrigation water, and spatial distribution of soil moisture content was primarily influenced by roots water uptake and evaporation.
- Review of N leaching simulation models has indicated that models that use cascading soil water balance approach in simulating water and solute transport through soil profile are much better compared with models that uses Richards' and Convection-Dispersion equations. Richards' (and Darcy's) and Convection-Dispersion equations are suitable to model unsaturated flow in laboratory-scale soil columns with limited heterogeneity, but have limited capability to simulate water flow in field soils which have high soil variability.
- The study has shown that N leaching can be delayed, which consequently means it can easily be managed. The results of this paper has indicated that N leaching is directly related to water, higher amount of applied water result in high N leaching and less amount of applied water result into less or zero N leaching. In order to minimize N leaching it is of paramount important to squarely manage applied water. Applied water in the soil should not exceed field capacity of the soil and in such way leaching of nitrogen will be minimized.
- The study has concluded that treatments that received high amount of inorganic N fertilizer lost more nitrogen through N leaching because plant roots only absorb

nitrogen it requires leaving excess N to be leached by water below the active rooting zone. The study has also concluded that with the use EU-Rotate N model, it is possible to minimize N leaching by reducing amount of applied water during the time when leaf area index is 1 or nearly there.

The following recommendations were concluded from this study:

- The study was conducted in sandy loam soils. Further study needs to be done in different types of soil to establish the maize responses to different levels of water and nitrogen for different types of soils.
- While it was not economicaly viable to apply 125% of TNPRA in the study, technically the treatment gave very good insight of behaviour of nitrogen in the soil when its content is 'high'. It is therefore recommended that further study needs to be done in which two or more treatments with high nitrogen application levels than TNPRA will be tested so as to know behaviour of nitrogen in soil when its application content is high.
- Further study needs to be done on the pulling effect of plant roots. Maize at different stages has different pulling effects. The study need to unearth whether the pulling effect is also influenced by soil types, soil moisture contents, availability of nitrogen in the soil etc. and to what extent does pulling effect affect the movement of solutes in the soil.
- N leaching is simply defined as N which is below active root zone of a crop. This means that for shallow-rooted crops, N leaching can be below few depth of soil while deep-rooted crops, N leaching can be below far deeper. In this case, N leaching can be managed by rotating shallow- and deep-rooted crops. Intercropping of shallow- and deep-rooted crops can also manage N leaching. This

is because deep-rooted crops can be efficiently absorbing nitrogen which has 'leached' from shallow-rooted crops.

DECLARATION

I, John Mthandi, do hereby declare to the Senate of the Sokoine University of Agriculture, Morogoro, Tanzania, that this Dissertation is my own original work done within the period of registration, and that it has never been submitted nor concurrently being submitted for a degree award in any institution.

Signature: Date
(PhD Candidate)

The declaration is confirmed by:

Signature: Date
Prof. F. C. Kahimba
(Supervisor)

Signature: Date
Prof. A. K. P. R. Tarimo
(Supervisor)

Signature: Date
Dr. B. A. Salim
(Supervisor)

COPYRIGHT

ACKNOWLEDGEMENTS

I wish to sincerely appreciate the intuitive and critical guidance and advise that I got from my advisers Prof. F. C. Kahimba, Prof. A. K. P. R. Tarimo, Dr. B. A. Salim, and Dr. M. Lowole. Advices and knowledge they provided me coupled with the classroom instructional notes constituted the core package of my research work and are so invaluable. Their inspirational and leadership, especially in upholding the ethics of student's own effort in research work were deeply appreciated. I am fortunate enough to have been under your command.

I wish to register my profound thanks to Alliance for Green Revolution in Africa (AGRA) for their munificent and unflinching financial support to my studies. Without this financial support all would have been in vain. The incessant financial support to students to study PhD cannot go without my recognition and appreciation.

I would also like to recognize all Professors of Sokoine University of Agriculture, University of Luenburg, and University of Malawi, who gave me the tastes of different courses and changed my being. The concepts they imparted in me constituted the core and sound basis for my research work.

I will cherish vivid memories of the hospitality and cordiality I enjoyed in Morogoro. The memories will go on and on and will be the core package worth to be shared to many in those future ages when life live on memories. During those ages when there are no hopes, no goals to achieve and nothing, memories tend to be driving force to live. VIVA!! MOROGORO.

Dr. Marie Rayiera, and Dr Bashir Jama of AGRA, and Dr. Abel Kaaya of SUA deserves my special recognition and immense gratitude.

I wish to recognize the following people for making my life in MOROGORO pleasant and thrilling: Assefa Menna (Ethiopia), Austin Phiri (Malawi), Jacob O. Omollo (Kenya), Sixbert Mourice (Tanzania), Sylvere Sirikare (Rwanda), Syphyline Kebeney (Kenya), Thomas Tiluhongelwa (Tanzania), Wogi Lemma (Ethiopia), Frank Mwenechanya (Malawi), Barnabas Msongeleli (Tanzania), and Darwin Dodoma Singa (Malawi). Not only do you deserve my recognition, but also my admiration for making my life simple but full of happiness at SUA. We shared the same experiences in MOROGORO, TANZANIA.

DEDICATION

I dedicate this work to The Almighty GOD, whose unwavering divine inspiration, has always given me courage to face life cheerfully with kindness, beauty and truth.

To my wife Anastanzia Mthandi, you have always been on my side during the time when I needed you most; you bring happiness and joy in my life. You add value to my life. You deserve nothing less.

To my children Juliana, Juliet, and Julius, to whom I am willingly giving this educational yard stick to which they should refer to. This is a reference point of your educational success, below which I will not be impressed.

TABLE OF CONTENTS

EXTENDED ABSTRACT ii

DECLARATION vii

COPYRIGHT viii

ACKNOWLEDGEMENTS ix

DEDICATION xi

TABLE OF CONTENTS xii

LIST OF PAPERS xvi

LIST OF TABLES xviii

LIST OF FIGURES xix

LIST OF APPENDICES xxi

LIST SYMBOLS AND ABBREVIATIONS xxiii

CHAPTER ONE 1

1.0 INTRODUCTION 1

1.1 Overview 1

1.2 Objectives 2

1.2.1 Overall objective 2

1.2.2 Specific objectives 2

1.3 Dissertation Organization 3

CHAPTER TWO 7

PAPER ONE 7

WATER AND NITROGEN APPLICATION REGIMES EFFECTS ON AGRONOMIC RESPONSES OF MAIZE (ZEA MAYS L.) PLANT 7

Abstract 7

2.1 Introduction 8

2.2 Materials and Methods 10

2.2.1 Site Description 10

2.2.2 Experimental design 11

2.2.3 Data Collection 12

2.2.4 Data analysis 13

2.3 Results and Discussions 13

2.4 Conclusions 27

References 28

PAPER TWO 32

NITROGEN MOVEMENT IN COARSE-TEXTURED SOILS AND ITS AVAILABILITY TO MAIZE (*ZEA MAYS L.*) PLANT 32

PAPER THREE 39

TEMPORAL DISTRIBUTION OF TOTAL NITROGEN CONCENTRATION IN ROOTZONE OF MAIZE (*ZEA MAYS L.*) 39

PAPER FOUR 49

ROOT ZONE SOIL MOISTURE REDISTRIBUTION IN MAIZE (*ZEA MAYS L.*) UNDER DIFFERENT WATER APPLICATION REGIMES 49

PAPER FIVE 58

REVIEW OF NITROGEN SIMULATION MODELS BASED ON CASCADING SOIL WATER BALANCE - EFFICACY OF EU-ROTATE_N MODEL 58

Abstract 58

5.1 Introduction 59

5.2 Water and Solute Transport Approaches 60

5.2.1 Cascading soil water balance approach 61

5.3 Comparison of Cascading Soil Water Balance Models 63

5.3.1 Cropping Systems Simulation Model (CropSyst) 63

5.3.2 Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS) 64

5.3.3 Solute Leaching Intermediate Model (SLIM) 65

5.3.4 Burns Model 66

5.3.5 SACFARM 66

5.3.6 Agricultural Nitrogen Model (ANIMO) 67

5.3.7 Agricultural Production System sIMulator (APSIM) 67

5.3.8 EU-Rotate_N 69

5.4 Advantages of EU-Rotate_N Model 70

5.5 Conclusion 71

References 72

PAPER SIX 80

HOW MUCH NITROGEN WOULD MOVE DOWN? EVALUATING THE EFFECT OF WATER APPLICATION REGIMES ON N LEACHING IN THE SOIL 80

PAPER SEVEN 89

USING EU-ROTATE_N MODEL TO DETERMINE EFFECTS OF NITROGEN APPLICATION DOSAGE ON N LEACHING 89

PAPER EIGHT 96

OPTIONS FOR MANAGING WATER AND NITROGEN IN IRRIGATED MAIZE PRODUCTION IN MALAWI 96

Abstract 96

8.1 Introduction 97

8.2 Methods and Materials 99

8.2.1 Site description 99

8.2.2 Experiemental design 100

8.2.3 Data collection..101

8.3 Results and Discussion..102

8.4 Conclusion and Recommendations 115

8.4.1 Conclusion..115

8.4.2 Recommendations 116

References 117

CHAPTER THREE 120

3.0 CONCLUSIONS AND RECOMMENDATIONS 120

3.1 Conclusions 120

3.2 Recommendations 122

APPENDICES 124

LIST OF PAPERS

Paper I: Mthandi, J., Kahimba, F. C., Tarimo, A. K. P. R., Salim, B. A., Lowole, M. W. 2014. Water and Nitrogen application regimes on agronomic responses of Maize (*Zea Mays L.*) Plant.

Status submitted: International Journal of Plant & Soil Science.

Paper II: John Mthandi, Fedrick C. Kahimba, Andrew K. P. R. Tarimo, Baandah A. Salim, Maxon W. Lowole. 2013. Nitrogen movement in coarse-textured soils and its availability to maize (*Zea mays* L.) plant.

Status published: Agricultural Sciences, Vol.4, No.8A, 30-35 (2013)

Paper III: Mthandi J., Kahimba F.C., Tarimo A.K.P.R., Salim B.A., Lowole M.W. 2013. Temporal Distribution of Total Nitrogen Concentration in root zone of Maize (*Zea mays L.*).

Status published: Journal of Experimental Biology and Agricultural Sciences, September - 2013; Volume – 1(4). ISSN No. 2320 – 8694.

Paper IV: John Mthandi, Fedrick C. Kahimba, Andrew K. P. R. Tarimo, Baanda A. Salim, Maxon W. Lowole. 2013. Root zone soil moisture redistribution in maize (*Zea mays* L.) under different water application regimes.

Status published: Agricultural Sciences, Vol.4, No.10, 521-528 (2013)

Paper V: Mthandi, J., Salim, B. A., Kahimba, F. C., Tarimo, A. K. P. R., Lowole, M. W. 2015**.** Review of Nitrogen Simulation Models based on Cascading Soil Water Balance - Efficacy of EU-Rotate_N Model.

Status submitted: Journal of Computer Science and Information Technology.

Paper VI: Mthandi, J., Salim, B. A., Kahimba, F. C., Tarimo, A. K. P. R., and Lowole, M. W. 2015. How much nitrogen would move down? Evaluating the effect of water application regimes on n leaching in the soil.

Status published: Research Journal of Agriculture and Environmental Management. Vol. 4(4), pp. 208-215, April, 2015. Available online at http://www.apexjournal.org ISSN 2315 - 8719© 2015 Apex Journal International

Paper VII: Mthandi, J., Salim, B. A., Kahimba, F. C., Tarimo, A. K. P. R., Lowole, M. W. 2015. Using EU-Rotate_N Model to Determine Effects of Nitrogen Application Dosage on N Leaching.

Status published: International Journal of Research in Agricultural Sciences. Volume 2, Issue 3, ISSN (Online): 2348 – 3997)

Paper VIII: Mthandi, J., Salim, B. A., Kahimba, F. C., Tarimo, A. K. P. R., Lowole, M. W. 2015. Options for managing Water and Nitrogen in irrigated Maize Production in Malawi.

Status submitted: Journal of Agriculture and Environmental Sciences.

LIST OF TABLES

Table 2.1: Characteristics of the top soil (0-20cm) at the research site 10

Table 2.2: Analysis of Variance summary 16

Table 2.3: Tukey multiple comparison of mean 18

Table 2.4: Maize agronomic responses to applied water and nitrogen 19

Table 8.1: Soil properties of the research site 100

LIST OF FIGURES

Figure 2.1: Schematic layout of the experiment setup 11

Figure 2.2: The box and whisker plot on maize yield 14

Figure 2.3: the box and whisker plot on water application regimes 15

Figure 2.4: The impact of water application levels on maize yields 20

Figure 2.5: The impact of nitrogen application levels on maize yields 21

Figure 2.6: Interactive effect of water and nitrogen application levels on maize yield 23

Figure 2.7: Relationship of WUE and NUE 25

Figure 8.1: Temporal distribution of nitrogen below 90 cm with 100%FWRR and 125%TNPRA 102

Figure 8.2: Temporal distribution of nitrogen below 90cm with 100%FWRR and 100%TNPRA 104

Figure 8 3: Temporal distribution of nitrogen below 90cm with 100%FWRR and 75%TNPRA 105

Figure 8.4: Temporal distribution of nitrogen below 90cm with 60%FWRR and 115%TNPRA 107

Figure 8.5: Temporal distribution of nitrogen below 90cm with 60%FWRR and 100%TNPRA 108

Figure 8.6: Temporal distribution of nitrogen below 90cm with 60%FWRR and 75%TNPRA 110

Figure 8.7: Temporal distribution of nitrogen below 90cm with 40%FWRR and 115%TNPRA 112

Figure 8.8: Temporal distribution of nitrogen below 90cm with 40%FWRR and 100%TNPRA 113

Figure 8.9: Temporal distribution of nitrogen below 90cm with 40%FWRR and 75%TNPRA 114

LIST OF APPENDICES

Appendix A 1: Primary Data of Phosphorus and Nitrogen taken on 27th May, 2012.......124

Appendix A 2: Primary Data of Organic Carbon taken on 27th May, 2012.....................126

Appendix A 3: Primary Data of Soil Texture taken on 27th May, 2012 128

Appendix A 4: Primary Data of Soil Moisture Content taken on 27th May, 2012...........130

Appendix A 5: Primary Data of Particle Density taken on 27th May, 2012.....................133

Appendix B 1: Raw Data of Total Nitrogen collected during first Growing Season of 2012..135

Appendix B 2: Raw Data of Total Nitrogen collected during first Growing Season........140

Appendix B 3: Raw Data of Total Nitrogen collected during first Growing Season of 2012 145

Appendix C. 1: Raw Data of Maize Yield Responses collected during first Growing Season 149

Appendix D 1: Main treatment effects 150

Appendix D 2: Water application regime effect on average maize yield 150

Appendix D 3: Interaction of water and nitrogen effect on maize yields 151

Appendix D 4: Water application regime effects...151

Appendix D 5: Nitrogen level effects 151

Appendix D 6: Interaction of Water application regimes and Nitrogen level effects.......152

Appendix D 7: Model diagnostic plots 152

Appendix D 8: Nitrogen levels (kg/ha) effect on average maize yield............................153

Appendix D 9: Irrigation water (mm) effect on average maize yield 153

Appendix D 10: Bar graphs with error bars showing impact o water application regime on maize yield (kg/ha) 154

Appendix D 11: Bar graphs with error bars showing impact of N application level on maize yield (kg/ha) 154

LIST SYMBOLS AND ABBREVIATIONS

AGRA	Alliance for Green Revolution in Africa
APSIM	Agricultural Production sIMulator
C	Concentration
C/N Ratio	Carbon/Nitrogen Ratio
Ca	Calcium
CEC	Cation Exchange Complex
CRBD	Completely Randomised Block Design
FAO	Food and Agriculture Organisation
FB	Farmer Based Practice
FWRR	Full Water Requirement Regime
Ha	Hectare
K	Potassium
k(h)	Unsaturated hydraulic conductivity
Kg	Kilogram
k_s	Saturated hydraulic conductivity
N	Nitrogen
N_u	Plant Nitrogen Uptake
OM	Organic Matter
P	Phosphorus
PPM	Parts Per Million
q	Volumetric flux density
SAR	Base Saturation Ratio
S_{max}	Potential water uptake rate

TCP	Troppenwasser Consulting Professionals
TNPRA	Typical Nitrogen Application Rate
VIC	Volumetric Ion Concentration
W	Water
WUE	Water Use Efficiency
θ	Soil moisture content
θ_r	Residual volumetric soil water content
θ_s	Saturated volumetric soil water content
τ	Shear strength of soil

CHAPTER ONE

1.0 INTRODUCTION

1.1 Overview

Nitrogen (N) is the most important determinant of plant growth and crop yield. Plants lacking N show stunted growth and yellowish leaves. Plant growth and crop yield usually increase when N is added (Hodge, 2008). However, too much N can also cause problems which may extend to plants, humans, animals, and the environment. For example, in plants, too much N will lead to weak stems in grain crops (lodging), reduce quality in fruits such as peaches and apples, lower sugar content in sugar beets, and may lead to accumulation of nitrate in the edible foliage of plants such as spinach and forage crops (Buresh *et al.,* 1997). Nitrate readily moves with water moving through soils and can contaminate groundwater to a point at which it may become a health hazard (10 ppm). Ingestion of such high-nitrate foods and water can cause health risks for animals and humans such as under-five children disease of methemoglobinemia (called the “blue baby" syndrome), which interferes with the blood's ability to carry oxygen. The problems posed to the environment occur when excess N in soils is carried away with surface runoff and water moving through soils and then finds its way to water and contributes to eutrophication and to air pollution. The problems associated with low and excess N prompted scientists to generate knowledge of optimum amounts of N that can give desirable crop yields while avoiding excess N-induced problems. Owing to the complexity of soil and crop systems, it was difficult to use generated knowledge to infer behavioral characteristics of N in soil and plants, to account for the observed N responses, and to ascertain that specified output is the result of a specified input (Haefner, 1996). In order to reduce these problems, soil and crop simulation models were developed to represent the reactions that occur within the plant and the interactions between the plant and its soil (Passioura, 1973, 1996). Since then, several simulation models have been developed, utilized, adopted, modified, and development of new ones is still taking place. Some of the crop and soil simulation models are: ISIAMod, CERES-Maize, Hybrid-Maize, EPIC, HYDRUS-D, ALMANAC, SWAP, SWBM, CropSyst, PARCHED-THIRST, APSIM, IRSIS, CROPWAT, SCHED, ISAREG, LEACHMN, DRAINMOD, WNMM, CROPGRO, PARCHED THIRST, QUEFTS, AQUACROP, and DSSAT (Igbadun, 2006).

Models are built for specific purposes and the level of complexity is accordingly adopted. Inevitably, different models are built for different subsystems and several models may be built to simulate a particular crop or a particular aspect of the production system (Brockington, 1979). Grouping of models has been attempted by various authors (e.g. France and Thornley, 1984; Brown and Rothery, 1994), but strong demarcations cannot be made since a model generally possesses characteristics of more than one group. Some models are good, user-friendly and can be applied to different range of crops while others cannot.

1.2 Objectives

1.2.1 Overall objective

The overall objective of the study was to develop management options for optimizing water and nitrogen utilization for enhanced maize crop productivity.

1.2.2 Specific objectives

The specific objectives include:

i. To evaluate the agronomic response of maize to different water and N application regimes.
ii. To determine the lateral and vertical movement of nitrogen under different irrigation regimes.
iii. To model the distribution pattern of nitrogen in the maize root zone.

1.3 Dissertation Organization

This Dissertation has been written according to the manuscript style outlined by Sokoine University of Agriculture guidelines. The main topics of the dissertation consist of manuscripts, each having an abstract, introduction, materials and methods, results and discussions, and conclusions. The main manuscripts topics have been preceded by the general introduction and literature review, and succeeded by the conclusions, and recommendations for future research work in the area. The dissertation has ten chapters.

Chapter One: The first chapter is general introduction of the thesis covering the general research overview, scope, main objectives of the research, and the organization of the dissertation.

Chapter Two: In Chapter Two is where all papers have been discussed.

Paper One: Paper one is tilted 'Water and Nitrogen application regimes effects on agronomic response of maize (*Zea Mays L.*) plant'. The paper is showing that amount of water and nitrogen applied was directly correlated with maize agronomic responses i.e. number of ears per plant, number of kernel per ear, and weight, that water-use efficiency (WUE) and nitrogen use efficiency (NUE) above 60% of FWRR are adversely related in maize production, that NUE is high when amount of water applied is low because leaching of nitrogen is reduced, that amount of moisture available in the soil affects water-use efficiency, and that Maize use less energy in extracting water from a soil at field capacity than it is close to wilting percentage.

Paper Two: Paper two is tilted 'Nitrogen movement in coarse-textured soils and its availability to maize (*Zea Mays L.*) plant'. The aim of the paper was to delineate changes of N concentration, its direction of movement and its pattern of disposition in the soil as influenced by amount of applied water and nitrogen so as to reduce N losses and maximise its absorption by maize roots. The paper infers that changes of N concentration, its direction of movement and its pattern of disposition in the soil are influenced by water flux and absorption rate of plants roots due to gradient created by absorption, noted that when N is in low supply, its movement towards maize roots is greatly influenced by diffusion, and concluded that to maximise N absorption by maize roots, the point of N application should be at 5 cm away from the planting station to minimise N losses through drifting away from the maize rooting zone.

Paper Three: Paper three is known as 'temporal distribution of total nitrogen concentration in root zone of maize (*Zea Mays L.*). The study inferred that movement, direction and distribution patterns of nitrogen concentration is influenced by evaporation of water from the soil surfaces, pulling effects by plant roots, deep percolation through gravitational force, and ability of plant roots to create environment that is conducive to diffusion of nitrogen. To minimize losses of nitrogen through leaching and ensure that nitrogen is deposited within active root zone, plant should not receive water after physiological maturity.

Paper Four: Paper four is 'Root zone soil moisture redistribution in Maize (*Zea Mays L.*) under different water application regimes'. The study aimed at evaluating the spatial redistribution of soil moisture within maize roots zone under different irrigation water application regimes. The study inferred that the degree of soil moisture loss depends on the amount of water present in the soil. The rate of soil moisture loss in 100% of full water requirement regime (100% FWRR) treatment was high than in 40% FWRR treatment. This was particularly noticed when maize leaves were dry. In 100% FWRR treatment, the attraction between water and the surfaces of soil particles was not tight and as such 'free' water was lost through evaporation and deep percolation while in 40% FWRR, water was strongly attracted to and held on the soil particles surfaces and as such its potential of losing water was reduced.

Paper Five: Paper five is 'Review of nitrogen simulation models based on cascading soil water balance - efficacy of EU-Rotate_N model' The aim of this paper was to evaluate N leaching simulation models that use cascading soil water balance approach to simulate movement of nitrogen in the soil and identify the best model to be used for simulation of water and nitrogen data collected from Nkango Irrigation scheme in Kasungu, Malawi. The models that were evaluated are: CropSyst STICS, SLIM, Burns Model, SACFARM, ANIMO, APSIM, and EU-Rotate_N model. The study identified EU-Rotate_N model as model to use in this study because of several advantages it has. The study concluded that Review of N leaching simulation model have indicated that models that use cascading soil water balance approach in simulating water and solute transport through soil profile are better compared with models that use Richards' equations. The management options that can be used to minimise N leaching and increase economic returns on nitrogen fertilizers were developed.

Paper Six: Paper six is 'How much nitrogen would move down? Evaluating the effect of water application regimes on n leaching in the soil'. The aim of this paper is to evaluate the impact of water application levels on the leaching of nitrogen. The research study was conducted at Nkango Irrigation Scheme in Kasungu district, Malawi. EU-Rotate_N model was run to quantify nitrogen leached below 90 cm of the soil profile. The study found out that water application regime has huge influence on N leaching. The study concluded that applied water in the soil should not exceed field capacity of the soil and in such way leaching of nitrogen will be minimised.

Paper Seven: Paper seven is Using EU-Rotate_N Model to Determine Effects of Nitrogen Application Dosage on N Leaching'. The aim of this paper was determine the impact of nitrogen application regime on leaching of nitrogen through soil profile. EU-Rotate_N model was used to run the field data. The research study was conducted at Nkango Irrigation Scheme in Kasungu district. The paper concluded that treatments that received high amount of inorganic N fertilizer lost more nitrogen through N leaching. Plant roots will only absorb nitrogen it requires leaving the excess to be leached by water below the active rooting zone. The study also concluded that EU-Rotate_N model to perfectly predict N leaching from irrigated maize production. The study also found out that applying N fertilizers at once increase its susceptibility to leaching and therefore the study recommended that to apply N fertilizer in several small applications during the cropping season.

Paper Eight: Paper eight is 'Options for managing water and nitrogen in irrigated maize production in Malawi'. This paper investigated the interactive effect of water and N on leaching and maize production. Four levels of water and N application regime were studied. EU-Rotate_N model stimulated water and N movement through soil profile and was used to identify option of managing water and N to reduce nitrogen loss through leaching while increasing maize production. The research study was conducted at Nkango Irrigation Scheme in Kasungu district, Malawi. The study informed development of management options that can be used to reduce N losses through leaching and increase maize production.

Chapter Three: This chapter has general conclusion and recommendations for future research. The 'Materials and Methods' section is incorporated into the manuscript-style chapters of this dissertation. The list of appendices at the end provides some of the data used in preparing the chapters.

CHAPTER TWO

PAPER ONE

WATER AND NITROGEN APPLICATION REGIMES EFFECTS ON AGRONOMIC RESPONSES OF MAIZE (ZEA MAYS L.) PLANT

Mthandi, J.[1*], Kahimba, F.C.[1], Tarimo, A. K.P.R.[1], Salim, B.A.[1], Lowole, M.W [2],

[1]Department of Agri. Eng. And Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Manuscript (submitted to ***International Journal of Plant & Soil Science***. peer reviewed journal).

Abstract

Nitrogen (N) and water management practices are key components in maize production. Plants cannot grow in soil without water, so too when soil is saturated with water. Plants lacking N show stunted growth and yellowish leaves. Too much N can also cause problems which may extend to plants, humans, animals, and the environment. This study was done to evaluate the impact of water and N application regimes on agronomic response of maize plant. The research study was conducted for two irrigation seasons from 1st June to 8th September, and from 10th September to 15th Decemebr, 2012 at Nkango Irrigation Scheme in Kasungu district, Malawi. Factors under study were water and nitrogen, and both were at four levels. Water regimes were farmers' practice regime; Full Water Requirement Regime (FWRR) of maize; 60% of FWRR; and 40% of FWRR. Nitrogen regime were the Typical Nitrogen Placement Rate in the Area (TNPRA) of 92 kg N/ha; 125% of TNPRA (115 kg N/ha); 75% of TNPRA (69 kg N/ha); and 50% of TNPRA

(46 kg N/ha). Agronomic responses were measured using weighing machine. The study showed that amount of water and nitrogen applied were directly correlated with maize agronomic responses i.e. number of ears per plant, number of kernel per ear, and weight. The study also indicated that Water-Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE) above 60% of FWRR are adversely related in maize production. NUE is high when amount of water applied is low because leaching of nitrogen is reduced. The study also revealed that amount of moisture available in the soil affects water-use efficiency. Maize use less energy in extracting water from a soil at field capacity than it is close to wilting percentage.

Key Words: Water-Use Efficiency, Nitrogen Use Efficiency, Full Water Requirement Regime (FWRR), The Typical Nitrogen Placement Rate In Area (TNPRA)

2.1 Introduction

Nitrogen and water management practices are key components in maize production because of the relatively large N inputs that are used, the high cost of N fertilizer, and public concerns over reactive N in the environment. Letey *et al.* (1983) reported that N management is inextriciably linked to irrigation water management. He argued that proper water management is the key to greater nitrogen use efficiency and water use efficiency in irrigated agriculture. Poor N nutrition may be due to inadequate N fertilization or temporal mismatch between N availability in soil solution and crop uptake needs. Matching N availability in soil solution and crop uptake needs is critical to improving maize production. Bauder *et al.* (2008) reported that best nitrogen and water management practices can reduce the probability of nitrate leaching into groundwater and maintain profitable yields. Plants lacking N show stunted growth and yellowish leaves. Plant growth and crop yield usually increase when N is added (Hodge, 2008). However, too much N can also cause problems which may extend to plants, humans, animals, and the environment. For example, in plants, too much N will lead to weak stems in grain crops (lodging), reduce quality in fruit such as peaches and apples, lower sugar content in sugar beets, and may lead to an accumulation of nitrate in the edible foliage of plants such as spinach and forage crops (Buresh *et al.,* 1997).

The majority of nitrogen available to plants is in the form of inorganic NH_4^+ and NO_3- forms. Ammonium ions (NH_4^+) bind to the soil's negatively-charged cation exchange complex (CEC) while nitrate ions (NO_3-) do not bind to the soil solids because they carry negative charges. Since none of the nitrate is adsorbed to soil particles it is abundant in the soil water and the movement of the nitrate to the root rarely limits its uptake. Nitrate readily moves with water moving through soils and can contaminate groundwater to a point at which it may become a health hazard (10 ppm). The problems posed to the environment occur when excess N in soils is carried away with surface runoff and water moving through soils and then finds its way to water and contributes to eutrophication and to air pollution.

With increasing concerns for water availability and the adoption of variable rate irrigation and nitrogen application systems in irrigated and rain fed agricultural crop production, development of concurrent management strategies for irrigation and nitrogen to enhance crop productivity are needed. The latter strategy is called deficit irrigation (DI), which will reduce reasonable crop yield per unit of land but increases the net return for the water applied. DI maximizes water productivity (WP), which is the main limiting factor (English, 1990).

2.2 Materials and Methods

2.2.1 Site Description

The research study was done at Nkango Irrigation Scheme in Kasungu district, Malawi. Data were taken in two irrigation growing seasons of 1st June to 8th September, 2012; and 10st September to 5th December, 2012.

Table 2.1: Characteristics of the top soil (0-20cm) at the research site

Soil properties	Values
Clay (%)	13
Silt (%)	17
Sand (%)	70
Carbon (%)	0.599
C/N ratio	13.011
OM (%)	1.0773
Total nitrogen (%)	0.046
Total phosphorus (ppm)	33.206
Total potassium (μeq K g-1)	1.2153
Exchangeable calcium (μeq Ca g-1)	19.254
Exchangeable magnesium (μeq Mg g-1)	28.964
Moisture Content (%)	4.163
Field Capacity (%)	20
Wilting Capacity (%)	10
Bulk Density (g/cm3)	1.59
pH	5.2

Nkango Irrigation Scheme is a traditional scheme which is owned and managed by the local communities and is situated at Latitude $12^0$35' South and Longitudes $33^0$31' East and is at 1186 m above mean sea level. The Study area has a unimodal type of rainfall with rains between December and April. The mean annual rainfall is about 800 mm. The site lies within maize production zone of Malawi and has dominant soil type of sandy loam.

Smallholder farmers in the area practise irrigation and are conversant with water application regimes.

The soil is a Ferric Lixisol with an average slope of 1.3%. The texture of the top soil (0–20 cm) is sandy loam with a low soil organic matter and nutrient concentration as described in (Table 2.1). The Cation Exchange Capacity is low (50.00 - 80.00 μeq g^{-1}), and the pH decreased from acidic (5.2) to strongly acidic (4.7). The salinity of the soil was low (1.7 mmhos/cm).

2.2.2 Experimental design

The plot size was 5 m by 5 m and ridges were spaced at 75 cm. The plots were separated from one another by a 2-metre boundary to avoid 'sharing' of responses, water and nitrogen (edge effects) as indicated in the Figure 2.1.

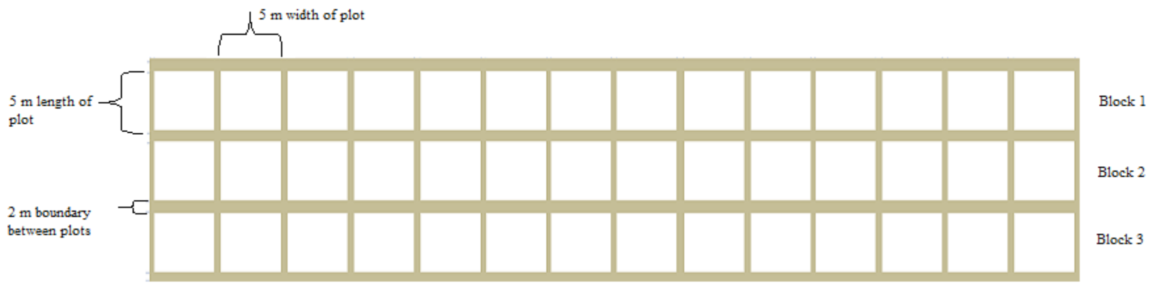


Figure 2.1: Schematic layout of the experiment setup

Three maize seeds of hybrid maize (SC 407) were planted per hole at spacing of 25 cm. They were later on thinned to one seed per station 7 days after germination. The trials had two irrigation seasons: the first season started on 1st June and ended on 8th September; and second season started on 10th September and ended on 15th December, 2012. The trials consisted of factorial arrangement in a Randomised Complete Block Design (RCBD). The factors were water and nitrogen and both were at four levels. Water had four application regimes and these were as follows: farmers' practice regime; full (100%) water requirement regime (FWRR) of maize plant; 60% of FWRR; and 40% of FWRR. A full maize water requirement was determined by using the procedure described by FAO Paper 56 (Allen *et al.,* 1998). Nitrogen had four application regimes and these were as follows: The Typical Nitrogen Application Rate in the area (TNPRA) of 92 kg N/ha was used as a basis to determine other dosage levels in the study (MoAFS, 2011). The nitrogen dosage levels were as follows: TNPRA, 92 kg N/ha; 125% of TNPRA, 115 kg N/ha; 75% of TNPRA, 69 kg N/ha; and 50% of TNPRA, 46 kg N/ha.

The fertlizer was applied two times, 14 days after emergence and 55 days after emergence. At each application time, the following methods were used to achieve the nitrogen dosage levels (MoAFS, 2011):

- To achieve 50% of TNPRA, 46 kg N/ha, 2.8g fertilizer scooped using one coke bottle top with inside lining was applied per station.
- To achieve 75% of TNPRA, 69 kg N/ha, 4.2g fertilizer scooped using one coke bottle top without inside lining was applied on each station.
- To achieve TNPRA, 92 kg N/ha: apply 5.6g fertilizer that is 2 coke bottle tops per station without inside lining.
- To achieve125% of TNPRA, 115 kg N/ha: apply 8.4g fertilizer using 3 coke bottle tops without inside lining.

2.2.3 Data Collection

The maize data was categorized into two categories namely ontogenic and agronomic data. Ontogenic data comprised of: date of planting, days to fifty percent emergence, stand count, days to begin tasseling, days to fifty percent tasseling, days to full tasseling, days to 50% silking , days to begin formation of cobs, days to fifty percent and full cobs formation and days to physiological maturity. Agronomic data comprised of: plant height at maturity, number of leaves at physiological maturity, number of ears per plant, ear length (cm), number of kernel per ear, weight in grams of 1000 kernels, and grain yield per plot which was subsequently converted into grain yield per hectare (kg/ha).

2.2.4 Data analysis

The data presented in this paper are maize yield data from all treatment combinations to see the main effects of the treatments and interaction of the treatments at various levels. The R version 3.2.2, open source statistical software was used to run ANOVA statistical analysis on yield data, separate treatment effect means and plot various graphical plots such as box and whisker and interaction effects. The standard multiple comparison procedure to address the all-pairwise comparison problem is the Tukey test.

$$\text{Average aize yield per hectare} = \mu + \beta_j + N_k + w_r + (NW)_{kr} + \varepsilon_{ikr}$$

Where:

μ is the overall mean yield (Kg/ha)

β_j is the jth block effect

N_k is the kth Nitrogen level effect

W_r is the rth irrigation water application regime

$(NW)_{kr}$ is the interaction effect of the kth Nitrogen level and the rth irrigation water application regime

2.3 Results and Discussions

Figure 2.2 shows the box and whisker plot on maize yield (Kg/ha) against Nitrogen (Kg N/ha) levels. At 50 % (46 Kg N/ha), mean yield is above 2000 Kg/ha, at 75 % Nitrogen (69 Kg/ha), mean yield is above 3000 Kg/ha, at the national recommended rate of N application in Malawi (92 Kg N/ha), mean maize yield is slightly above 4000 Kg/ha while at 115 Kg N/ha (25 % more than the national or area Nitrogen application level for maize, mean yield is slightly above 4,000 Kg/ha while N application level 25 % higher than the area recommended rate (115 Kg N/ha) gave mean yield of around 4,300 Kg/ha. The plots reveal that there is a linear relationship between N level and maize yield. That is, as N increases, average maize yield increase but seem to increase sharply between 50 % and 100 % of TNPRA. Above the range of 100% of TNPRA, the analysis revealed that a polynomial model would best fit the data.

Figure 2.2 below is a box and whisker plot on water application regime (mm) against mean maize yield (Kg/ha). The plot show that at 40 % full water requirement regime, average maize yield was approximately 2800 Kg/ha; at 60 % full water requirement regime, average maize yield was mean maize yield was approximately 3750 kg/ha, at 100% full water requirement regime, average maize yield was approximately 4800 kg/ha.

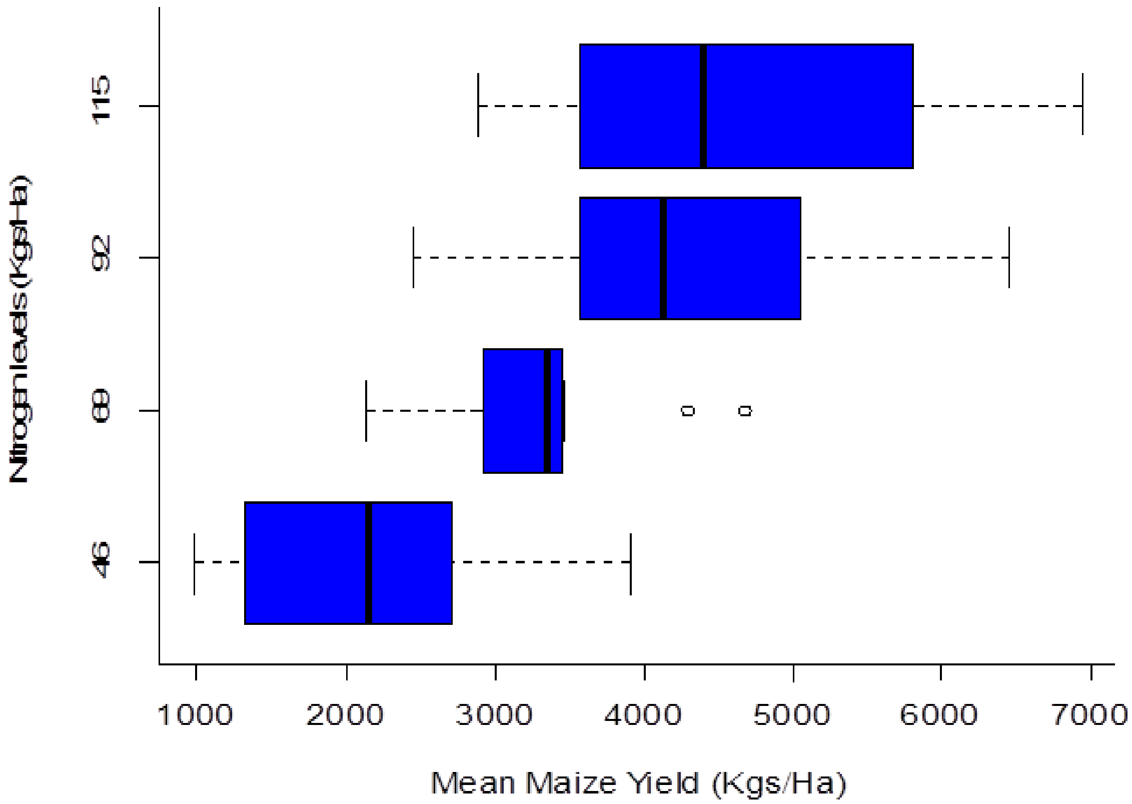


Figure 2.2: The box and whisker plot on maize yield

Figure 2.3 indicates that increase of 20% of applied water from 40%FWRR to 60%FWRR resulted into an increase of maize yield by 25%, and increase of applied water from 60%FWRR to 100%FWRR resulted into an increase of maize yield by 22%. Table 2.2 below indicates that generally amount of water and nitrogen applied were directly correlated with maize agronomic responses of number of ears per plant, number of kernel per ear, and weight (in grams) of 1,000 kernels/.

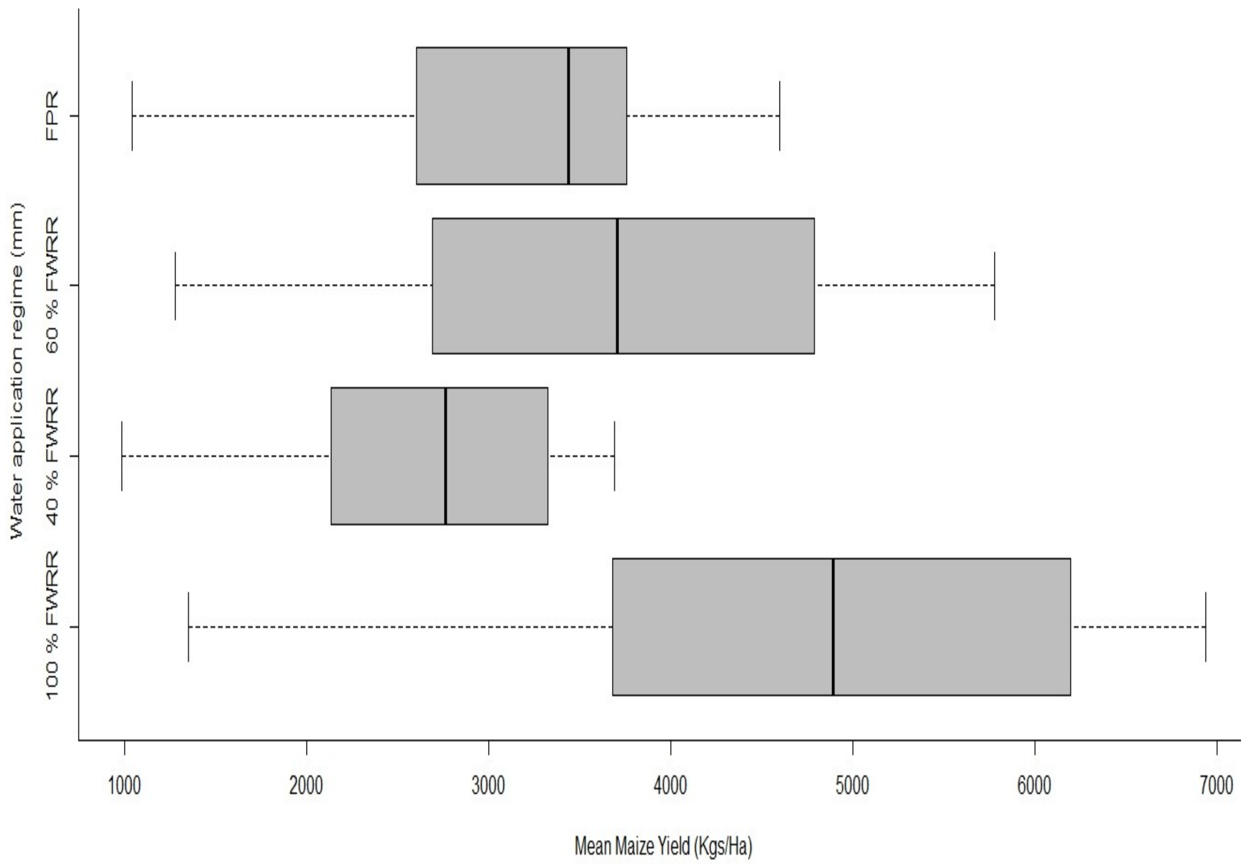


Figure 2.3: the box and whisker plot on water application regimes

Table 2.2 show analysis of variance summary. It shows that the water application regimes and Nitrogen levels have a significant effect on maize yield (*p-values* <0.001). However, ANOVA in table showed that interaction of water and nitrogen on maize yield was not significant. Further analysis was performed to find out which main treatment level effects are statistically different using Tukeys multiple comparison procedures using functions in the multcomp R package.

Though the ANOVA show insignificant interactions between water application regime and nitrogen levels, multiple comparisons using Tukey reveal that there are significant differences between interactions of the main treatments at various levels. Results of differences in mean maize yield from interaction of water application regimes and nitrogen levels are shown in Table 2.3.

Table 2.2: Analysis of Variance summary

Source of variation	**Df**	**Sum of Squares**	**Mean Sum of Squares**	**F-value**	**Pr(>F)**
Water application regimes	3	29706351	9902117	21.327	8.92e-08***
Nitrogen levels	3	46388534	15462845	33.303	5.84e-10***
Interaction of W & N	9	6651840	739093.33	1.592	0.16
Residuals	32	14857851	464307.84		
Total	47	97604576	2076693.1		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Tukey multiple comparison of means indicates that 60%FWRR and 100%FWRR is not highly significant (*p-values* <0.01), but the effect of 40%FWRR and 100%FWRR on maize yield is highly significant (*p-values* <0.001). The analysis of effect of nitrogen application dosage on maize yield has indicated that there is no significant difference of 92 and 115 kg N/ha. There is slight significance difference (*p-values* <0.01) of effect of 92 and 69 kg N/ha on maize yield. The interactive effect of nitrogen and water on maize yield has indicated that is only combination of 100% FWRR: 92 Kgs N/Ha – 60% FWRR: 92 Kgs N/Ha that has no significant difference on maize yield (*p-values* <0.1).

The plots that received full irrigation and high dosages of nitrogen had registered good agronomic responses than the plots that received fewer amounts of water and nitrogen. Nitrogen availability affects leaf area index, leaf area duration, crop photosynthetic rate, percent radiation interception, plant height, shoot weight and plant N uptake along with several other plant physiological processes. Consequently, this influences crop growth, kernel number, grain yield, crop water uptake and ultimately ETa (Eck, 1984; Pandey *et al.,* 1984; Muchow, 1988; McCullough *et al.,* 1994; Aghdaii and Sattar, 2000). Table 2.4 shows that maize development and growth is very dependent on availability of water that facilitates its growth and maturity. These findings agreed with Oktem (2008) who showed a significant (direct) effect of the levels of irrigation water on maize yield and 100% irrigation level gave the maximum yield. Chen *et al.,* (2009) reported that increasing irrigation amount resulted in higher crop yields. Nagy (1995) demonstrated that the relationships between ear yield and irrigation level treatments were statistically significant and the yield decreased with increasing deficit irrigation.

Table 2.3: Tukey multiple comparison of mean

	95 % family-wise confidence level factors have been ordered			
Water application regime main effects	**Difference**	**Lower**	**Upper**	**p-adjusted**
60 % FWRR – 40% FWRR	1066.2	312.5	1819.9	0.0029895*
100 % CWR - 40 % FWRR	2133.7	1380.0	2887.4	0.0000001***
100 % FWRR - 60 % FWRR	1076.5	313.8	1821.2	0.0029510*
Nitrogen effects				
69 Kgs N/Ha - 46 Kgs N/Ha	1170.3	416.6	1924.0	0.0010684**
92 Kgs N/Ha - 46 Kgs N/Ha	2160.3	1406.6	2914.0	0***
115 Kgs N/Ha - 46 Kgs N/Ha	2537.0	1783.3	3290.7	0***
92 Kgs N/Ha - 69 Kgs N/Ha	990.0	236.3	1743.7	0.006205*
115 Kgs N/Ha - 69 Kgs N/Ha	1366.7	613.0	2120.4	0.0001444***
115 Kgs N/Ha - 92 Kgs N/Ha	376.7	-377.0	1130.4	0.5364742 (***ns***)
Interaction effects				
100 % FWRR:69-40 % FWRR:46	2504.7	441.6	4567.7	0.0067443**
60 % FWRR:92-40 % FWRR:46	2874.7	811.6	4937.7	0.0011014**
60 % FWRR:115-40 % FWRR:46	3558.0	1495.0	5621.0	0.0000351***
100 % FWRR:92-40 % FWRR:46	4274.7	2211.6	6337.7	0.0000010***
100 % FWRR:115-40 % FWRR:46	4698.0	2635.0	6761.0	0.0000001***
60 % FWRR:92-60 % FWRR:46	2363.3	300.3	4426.4	0.0131296*
60 % FWRR:115-60 % FWRR:46	3046.7	983.6	5109.7	0.0004649***
100 % FWRR:92-60 % FWRR:46	3763.3	1700.3	5826.4	0.0000125***
100 % FWRR:115-60 % FWRR:46	4186.7	2123.6	6249.7	0.0000015***
60 % FWRR:115-100 % FWRR:46	2353.3	290.3	4416.4	0.0137529*
100 % FWRR:92-100 % FWRR:46	3070.0	1007.0	5133.0	0.0004133***
100 % FWRR:115-100 % FWRR:46	3493.3	1430.3	5556.4	0.0000486***
60 % FWRR:92 Kgs N/Ha - 40 % FWRR: 92 Kgs N/Ha	2340.0	277.0	4403.0	0.0146279*
100 % FWRR:92 Kgs N/Ha - 40 % FWRR:92 Kgs N/Ha	3056.7	993.6	5119.7	0.0004421***
100 % FWRR:115 Kgs N/Ha - 40 % FWRR:92 Kgs N/Ha	3480.0	1417.0	5543.0	0.0000520***
60 % FWRR:92 Kgs N/Ha - 40 % FWRR:69 Kgs N/Ha	2270.0	207.0	4333.0	0.0201536*
100 % FWRR:92 Kgs N/Ha - 40 % FWRR:69 Kgs N/Ha	2986.7	923.6	5049.7	0.0006287**
100 % FWRR:115 Kgs N/Ha - 40 % FWRR:69 Kgs N/Ha	3410.0	1347.0	5473.0	0.0000741***
60% FWRR:115 Kgs N/Ha – 60% FWRR:69 Kgs N/Ha	2090.0	27.0	4153.0	0.0445849*
100% FWRR:92 Kgs N/Ha – 60% FWRR:92 Kgs N/Ha	2806.7	743.6	4869.7	0.3115449(***ns***)
100% FWRR:115 Kgs N/Ha – 60% FWRR: 69 Kgs N/Ha	3230.0	1167.0	5293.0	0.0001842***
100 % FWRR: 92 Kgs N/Ha - 40 % FWRR: 115 Kgs N/Ha	2633.3	570.3	4696.4	0.0036246**
100 % FWRR:115 Kgs N/Ha - 40 % FWRR:115 Kgs N/Ha	3056.7	993.6	5119.7	0.0004421***
100 % FWRR:115 Kgs N/Ha – 100% FWRR:69 Kgs N/Ha	3246.7	1183.6	5309.7	0.0284254*

Table 2.4: Maize agronomic responses to applied water and nitrogen

Water Regime		W (m3/ha)	N (kg/ha)	Y (kg/ha)	WUE	NUE	Ears /plant	Kernel/ear	1,000 kernel weight (g)
	T1	6000	92	4300	0.72	47	1.03	418	185
	T2	4200	115	4600	1.10	40	1.03	426	189
	T3	9600	69	3400	0.35	49	1.02	340	175
FB	T4	7300	46	2650	0.36	58	1.02	332	139
	T1	3300	92	3470	1.05	38	1.03	343	176
	T2	3400	115	3690	1.09	32	1.02	349	179
	T3	3700	69	3240	0.88	47	1.03	338	167
40%	T4	4600	46	2140	0.47	47	1.02	327	117
	T1	5300	92	4980	0.94	54	1.05	436	199
	T2	5100	115	5600	1.10	49	1.04	473	206
	T3	4900	69	3460	0.71	50	1.03	341	175
60%	T4	5200	46	2380	0.46	52	1.02	329	126
	T1	8500	92	6450	0.76	70	1.06	496	227
	T2	8900	115	6940	0.78	60	1.07	501	241
	T3	8400	69	4670	0.56	68	1.04	489	195
100%	T4	8600	46	3910	0.45	85	1.03	356	182

Nagy (1995) showed that ears per plant and kernel weight were reduced under limited irrigation. Under full irrigation the WUE was lower than under deficit irrigation. The weight (g) of 1,000 kernels was low in these plots indicating that amount of water applied to maize plants influences the kernel development process and plants subjected to low water result into low quality. The highest yield was noted in treatment of 100% of CWR and 125% of N.

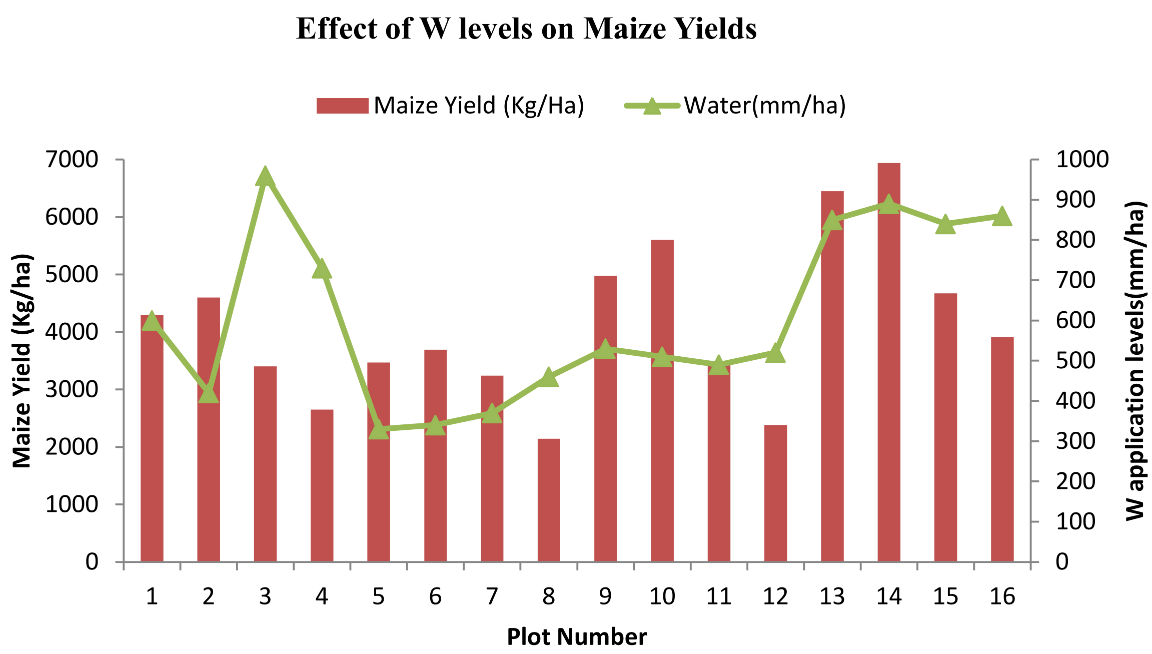


Figure 2.4: The impact of water application levels on maize yields

Water in itself cannot give adequate information regarding yield. There is no relationship that can be explained between yield and water. For example, bar Graph 2, less amount of water was applied but obtained higher yield than bar Graph 3 where more water was applied. The same applies to plots 10 and 11 where relatively same amount of water was applied yet the yield difference was very high.

Figure 2.5, shows that amount of applied nitrogen result in high maize yield. Generally, the plots that had high nitrogen application registered high yields, The bars 2, 6, 10 and 14 had high yields and application dosage in these plots was 115 N kg/ha. However, with the same nitrogen application dosage, there is difference in maize yields.

Just as in Figure 2.4, the differences in maize yields under the same water application levels cannot adequately be explained; in Figure 2.5 the differences of maize yields under the same nitrogen application dosage cannot adequately be explained. This is because all the plots received the same agronomic management practices i.e. maize seeds were planted on the same day, plots were weeded on the same day, fertilizer applications were done on the same day.

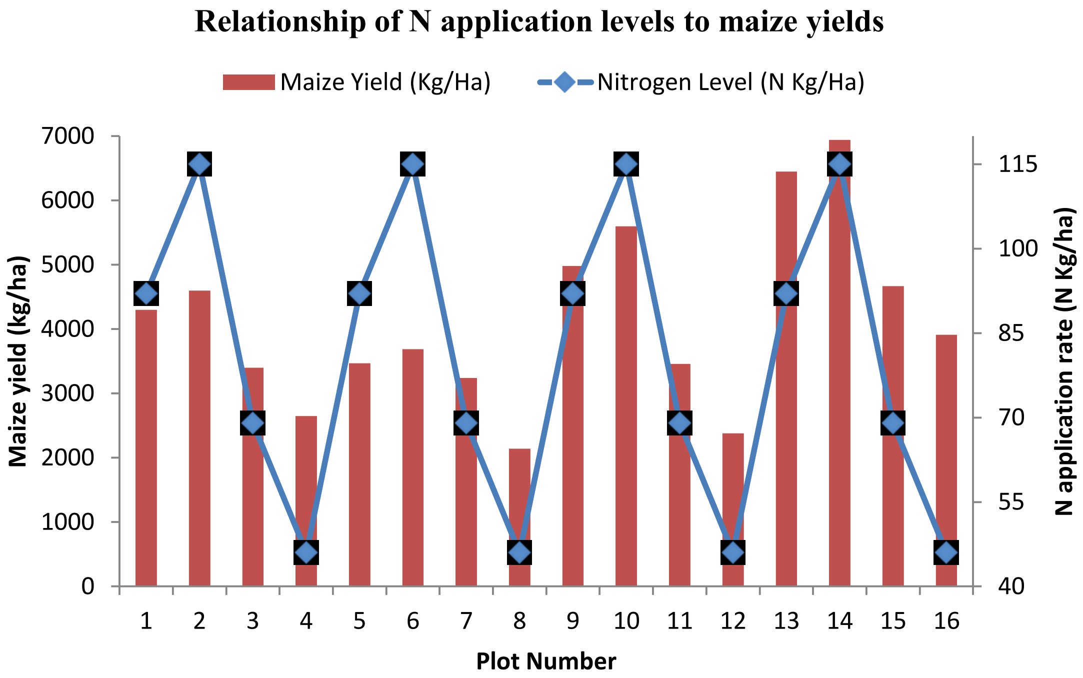


Figure 2.5: The impact of nitrogen application levels on maize yields

In Figure 2.6, the differences in maize yields under the same nitrogen application dosages can be adequately explained as is due to differences in water application levels just as the case with differences in maize yields under the same water application levels can be explained as due to differences in nitrogen application levels. The Figure 2.6 indicates that increase of water and nitrogen application levels at the same time resulted in high maize yields as in plot 14. Nagy (1996, 1999); Benbi (1989) reported that irrigation improves the efficiency of fertilizer usage and there is a strong correlation between fertilizer utilization and the water supply of a plant. They have proved that irrigation increases the efficiency of fertilizer usage. Interestingly at the same nitrogen level, the numbers were high in plots that received higher amounts of water than plots that received lower water levels. This indicates the close relationship of water and nitrogen on agronomic responses. Pandey *et al.* (2000) reported that nitrogen availability is interrelated to water availability given that water is the transporting fluid by which plants uptake nitrogen. Pandey *et al.* (2000) found that N application increased maize water uptake by 62 and 71 mm in a sandy loam and loam soil, respectively. Carlson *et al.* (1959) observed that water use, measured as total ETa, was greater at high N rates and under full irrigation as compared with low N rates and limited irrigation. It is widely accepted that N fertilizer increases water-use efficiency on N-deficient soils when water status is adequate (Viets, 1962; Al-Kaisi and Yin, 2003; Gonzalez-Dugo *et al.,* 2009).

Therefore, nitrogen uptake is directly influenced by plant water uptake (e.g., transpiration). Hati *et al.* (2001) observed that when transpiration rates are reduced under water-stressed conditions, N absorption by crops is automatically reduced even when mineral N is present in the soil occupied by roots. In addition, plant water availability is affected by several external factors including climatic conditions (e.g., precipitation amounts and timings); crop type; land, crop and irrigation management practices; planting density; phenological development stage; and physical and chemical properties of the soil, which further increases the complexity of the water and nitrogen interactions and its effect on crop response.

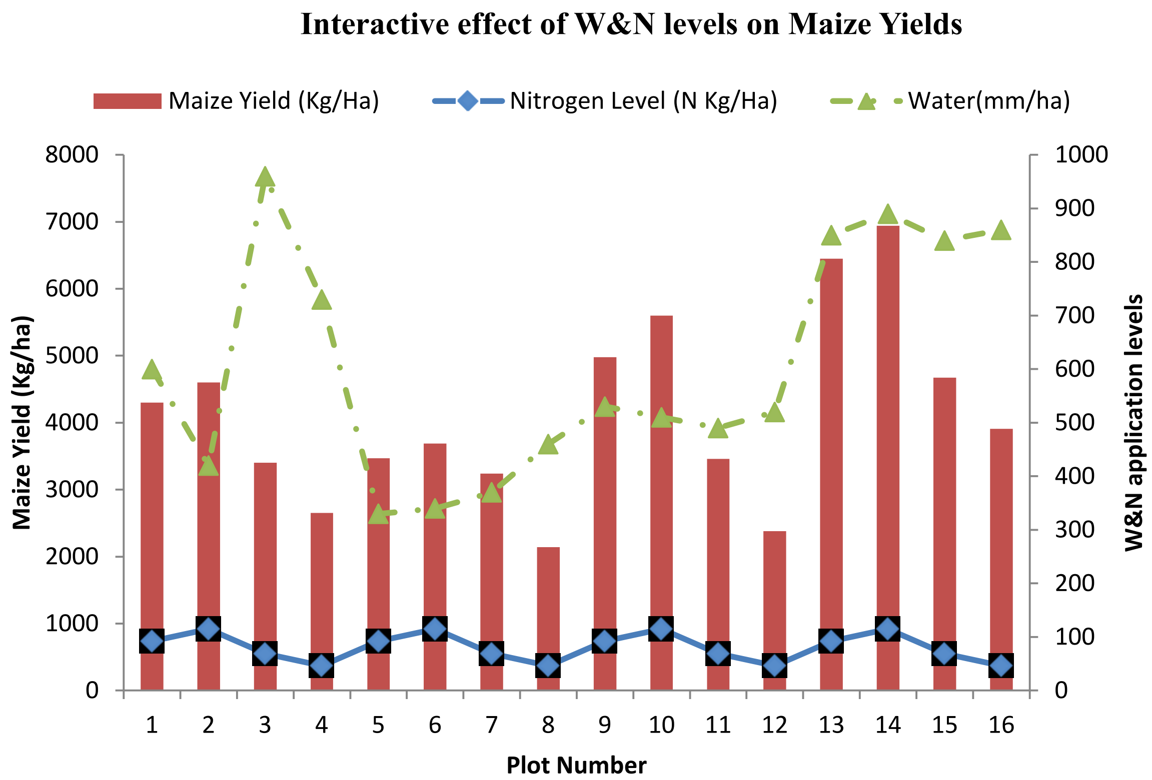


Figure 2.6: Interactive effect of water and nitrogen application levels on maize yield

In Figure 2.6, the maize yields compared at different levels of N application, were higher under the plots that had high water application regimes than the plots that were under deficit irrigation regimes. The primary reason of this is due to the dynamic relationship between N and water availability on crop response. Crops are usually subjected to water deficiency, which will affect crop N uptake and availability. In other words, a lower fraction of applied N will actually be taken up by water stressed crops, which often translates into differences in yield response.

The rate of soil moisture depletion change was greatest at the top soil layer (0 – 0.30 m) due to irrigation events coupled with high surface soil evaporative losses and plant water uptake due to greater effective root density in the top layer. The plots that had low N application levels, on average, had more available water in individual soil layers and profile at the end of the growing season than the fertilized treatments. In general, final available soil water trends were proportional to N application amount with less available soil water at the end of the growing season at higher N treatments for all irrigation regimes. Carlson *et al.* (1959) reported a linear response between water extraction and nitrogen amount. Lenka *et al.* (2009) found unfertilized plots retained more water in the soil profile at harvest along with water extraction occurring in deeper soil layers for the fertilized plots. Rudnick (2013) also found greater water extraction amounts deeper in the soil profile with higher N application amounts.

In addition, higher N treatments typically experienced a greater increase in grain yield with increasing irrigation water than the lower N treatments. The greater variability in the grain yield versus irrigation amount relationship at lower N treatments was attributed to nitrogen deficiency, water deficiency and their combined effect on the plant response to inter-annual differences in climate: precipitation, relative humidity, solar radiation, temperature, etc. as well as differences in residual nutrients (e.g., nitrogen). The higher N treatments in general did not impose nitrogen deficiency on the crop, therefore the grain yield vs. irrigation amount relationships were stronger. Plant nitrogen availability is interrelated to water availability; given the fact that water is the transporting fluid by which plants uptake nitrogen. Mansouri *et al.* (2010) reported minimal information is currently available on concurrent management strategies. Furthermore developed concurrent management strategies are subjected to a multitude of factors, which prohibits their applicability outside of similar conditions found at the study location in which they were developed. At 40%, nitrogen use efficiency was high in at 69 kg N/ha indicating that when less water is applied so too less nitrogen should be applied to maximise yield production. Carlson *et al.* (1959) concluded that under deficit irrigation, N must be correspondingly adjusted to optimize economic crop production. Moser *et al.* (2006) evaluated the effects of water stress imposed at less-sensitive crop growth stages and level of nitrogen supply on two maize hybrids. Zhang (2003) reported that maize grown under water-limiting conditions (e.g., deficit irrigation) requires less N fertilizer to achieve maximum grain yield than that required with well-watered conditions.

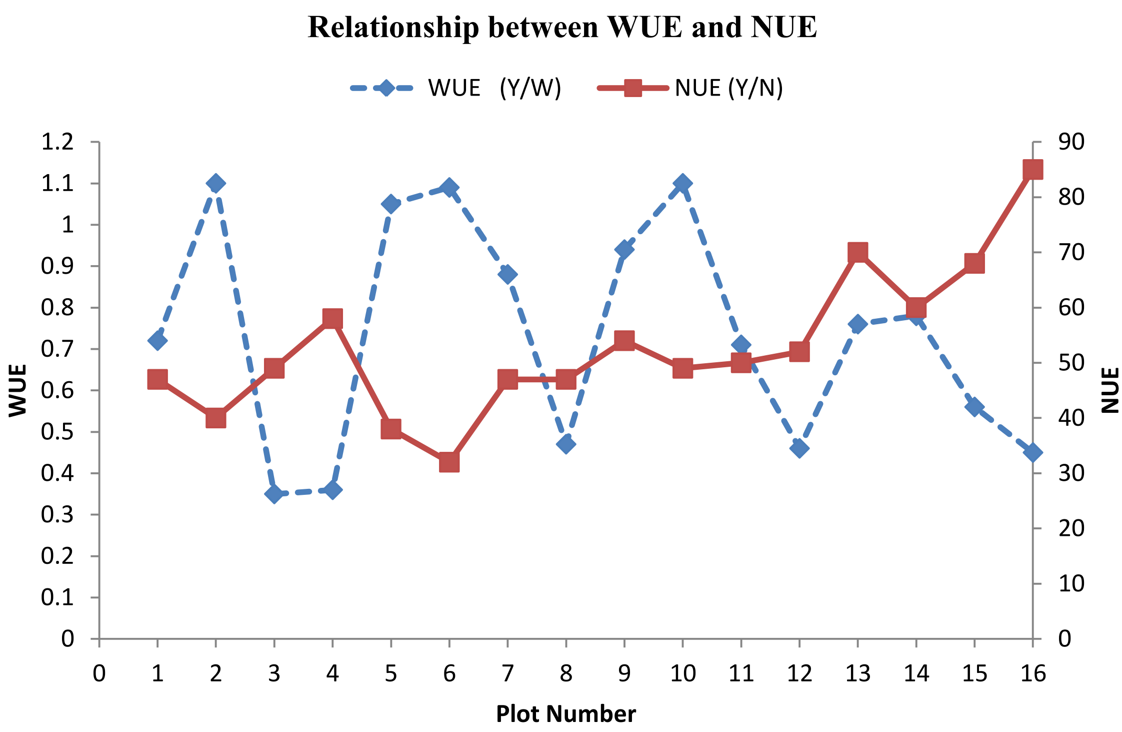


Figure 2.7: Relationship of WUE and NUE

In general, NUE decreased at higher grain yield, which corresponded to higher N application treatments. This implies that in areas of water scarcity or when irrigation water is priced, farmers are advised to follow deficit irrigation because they will still harvest reasonable maize yield. Compared with other crops, maize has a relatively high WUE of about 1.2-1.5 kg m^{-3} (Emam and and Ranjbar, 2000). Zwart and Bastiaanssen (2004) studied the effects water stress on grain yield (GY) and water use efficiency of the maize and they showed that water use efficiency increased in water stress plots. Li *et al.* (2005) reported that the range of crop Water Productivity (WP) of maize, based on a review of 84 literature sources, is very large (1.1–2.7 kg m^{-3}) and it thus offers new water management practices for increasing crop production with 20–40% less water resources. They concluded that in order to achieve optimum crop WP in water short regions, it would be wise to irrigate maize with less water. Kadyampakeni (2004) demonstrated that irrigation water use efficiency was negatively correlated with irrigated water volume.

However, though these plots gave highest yield due to highest combination of water and nitrogen, they gave low water and nitrogen use efficiencies. The highest levels of water use efficiencies were registered in plots that received 40% of its requirement while highest nitrogen use efficiency was registered in plot that received 50% of the TNPAR and full water requirement. The ideal situation is when water use efficiency is above 1.1 kg/m^3 while nitrogen use efficiency is also high. It is likely for farmers to increase WUE by applying more water to maize plants during its reproductive stage than during its vegetative growth phase. Water use efficiency increases when deficit irrigation is imposed during vegetative phase of maize plants and it decreases when deficit irrigation is imposed during reproductive phase (Mloza-Banda, 1994). The amount of water used by a crop is exposed is expressed (ha-mm). The amount of water used is directly related to yield in all crops. As yield increases, total water-use increases because more water is needed for increased maize growth. Within the limits of available moisture, nutrients and other variables, as stand densities increase, yields increase and total ware-use also increases. Water use efficiency may also increase because soil is permeated with roots so that the maximum amount moisture available in the soil is extracted from it and transpired by the crop. The amount of moisture available in the soil affects water-use efficiency. Maize use less energy in extracting water from a soil at field capacity than it is close to wilting percentage. This saving is converted into greater maize yields (Mloza-Banda, 1994).

2.4 Conclusions

In water-limited agricultural environments, it is important to obtain a maximum yield for minimal water and nutrient input. In terms of yield returns per water used (water use efficiency), the plots in 100% category registered low productivity. The plots in this category registered highest N productivity rate. This implies that when less N is applied to the plants i.e. if N is limiting factor, maize plants should receive its full water requirement so that it registers optimum yield. To increase WUE, maize should receive more water during its reproductive stage which is mid-growth stage than during its vegetative growth stage, and again decrease amount of water in its late-stage. To increase NUE, It is very important to know when to apply nitrogen to maize plants, in coarse-textured soils, high amount of N should be applied few days after its reproductive stage starts to minimise chances of being leached because it moves quickly with water flow. The study has indicated that statistically interactive effect of 60% of FWRR and 92 N Kg/ha gave optimum yields compared to other combination of treatments. In this case, smallholder farmers can be advised to use this combination of treatments in irrigated maize production.

References

Aghdaii, M., and Sattar, M. 2000. Determination of water and fertilizer requirements of different Maize varieties. Soil and Water Research Division, *Isfahan Agricultural Research Centre*, Research report No.70/232, Isfahan, Iran.

Al-Kaisi, M. M., and X. Yin. 2003. Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency. *Agron. J.* 95: 1475 – 1482.

Allen, G. R., Pereira, S. L., Raes, D. and Smith, M. 1998. FAO Irrigation and Drainage Paper No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements). FAO - Food and Agriculture Organization of the United Nations, Rome, M-56 ISBN 92-5-104219-5.

Bauder, T. A. Waskom, R. M. and Andales, A. 2008. Nitrogen and Irrigation Management no. 0.514 Colorado State University Extension. 3/99.Revised 6/08. www.ext.colostate.edu.

Benbi, D. K. 1989. Effect of farm yard manure on water use in maize-wheat sequence under rainfed conditions. *Ann. Biol.* 5(2): 147 – 152.

Buresh, R. J., Sanchez, P. A., and Calhoun, F. 1997. Replenishing soil fertility in Africa. Soil Society of America, Special Publication No. 51. Madison, USA.

Carlson, C. W., Alessi, J., and Mickelson, R. H. 1959. Evapotranspiration and yield of corn as influenced by moisture level, nitrogen fertilization, and plant density. Soil Sci. Soc. Am. Proc. 23(3): 242 – 245.

Chen, C., Wang, E., and Yu, Q. 2009. Modeling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. *Agricultural Water Management*, 10.

Eck, H. V. 1984. Irrigated corn yield response to nitrogen and water. Agron. J. 76, 421-428.

Emam, Y., and Ranjbar, G. H. 2000. The effect of plant density and water stress during vegetative phase on grain yield, yield components and water use efficiency of Maize. *Iranian Journal of Crop Science*, *2*(3), 50-62.

English, M. 1990. Deficit irrigation. Analytical framework. *Journal of Irrigation and Drainage Engineering*, *116*(3), 399-412.

Gonzalez-Dugo, V., Durand, J. L., Gastal, F. 2009. Water deficit and nitrogen nutrition of crops. A review. *Agron. Sustain. Dev.* 30(3): 529 – 544. doi: 10.1051/agro/2009059.

Hati, K. M., Mandal, K. G., Mishra, A. K., Ghosh, P. K., and Acharaya, C. L. 2001. Effect of irrigation regimes and nutrient management on soil water dynamics, Evapotranspiration and yield of wheat in vertisols. *Indian J. Agric. Sci.* 71(9): 581 – 586.

Hodge, A. 2008. The plastic plant: root responses to heterogeneous supplies of nutrients. New Phytologist 2004; 162:9–24.

Kadyampakeni, D. S. M. 2004. Comparative analysis of Agronomic, socio-economic, technical and financial aspects of dry season cultivation of beans (phaseolusvulgaris) under different irrigation technologies and water management techniques for Chingale Area Development Programme (ADP)- Zomba. - M.Sc Thesis, Bunda College of Agriculture, Lilongwe, Malawi.

Lenka, S., Singh, A. K., Lenka, N. K. 2009. Water and nitrogen interaction on soil profile water extraction and ET in maize-wheat cropping system. *Agric. Water Manage.* 96(2): 185 – 207.

Letey, J., Jarell, W. M., Valora, N., and Beverly, R. 1983. Fertilizer application and irrigation management of broccoli production and fertilizer use efficiency. Agronomy Journal. American Society of Agronomy Publication. Volume 75:

p.502 – 507. Passioura, J.B. (1996). Simulation models: science, snake oil, education or engineering? *Agronomy Journal* 88: 690-694.

Li, J., Inanaga, S., Li, Z., Eneji, A. E. 2005. Optimizing irrigation scheduling for winter wheat in the North China Plain. *Agricultural Water Management*, *76*, 8-23.

Mansouri, C., Modarres Sanavy, A. M. S., and Saberali, S. F. 2010. Maize yield response to deficit irrigation during low-sensitive growth stages and nitrogen rate under semiarid climatic conditions. Agric. Water Manage. 97: 12 – 22.

McCullough, D. E., Giradin, P., Mihajlovic, M., Guilera, A. A., Tollenaar, M. 1994. Influence of N supply on development and dry matter accumulation of an old and new maize hybrid. *Can. J. Plant Sci.* 74(3): 471 – 477.

Ministry of Agriculture and Food Security. (2011). Annual reports and notes. Lilongwe, Malawi.

Mloza-Banda, H. R. 1994. Principles and practices of crop management. A field study guide. Bunda College of Agriculture, Lilongwe, Malawi.

Moser, B. Feil, S. Jampatong, Stamp, P. 2006. Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. Agric. Water Manage. 81: 41 – 58.

Muchow, R. C. 1988. Effect of nitrogen supply on the comparative productivity of maize and sorghum in semiarid tropical environment I. Leaf growth and leaf nitrogen. *Field Crops Res.* 18(1): 1 – 16.

Nagy, J. 1995. Evaluating the effect of fertilization on the yield of maize (*Zea mays* L.) in differ Németh, T.-Buzás, I. 1991: L homok- és mészlepedékes csernozjom talajon.

Nagy, J. 1996. Ev fertilization on the yield of maize (*Zea mays* L.). Ag és Talajtan, 45. 1-2. 113-124. Nagy, J. (*Zea mays* L.) Agrokémia és Ta Nagy, J. (1999): Ev soil cultivation in m 181-190.

Nagy, J. 1999. Evaluation of interaction between irrigation and soil cultivation in maize production. 181-190. Acta Agronomica, 47.

Novoa, R., and Loomis, R. S. 1981. Nitrogen and plant production. *Plant and Soil.* 58(1-3): 177 – 204.

Oktem, A. 2008. Effect of water shortage on yield, and protein and mineral compositions of drip-irrigated sweet corn in sustainable agricultural systems. *Agricultural Water Management*, *95*(9) 1003-1010.

Pandey, R. K., Maranville, J. W., Admou, A. 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment I. Grain yield and yield components. *Agric.Water Manage.* 46(1): 1 – 1.

Pandey, R. K., Herrera, W. A. T., Pendelton, J. W. 1984. Drought response of grain legume under irrigation gradient: I. Yield and yield components. *Agron. J.* 76(4): 549 – 553.

Rudnick, D. 2013. "Impact of Water and Nitrogen Management on Maize Actual Evapotranspiration, Soil Water Extraction and Crop Water Productivity in South Central Nebraska, USA" (2013). Biological Systems Engineering--Dissertations, Theses, and Student Research. Paper 35. http://digitalcommons.unl.edu/biosysengdiss/35.

Viets, F. G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14: 223 – 264.

Zhang, H. 2003. Improving water productivity through deficit irrigation: examples from Syria, the North China Plain and Oregon, USA. In: Water productivity in agriculture: limits and opportunities for improvement (Kijne, J. W., Barker, R., Molden, D., eds). CAB International, Wallingford, UK.

Zwart, S. J., Bastiaanssen, W. G. M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, *69*, 115-133Nag ent years. Növénytermelés, 4. 5-6. 493-506.

PAPER TWO

NITROGEN MOVEMENT IN COARSE-TEXTURED SOILS AND ITS AVAILABILITY TO MAIZE (*ZEA MAYS L.*) PLANT

Mthandi, J.[1*], Kahimba, F.C.[1], Tarimo, A.K.P.R.[1], Salim, B.A.[1], Lowole, M.W [2],

[1]Department of Agri. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Published in Agricultural **Sciences, Vol.4, No.8A, 30-35 (2013)** peer reviewed journal).

PAPER THREE

TEMPORAL DISTRIBUTION OF TOTAL NITROGEN CONCENTRATION IN ROOTZONE OF MAIZE (*ZEA MAYS L.*)

Mthandi, J.[1*], Kahimba, F.C.[1], Tarimo, A.K. P.R.[1], Salim, B.A.[1], Lowole, M.W[2],

[1]Department of Agri. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Published in **Journal of Experimental Biology and Agricultural Sciences, September - 2013; Volume – 1(4). ISSN No. 2320 – 8694** peer reviewed journal).

PAPER FOUR

ROOT ZONE SOIL MOISTURE REDISTRIBUTION IN MAIZE (*ZEA MAYS* L.) UNDER DIFFERENT WATER APPLICATION REGIMES

Mthandi, J.[1*], Kahimba, F. C.[1], Tarimo, A. K. P. R.[1], Salim, B. A.[1], Lowole, M.W[2],

[1]Department of Agricultural Engineering and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Published in **Agricultural Sciences, Vol.4, No.10, 521-528 (2013)** peer reviewed journal).

PAPER FIVE

REVIEW OF NITROGEN SIMULATION MODELS BASED ON CASCADING SOIL WATER BALANCE - EFFICACY OF EU-ROTATE_N MODEL

Mthandi, J.[1*], Salim, B. A.[1], Kahimba, F. C.[1], Tarimo, A. K. P. R.[1], Lowole, M.W [2],

[1]Department of Agric. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Manuscript (submitted to ***Journal of Computer Science and Information Technology*** peer reviewed journal).

Abstract

Nitrogen is the nutrient most often deficient for crop production and its proper use can result in substantial economic return for farmers. However, when N inputs to the soil system exceed crop needs, excess N may leach and contaminate water. The complex question has been "how much is optimal N application for crop production?". To avoid such uncertainties, simulation models have been developed to simulate N movement in the soil. The aim of this paper was to evaluate N leaching simulation models that use cascading soil water balance approach to simulate movement of nitrogen in the soil and identify the best model to be used for simulation of water and nitrogen data collected from Nkango Irrigation scheme in Kasungu district, Malawi. The models that were evaluated are: CropSyst STICS, SLIM, Burns Model, SACFARM, ANIMO, APSIM, and EU-Rotate_N model. The study identified EU-Rotate_N model as model to use in this study because of several advantages it has such as, a Minimum Information Requirement (MIR) model and does not need high level of computer expertise or detailed information to run the model, and advantages of generality. The study concluded that Review of N leaching simulation model have indicated that models that uses cascading soil water balance approach such as EU-Rotate_N model in simulating water and solute transport through soil profile are better compared with models that uses Richards' equations. The management options that can be used to minimise N leaching and increase economic returns on nitrogen fertilizers were developed.

Key words: Cascading soil water balance approach, N leaching, Models, N-management options

5.1 Introduction

Environmental and economic issues combined have increased the need to better understand the role and fate of nitrogen (N) in crop production systems. Nitrogen is the nutrient most often deficient for crop production and its proper use can result in substantial economic return for farmers. However, when N inputs to the soil system exceed crop needs, excess N may contaminate water. Jungkunst *et al.* (2006) reported that imbalance in N supply relative to crop demand can also compromise growth and quality of produce. N Management is therefore important to achieve a balance between profitable crop production and environmentally tolerable levels in water. Downward N movement below root zone represent an economic loss and poses a high environmental risk. Therefore, it is important to develop effective systems to optimize fertilizer-N application in agricultural systems to maintain sustainable crop production and minimize risks to the environment.

The complex question has been "how much is optimal fertilizer-N application?" because determining how much N fertilizer is required by a maize crop is an imperfect science at its best. While this question can be adequately answered by conducting field trials for each soil type to establish optimal N and water application levels, field trials are very expensive, time consuming and are subject to uncontrolled conditions (Drooger *et al*., 2000). To avoid such uncertainties, crop models have been developed by various researchers to represent water and solutes movement through profile (e.g. CropSyst STICS, SLIM, Burns Model). van der Laan *et al.* (2014) reported that a large number of crop models have been applied to investigate N leaching losses at the local to field scale, including RZWQM (Ma *et al.,* 1998), GLEAMS (Webb *et al.,* 2001), APSIM (Keating *et al.,* 2003), CropSyst (Stöckle *et al.,* 2003), CERES, CROPGRO and CANEGRO within the DSSAT framework (Daroub *et al.,* 2003; Van der Laan *et al.,* 2011), and SWB-Sci (Van der Laan *et al.,* 2010), HYDRUS (Šimunek *et al.,* 2008). However, as reported by Liang *et al.* (2007) these models cannot describe and include all major N-transformation processes and factors, and discontinuous fertilizer input was often missing. Magesan *et al.* (1999) also reported that most of these models were developed for aerobic conditions and hence their applicability is limited to the unsaturated zone. This is why Phogat *et al.* (2013) reported that no single model has been used extensively to simulate N leaching.

5.2 Water and Solute Transport Approaches

There are two main approaches that crop simulation models use to simulate movement of water and solute through soil profile. These approaches are cascading soil water balance and numerical solutions based on the Richards' and Convection-Dispersion equations. Richards' equation is often used to describe water transport in variably saturated soil profiles (Maggi and Porporato, 2007). However, while Richards' equation is suitable to model unsaturated flow in laboratory-scale soil columns with limited heterogeneity, its applicability to field-scale studies, where local scale variability is significant, has been debated (Ritsema, 1999; Steenhuis *et al.,* 1996). At the field scale, unsaturated flow is often governed by the heterogeneous distribution of the hydraulic properties, soil water repellence, instability and preferential flow paths (Lennartz *et al.,* 2008; Morales et al., 2010). Richards' (and Darcy's) equation do not consider preferential flow paths (van der Valaan, 2014). Preferential flow is defined as a transport mechanism in which non-uniform, rapid flow of water and transport of dissolved solutes occur through preferred pathways within the soil profile to a certain point below the root zone (Strock *et al.,* 2001; Mulla and Strock, 2008). In the preferential flow process, the solute does not have sufficient time to interact with the soil matrix due to the rapid and turbulent pattern of flow in the soil pores. Preferential flow is the principal mechanism responsible for accelerated movement of solutes such as NO3-N, in many agricultural soils (Luxmoore, 1991; Li and Ghodrati, 1994). The preferential flow pathways are mostly common in a well-structured field soils which has macropores whose diameters range from 0.03 to 30 mm (Beven and Germann, 1982). In smallholder agricultural systems where farmers cultivate their small pieces of land on annual basis, preferential flow pathways are thus common. The main aim of this paper was to review models that simulate leaching of nitrogen based on cascading soil water balance approach.

5.2.1 Cascading soil water balance approach

A cascading or 'tipping bucket' soil water balance approach accounts for moisture changes in the soil profile (Barry *et al.,* 1983; Parton *et al.,* 1987; Porporato *et al.,* 2003;

Rose *et al.,* 1982). The water budget approach is a suitable practical means to represent the soil moisture dynamics of the upper part of the soil profile rather than computationally intensive numerical schemes based on solutions of Richards' equation (Struthers *et al.,* 2006). Van der Laan *et al.* (2014) reported that models using cascading soil water balance approach are more commonly used because (1) they are easier to parameterize, (2) long standing and geographically widespread use has resulted in large databases of soil input data, (3) options for deriving soil input data from simple soil measurements are often available, and (4) they have a shorter run time (Huth *et al.,* 2012).

The cascading model of SoilWat uses the water balance (Equation 1) (Ahmed *et al.,* 2013):

$$R + I = \Delta SW + ET + RO + D \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where R = rainfall, I = Irrigation, ΔSW = change in soil water, ET = evapotranspiration, RO = runoff and D = drainage. All variables measured in mm. Under Irrigation condition, inputs of Precipitation and Upward capillary are assumed to be zero, and output variable of Runoff can also be assumed zero, especially when irrigated water is not flowing out of the sink. Therefore, modified water balance as shown in Equation 2:

$$\Delta SW = (I) - (ET + D) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The water balance Equation 2 shows that changes of soil water and its movement is heavily influenced by properties of soil, for example in loose, coarse textured soils, movement of water can be quicker than in cohesive, fine textured soils. Soil profiles have different layers with most upper layers having more macrospores. Movement of water and solutes in these upper layers is much quicker than their underlying layers. The soil properties of lower limit (also referred to as permanent wilting point), drained upper limit (also referred to as field capacity) and saturation volumetric water content (VWC) values are specified for each soil layer. These parameters are used to determine the amount of infiltrating water in a soil layer above the drained upper limit that will 'cascade' to the layer below. A user- defined factor determines what fraction of the water volume above the drained upper limit can drain to the layer below during each daily time-step. This approach considers how much water has moved to the next layer regardless of whether this movement was through preferential flow pathways or not.

5.3 Comparison of Cascading Soil Water Balance Models

5.3.1 Cropping Systems Simulation Model (CropSyst)

CropSyst (Cropping Systems Simulation Model; Stöckle *et al.,* 2003) and SWB-Sci (research version of the Soil Water Balance model; van der Laan *et al.,* 2010) use a simple cascading soil water balance approach and account for incomplete N mixing based on the approach developed by Corwin *et al.* (1991). This approach utilizes a mobility coefficient (γ) which represents the fraction of the liquid phase that is subject to piston-flow displacement, with the fraction 1- γ representing the liquid phase that is bypassed. Both NO_3^- and NH_4^+ leaching are taken into account. van der Laan *et al.* (2010) observed that when using this approach in SWB-Sci, simulated draining NO_3^- concentrations aligned closely with draining concentrations measured in passive samplers intercepting draining water, while simulated resident soil water concentrations aligned closely with concentrations measured in active samplers ('resident' soil water is collected using a suction force).

5.3.2 Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS)

STICS is a soil-plant-atmosphere model with an atmospheric Upper boundary (characterized by standard climatic variables: net radiation, minimum and maximum temperatures, precipitations, reference evapotranspiration or eventually wind and air moisture) and with a soil/subsoil lower boundary. The soil is described as a vertical succession of layers (Tournebize *et al.,* 2004). STICS assumes that upon application of fertilizers, nitrogen can be converted to other forms through the processes volatilization, denitrification and mineralization. STICS has therefore introduced the efficiency of the nitrogen fertilizers (EFFN), which defines the fraction of supplied nitrogen which remains in its mineral form. This is amount of nitrogen that can be reached by soil water compared to other forms of nitrogen loss (Brisson *et al.,* 1998). STICS has another efficiency factor known as $C_{critNO3}$. This factor defines amount of nitrogen in mineral form that can be absorbed by plant roots depending on its nitrogen demand. A critical value of $C_{critNO3}$ (kg NO_3-N $ha^{-1}mm^{-1}$ water cm^{-1} soil depth is used to account for NO_3^- adsorption on soil and the prevention of this fraction of NO_3^- from being transported to lower soil layers. NO_3^- above the $C_{critNO3}$ is assumed to mix completely between resident and draining soil water for that layer. $C_{critNO3}$ is set up as a comparison between the nitrogen supply of the soil and the nitrogen demand of the crop. The nitrogen demand of the crop is the upper limit of absorption; that is, set by the regulation mechanisms of the plant when the nitrogen supply near the roots is not limiting. Sierra *et al.* (2003) demonstrated that NO_3- transport was overestimated when there factors were not accounted for. Brisson *et al.* (1998) reported that nitrate arriving by convection with the water in an elementary layer is mixed with the already present nitrate – complete mixing. The excess water then leaves with the new concentration of the mixture. Brisson *et al.* (1998) reported that STICS assume a complete meaning that water draining from a layer (Z) to the layer immediately below (Z+ 1) carries along a certain amount of nitrate. This nitrate is assumed to mix completely with the water in the layer Z+ 1. Thereafter, the excess water in this layer (in comparison with the field capacity) drains to the next layer (Z + 2) with its new nitrate concentration. The process continues down to the bottom of the profile or to the layer in which the water content remains lower than the field capacity. The model assumes that all the water in a particular soil layer can drain to the underlying soil layer.

5.3.3 Solute Leaching Intermediate Model (SLIM)

SLIM was developed and outlined by Addiscott *et al.* (1986) and described in detail by Addiscott and Whitmore (1991), the soil is divided into a number of layers, each of which contains mobile and immobile categories of water and solute. Nitrate, or any other solute, is prevented from leaching as long as it remains in the immobile phase. The immobile category of water is not decreased by drainage, but can be diminished by evaporation. The parameters of the SLIM model can be calibrated or estimated from the clay percentage and aggregate size distribution (Addiscott, 1983; Addiscott and Bland, 1988). Water and solute entering a given layer from the layer above, or from rainfall, are added to the current proportion of the new mobile water and solute categories, determined by the rate parameter α, moves to the next layer. Solutes and water move laterally by diffusion and the limits imposed by diffusion can be described by partially equalizing concentrations between mobile and immobile water categories, using a “hold-back” factor (Moreels *et al.,* 2003).

5.3.4 Burns Model

Nitrate can be translocated by leaching during periods of excess precipitation or irrigation and by upward movement during periods of excess evapotransipiration (Moreels *et al.,* 2003). Burns (1974) developed a simple model to predict the distribution of non-adsorbed solutes subject to leaching and upward movement. The original evaporations excess module was modified according to the suggestions by Mary *et al.* (1999). They proposed that that evaporation effects the upper layers to a maximum depth. The relative contribution of each soil layer to the total evaporation declines exponentially with depth. The evaporative demand is met from several layers concurrently, contrary to the Burns' original idea of successive layer exhaustion. Although some simplifying assumptions were made, this model has the advantage of accounting for both upward and downward movement of solutes without using parameters that may be difficult to measure or have to be determined during model calibration. One of the major drawbacks of the Burns model is that no water content above field capacity can be simulated, thus limiting its use to light textured soils only.

5.3.5 SACFARM

SACFARM (Addiscott *et al.,* 1991) is user-friendly model intended to be used by farmers as an N fertilization decision support model. SACFARM simulates mineral N in the soil and N in the crop (Moreels *et al.,* 2003). The model includes leaching, mineralization of soil organic N and growth and N uptake of the crop. The leaching component of this model is the SLIM model, whose main parameters, α and Ɓ, can be derived from the particle distribution of the soil (Addiscott and Whitmore, 1991). When the particle size distribution is not available, the description of the soil can be used, as this management model presents a ‘menu’ of soil types, which were assigned particle size distributions on the basis of published results of the Soil Survey and Land Research Center (Addiscott *et al.,* 1991).

5.3.6 Agricultural Nitrogen Model (ANIMO)

ANIMO is a complex model, aiming to quantify the relation between fertilization level, soil management and leaching of nutrients to groundwater and surface water systems for a wide range of soil types and different hydrological conditions (Rejtema and Kroes, 1991). The model describes all main processes of nitrogen dynamics in the soil: mineralization and immobilization of nitrogen related to processes in the carbon cycles, nitrogen uptake by plants, denitrification, soil moisture dynamics and nitrogen transport. The central part of the model is the transport and conservation equation. By means of this equation, the new concentration of soluble compounds in all layers can be calculated after simultaneous transport and transformation processes. The major drawback of ANIMO is that it must be linked to a hydrological model for calculation of the fluxes and changes in moisture content in each layer i.e. hydrological simulations must be executed completely before ANIMO can be applied.

5.3.7 Agricultural Production System sIMulator (APSIM)

APSIM model (McCown *et al*., 1996) is a multi-purpose and comprehensive model developed as a tool for exploring crop management strategies that can improve the economics of agricultural production systems and the consequences of the soil resources and environment (Probert *et al.,* 1998). The APSIM is a centralized engine into which modules could be connected. Each module provides a small piece of simulation functionality with the 'engine' coordinating the flow of data/variables between the modules. APSIM has SoilWat module that govern water and solute transport in the soil. After the drainage fluxes are calculated for each soil layer, SoilWat determines how much solute would have accompanied this water. For this SoilWat uses a "mixing" algorithm, which implies that all water and solute entering a layer is completely mixed with what was already there, before the solute flux out of the layer is calculated. Equation 3 is the governing equation is (Verburg, 1995):

solute_out(i) = solute_conc* water_out* N_flux_eff……………..……………..(3)

Where N_flux_eff is an efficiency factor assumed as 1, and (Verburg, 1995):

solute_conc = (solute (i) + solute_in(i)) / (new_sw(i)* d(i) + water_out)………..(4)

With new sw(i) the water content after calculation of the drainage fluxes. Note that the total water over which the solute is averaged (new sw(i) * d(i) + water_out), can be more than SAT(i)* d(i). In addition, when large amounts of water cascade through the profile, considerable dilution of solute occurs, but it can never be totally eluted from a layer. In this respect the algorithm is relatively inefficient in moving solutes. However, looking into assumption of solute conc equation (4), you will note that Water-out component was not supposed to be included. This is because its addition to the denominator is just increasing amount of water which consequently is reducing the solute concentration. If the assumption of thorough mixing of solute and water in a layer still stands it means that this water-out has equal concentration of solute as water in the proceeded layer. So adding only water component to water in the layer is only increasing amount of water while solute component remain the same hence low concentration of solute going to the next layer.

5.3.8 EU-Rotate_N

EU-Rotate_N is a model specifically used to simulate N response for vegetable and arable crops only (Rahn *et al.,* 2007). The model is much more advanced and more mechanistic in dealing with many soil and plant processes. The model has module that define the fate of water in the soil-plant system and is known as soil water balance module. The soil water balance module allows calculation of water use and water movement both vertically and horizontally (Rahn *et al.,* 2007). Thus it is suited for situations such as wide-row crops and trickle- and furrow-irrigation, as well as conventional conditions. The soil water balance module has different parts that calculate Crop evapotranspiration (soil evaporation and transpiration); Effective water infiltration (applied water minus runoff); Drainage; and Water redistribution in soil. Crop evapotranspiration is calculated using basically the FAO approach (Allen *et al.,* 1998). The main parameters that enter in these calculations are those related to the evaporative demand of the atmosphere, summarized by the reference evapotranspiration (ETo) and a crop coefficient that varies with crop development. The effects of water stress on plant growth are considered assuming that the reduction in dry matter accumulation due to water deficit is proportional to the transpiration reduction (Hanks, 1983; Shani and Dudley, 2001). Water infiltration and redistribution in soil follows a capacitance approach with a drainage coefficient that allows the water transfer between layers above field capacity to be done progressively (in more than one day) and more or less rapidly depending on soil type (Ritchie, 1998).

Doltra and Muñoz (2010) compared nitrogen leaching prediction performance of EU-Rotate_N and Hydrus-2D models. They reported good correlations of both models between the simulated water draining below 60 cm and that calculated by water balance.

The uptake of nitrate was better simulated with EU-Rotate_N than in Hydrus-2D. Simulated N leaching below a depth of 60 cm was higher with Hydrus-2D due to a higher nitrate concentration in percolated water and more acceptable in EU-Rotate_N

5.4 Advantages of EU-Rotate_N Model

EU-Rotate_N model has several advantages over other models that use cascading soil water balance approach. Some of the advantages are as follows:

- EU-Rotate_N model has high level of flexibility by allowing users to enter data of discontinuous fertilizer application dates. Most of the models do not have such flexibilities reported by Liang *et al.* (2007) that most of crop simulation models cannot describe and include all major nitrogen transformation processes and factors, and discontinuous fertilizer input was often missing
- The input parameters of the EU-Rotate_N model are included in the parameter files allowing calibration without need to access the model code (Rahn *et al.,* 2007). The main parameters that define the hydraulic soil properties such as the water content at field capacity and wilting point are input by the user for the different soil layers, although default values depending on soil texture are available.
- EU-Rotate_N model is a Minimum Information Requirement (MIR) model and does not need high level of computer expertise or detailed information to run the model
- EU-Rotate_N model is specifically used for vegetables and arable crops only. This means great deal of emphasis is put to ensure that this model is correctly simulating these crop processes. Other models are used to many different types of

crops and as such they omit key processes of vegetables and arable crops that would have otherwise been included.

- Unlike other N leaching simulation models that use cascading soil water balance approach, EU-Rotate_N model utilise readily available data and has ability to simulate crop rotations.
- EU-Rotate_N has the advantages of generality, 2-D which is able to simulate N dynamics in the soil domain in the horizontal and vertical directions. The generality of the model was made possible due to the discoveries that both crop critical %N for maximum growth and crop dry matter increments during growth could be described by unified equations (Greenwood *et al.,* 1985). The 2-D nature of the model makes it more accurate in simulating N-economy for row crops.

5.5 Conclusion

Review of N leaching simulation models has indicated that models that use cascading soil water balance approach in simulating water and solute transport through soil profile are better compared with models that uses Richards' and Convection-Dispersion equations. Richards' (and Darcy's) and Convection-Dispersion equations are suitable to model unsaturated flow in laboratory-scale soil columns with limited heterogeneity, but have limited capability to simulate water flow in field soils which have high soil variability. Richards' (and Darcy's) and Convection-Dispersion equations do not consider preferential flow paths. Preferential pathways are common in smallholder agricultural systems where farmers cultivate their small pieces of land on annual basis.

Critical review of models that use cascading soil water balance have shown that EU-Rotate_N model has several advantages over other models and can easily adapted for soils in Malawi. This study has therefore selected EU-Rotate_N model to simulate nitrogen leaching for different water and nitrogen application regimes in a study conducted at Nkango irrigation scheme in 2012. The model has further been used to develop management options that can be used to minimise nitrogen losses through leaching and increase economic returns on nitrogen fertilizers.

References

Addiscott T. M. 1983. Kinetics and temperature relationships of mineralization and nitrification in Rothamsted soils with differing histories. J. Soil Sci. 34: 343–353.

Addiscott, T. M., and Bland, G. J. 1988. Nitrate leaching models and oil heterogeneity. In: Smith K.E. and Jenkinson D.S. (eds), Nitrogen Efficiency in Agricultural Soils. Elsevier Applied Science, Barking, UK, pp. 394–408.

Addiscott, T. M., and Whitmore, A. P. 1991. Simulation of solute leaching in soils of differing permeabilities. Soil Use Manage. 7: 94–102.

Addiscott, T. M., Bailey, N. J., Bland, G. J., and Whitmore, A. P. 1991. Simulation of nitrogen in soil and winter wheat crops: a management model that makes the best use of limited in- formation. Fert. Res. 27: 305–312.

Addiscott, T. M., Philippa, J., Heys P. J., and Whitmore, A. P. 1986. Application of simple leaching models in heterogeneous soils. Geoderma 38: 185–194.

Ahmed, M., Hirani, H. A., Asif, M., Sajad, M. 2013. Modelling Soil Water Dynamics under Rainfed Agriculture to Mitigate Climate Change. PMAS Arid Agriculture University Rawalpindi, Pakistan. Tel: 92-51-929-0757. E-mail:

ahmadmukhtar@uaar.edu.pk. Journal of Agricultural Science; Vol. 5, No. 3; 2013. ISSN 1916-9752 E-ISSN 1916-9760. Published by Canadian Center of Science and Education.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M.1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper n° 56, FAO, Roma.

Barry, D. A, Parlange, J. Y., Saffigna, P. G., Rose C. W. 1983. Theory of solute transport in soils from the method of 37 characteristics. Irrigation Science 1983; 4: 277-287. OI:10.1007/BF00389650.

Beven, K., and Germann, P. 1982. Macropores and water flow in soils. Water Resour. Res. 18: 1311-1325.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M. H., Ruget, F., Nicoullaud, B., Gate, P., Devienne-Barret, F., Antonioletti, R., Durr, C., Richard, G., Beaudoin, G., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J. M., Meynard, J. M., Delécolle, R. 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balance. I. Theory and parameterization applied to wheat and corn. Agronomie 18, 311-346.

Burns, I. G. 1974. A model for predicting the redistribution of salts applied to fallow soils after excess rainfall or evaporation. J. Soil Sci. 25: 165–178.

Corwin, D. L., Waggoner, B. L., Rhoades, J. D. 1991. A functional model of solute transport that accounts for bypass flow. J. Environ. Qual. 20, 647-658.

Daroub, S. H., Gerakis, A., Ritchie, J. T., Friesen, D. K., Ryan, J. 2003. Development of a soil-plant phosphorus simulation model for calcareous and weathered tropical soils. Agric. Sys. 76, 1157-1181.

Doltra, J., and Muñoz, P. (2010). Simulation of nitrogen leaching from a fertigated crop rotation in a Mediterranean climate using the EU-Rotate_N andHydrus-2D models. *Agric. Water Manag.* 97(2): 277285.

Drooger, P., Bastiaanssen, W. G. M., Beyazgul, M., Kayam, Y., Kite, G. W. and Murray-Rust, H. 2000. Distributed agro-hydrological modelling of an irrigation system in Western Turkey. *Agricultural Water Management* 43: 183-202.

Greenwood, D. J., Neeteson, J. J., Draycott, A., 1985. Response of potatoes to N-fertilizer: Dynamic model. Plant Soil 85, 185-203.

Hanks, R. J. 1983. Yield and water-use relationships: An overview. In H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI., pp. 393-411.

Huth, N., Bristow, K.L., Verburg, K. 2012, SWIM3: Model use, calibration, and validation. *Trans. ASABE* 55, 1303-1313.

Jungkunst, H. F., Freibauer, A., Neufeldt, H., Bareth, G., 2006. Nitrous oxide emissions from agricultural land use in Germany—a synthesis of available annual field data. J. Plant Nutr. Soil Sci. 169, 341–351.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., Smith, C. J. 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 235-266.

Lennartz, B., Jarvis, N., Stagnitti, F. 2008. Effects of heterogeneous flow on discharge generation and solute transport. Soil Science 2008; 173: 306-320.

Li, Y., and Ghodrati, M. 1994. Preferential flow of nitrate through soil columns containing root channels. Soil Sci. Soc. Am. J. 58: 653-659.

Liang, X. Q., Chen, Y.X., Li, H., Tian, G. M., Ni, W. Z., He, M. M., Zhang, Z. J. 2007. Modeling transport and fate of nitrogen from urea applied to a near-trench paddy field. Environ. Pollut. 150, 313-320.

Luxmoore, R. J. 1991. On preferential flow and its measurement. Pages 113121. *In* T.J. Gish and A. Shirmohammadi (ed.). Preferential flow. Proc. Symp., Chicago. 16-17 Dec. 1991. ASAE, St. Joseph, MI.

Maggi, F., and Porporato, A. 2007. Coupled moisture and microbial dynamics in unsaturated soils. Water Resources Research 2007; 43: WR005367. DOI:10.1029/2006WR005367.

Mary, B., Beaudoin, N., Justes, E., and Machet, J. M. 1999. Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model. Eur. J. Soil Sci. 50: 549–566.

Magesan, G. N., Clothier, B. E., Heng, L., Vogeler, I. 1999. The measured mobile-water content of an unsaturated soil as a funcation of hydraulic regime. Aus. J. Soil Res. 33; 397-414

McCown, R. L., Hammer, G. L., Hargreaves, J. N. G., Holzworth, D. P. and Freebairn, D. N. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural research. *Agricultural Systems* 50: 255-271.

Morales, V. L., Parlange, J. Y., Steenhuis, T. S. 2010. Are preferential flow paths perpetuated by microbial activity in the soil matrix? A review. Journal of Hydrology 2010; 393: 29-36. DOI:10.1016/j.jhydrol.2009.12.048.

Moreels, E, Neve, D. S., Hofman, G., Meirvenne, M. 2003. Simulating nitrate leaching in bare fallow soils: a model comparison. Nutrient Cycling in Agroecosystems 67: 137–144, 2003. 2003 Kluwer Academic Publishers. Printed in the Netherlands. Department of Soil Management and Soil Care, Faculty of Agricultural and Applied Biological Sciences, Ghent University, Coupure Links 633, B-9000 Ghent, Belgium; Author for correspondence (e-mail: edwin.moreels@rug.ac.be).

Mulla, D. J., and Strock, J. S. 2008. Nitrogen transport processes in soil. *In* Schepers, J.S., and Raun, W.R. (eds.) Nitrogen in agricultural systems, Agronomy monograph 49. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 667 S. Segoe Rd., Madison, WI 53711, USA.

Parton, W. J., Schimel, D. S., Cole, C. V., Ojima, D. S. 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am.J. 51, 1173_/1179.

Phogat, V., Skewes, M. A., Cox, J. W., Alam, J., Grigson, G., Šimunek, J. 2013. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. Agric. Wat. Manage. 127, 74-84.

Porporato, A., D'Odorico, P., Laio, F., Rodriguez-Iturbe, I. 2003. Hydrologic controls on soil carbon and nitrogen cycles. I. Modelling scheme. Advances in Water Resources 2003; 26: 45-58. DOI:10.1016/S0309-205 1708(02)00094-5.

Probert, M. E., Dimes, J. P., Keating, B. A., Dalal, R. C., and Strong, W. M. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* 56(1), 1-28.

Rahn, C. R., Zhang, K., Lillywhite, R., Ramos, C., Doltra, J., de Paz, J. M., Riley, H., Fink, M., Nendel, C., Thorup-Kristensen, K., Piro, F., Venezia, A., Firth, C., Schmutz, U., Raynes, F., Strohmeyer, K. 2007. Using the EU-Rotate_N model to forecast the effects of nitrate legislation on the economic output and environmental benefits on cropping rotations. Proc. of 16th 9 International CIEC Symposium, 16-19 September 2007, Gent, Belgium, 433-439.

Rijtema, P. E., and Kroes, J. G. 1991. Some results of nitrogen simulations with the model ANIMO. Fert. Res. 27: 189–198.

Ritsema, C. J. 1999. Preferential flow of water and solutes in soil. Journal of Hydrology 1999; 215: 1-3. DOI: 10. 1016/S0022-1694(98)00257-1.

Rose, C. W., Chichester, F. W., Williams, J. R., Ritchie, J. T. 1982. A contribution to simplified models of field solute transport. Journal of Environmental Quality 1982; 11: 146-151.

Shani, U., and Dudley, L. M. 2001. Field studies of crop response to water and salt stress. Soil Sci. Soc. Am. J. 65:1522–1528.

Sierra, J., Brisson, N., Ripoche, D., Noël, C. 2003. Application of the STICS crop model to predict nitrogen availability and nitrate transport in a tropical acid soil cropped with maize. Plant Soil 256, 333-345.

Šimunek, J., van Genuchten, M.T., Šejna, M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. Vadose Zone J. 7, 587-600.

Steenhuis, T. S., Ritsema, C. J., Dekker, L. W. 1996. Fingered flow in unsaturated flow: From nature to model. Geoderma 1996; 70: 83-85. DOI:10.1016/S0016-7061(96)90000-2.

Stöckle, C. O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289-308.

Strock, J. S., Cassel, D. K. and Gumpertz, M. L. 2001. Spatial variability of water and bromide transport through variably saturated soil blocks. Soil Sci. Soc. Am. J. 65:1607-1617.

Struthers, I., Hinz, C., Sivapalan, M. A. 2006. multiple wetting front gravitational infiltration and redistribution model for water balance applications. Water Resources Research 2006; 42: W06406. 239 DOI:10.1029/2005wr004645.

Tournebize Julien, Cyril Kao, Nenad Nikolic, Daniel Zimmer. 2004. Adaptation of the STICS model to subsurface drained soils. Agronomie, EDP Sciences, , 24 (6-7), pp.305-313. <10.1051/agro: 2004030 >. <hal-00886025>.

Van der Laan, M., Miles, N., Annandale, J. G., du Preez, C. C. 2011. Identification of opportunities for improved nitrogen management in sugarcane cropping systems using the newly developed Canegro-N model. Nut. Cycl. Agroecosys. 90, 391-404.

Van der Laan, M., Stirzaker, R. J., Annandale, J. G., Bristow, K. L., du Preez, C. C. 2010. Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses. Agric Wat Manage 97, 1779-1786.

van der Laan, M., Thorburn, P. J., Annandale, J. G., , Bristow, K. L, Stirzaker, R. J., du Preez, C. C. 2014. Modelling nitrogen leaching: Are we getting the right answer for the right reason? Department of Plant Production and Soil Science, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa. CSIRO Sustainable Agricultural National Research Flagship and CSIRO Land and Water, Australia.

Verburg, K. 1995. Divisional Report Methodology in soil-water-solute balance modelling: An evaluation of the APSIM-SoilWat and SWIMv2 models. Report of an APSRU / CSIRO Division of Soils workshop held in Brisbane, Australia Program

Management Modules Manager APSIM engine from 16-18 May 1995. Kirsten Verburg, Editor.

Webb, T. H., Lilburne, L. R., Francis, G. S. 2001. Validation of the GLEAMS simulation model for estimating net nitrogen mineralisation and nitrate leaching under cropping in Canterbury, New Zealand. Aust. J. Soil Res. 39, 1015-1025.

PAPER SIX

HOW MUCH NITROGEN WOULD MOVE DOWN? EVALUATING THE EFFECT OF WATER APPLICATION REGIMES ON N LEACHING IN THE SOIL

Mthandi, J.[1*], Salim, B.A.[1], Kahimba, F.C.[1], Tarimo, A.K. P.R.[1], Lowole, M.W[2],

[1]Department of Agric. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Published in ***Research Journal of Agriculture and Environmental Management. Vol. 4(4), pp. 208-215, April, 2015. Available online at http://www.apexjournal.org ISSN 2315 - 8719© 2015 Apex Journal International***

PAPER SEVEN

USING EU-ROTATE_N MODEL TO DETERMINE EFFECTS OF NITROGEN APPLICATION DOSAGE ON N LEACHING

Mthandi, J.[1*], Salim, B. A.[1], Kahimba, F. C.[1], Tarimo, A. K. P. R.[1], Lowole, M. W[2],

[1]Department of Agric. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Published in ***International Journal of Research in Agricultural Sciences. Volume 2, Issue 3, ISSN (Online): 2348 – 3997)***

PAPER EIGHT

OPTIONS FOR MANAGING WATER AND NITROGEN IN IRRIGATED MAIZE PRODUCTION IN MALAWI

Mthandi, J.[1*], Salim, B. A.[1], Kahimba, F. C.[1], Tarimo, A. K. P. R.[1], Lowole, M.W[2],

[1]Department of Agric. Eng. and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania

[2]Department of Crop Science, Bunda College of Agriculture, Lilongwe, Malawi

[*]*Corresponding author e-mail: johnmthandi@yahoo.com*

Status: Manuscript (submitted to ***Journal of Agriculture and Environmental Sciences.*** peer reviewed journal).

Abstract

Nitrogen is the most important macronutrient in the production of maize in Malawi. Previous studies indicate that most agricultural soils are deficient of nitrogen. Lack of fertile soils coupled with diminishing water resource and poor land management have led to a decline in land productivity and low yield returns. Farmers are enticed to use high levels of N fertilizers because of high crop production associated with such application. This study investigated the interactive effect of water and N on leaching and maize production. Four levels of water and N application regime were studied. EU-Rotate_N model stimulated water and N movement through soil profile and was used to identify option of managing water and N to reduce nitrogen loss through leaching while increasing maize production. The research study was conducted at Nkango Irrigation Scheme in

Kasungu district. The study informed development of management options that can be used to reduce N losses through leaching and increase maize production.

Key words: management options, maize, interactive effects, N fertilizer

8.1 Introduction

Nitrogen is the most important macronutrient in the production of maize in Malawi. However, like many soils in sub-Saharan Africa, most soils in Malawi are reported to be deficient of nitrogen. Thiombiano *et al.* (2006) reported that African soils have poor fertility because of old age and lack of volcanic rejuvenation. Many studies have shown that decline in crop production in sub-Saharan Africa is greatly due to fertility depletion of structurally degraded soil (Morin, 1993; Buresh *et al.,* 1997). Lack of fertile soils coupled with diminishing water resources and poor land management have led to a decline in land productivity and low yield returns. Kanyama-Phiri *et al.* (1998) reported that maize productivity in Malawi is declining due to low inherent soil nutrients, dominated by high nitrogen deficiency. Many studies have indicated that nitrogen is a major limiting nutrient in maize production in Malawi agriculture. Mloza-Banda (1994) reported that soils in Malawi are so degraded such that it is only when application rates of nitrogen are increased three-to four-fold that the potentialities of high maize productivity are fully realized.

Farmers are enticed to use high levels of nitrogen fertilizers because of high crop production associated with such nitrogen application (Zotarelli *et al.,* 2007). However, such over-application of nitrogen fertilizer is very costly to farmers, and has triggered many environmental concerns such as surface and groundwater contamination, eutrophication, and air pollution. Leaching of nitrogen has been identified as the main physical process of environmental concerns. Leaching is defined as a downward transport of soil solutes out of the root zone by water flow. Nitrate is highly soluble and mobile in the soil (Nielsen *et al.,* 1986) and can be easily leached from agricultural systems through soil water movement. Jansen (1999) studied the movement and leaching of residual nitrogen in the soil under a lysimeter experiment in order to test a leaching equation under field-like conditions with a view to predictive use under field conditions. The study indicated that nitrogen is slowly translocated to greater soil profile depths partly by diffusion and partly by slow downward movement of soil water.

Identifying the most economic rate of N fertilizer is very important in high N demanding crops such as maize, to maximize profitability and reduce N losses to the environment (Holland and Schepers, 2010). However, determining how much N fertilizer is required by a maize crop is an imperfect science at its best (Jansen, 1999). Over-application of nitrogen contributes to leaching. Malhi *et al.* (2004) reported that nitrogen fertilizers applied in excess of crop requirement may be susceptible to leaching below the root zone.

Irrigation water is also one of the key factors that influence nitrogen leaching. Several studies have studied the interactive effect of water and nitrogen on nitrogen leaching. Randall and Mulla (2001) concluded that when there is no water, nitrogen accumulates in upper layers of soil and can stay there even for many years, but when exposed to wet conditions, accumulated N is washed down. This underscores the importance of water in the movement of nitrogen in the soil. Srensen *et al.* (2010) reported that N can be leached from any soil when water holding capacity of soil is exceeded leaving additional water to freely move down through the soil profile with soluble nitrogen. Zumani (2001) compared border and furrow irrigations and concluded that conventional methods provided extra quantity of water which acts as carrier of nitrate to move down. Mthandi *et al.* (2013) reported that excessive irrigation promotes nitrogen loss not only by promoting nitrate leaching from the plant root zone, but also by creating wet soil conditions that favors denitrification. Good agricultural practices of managing nitrogen leaching are entwined in applying optimal amount of water and nitrogen to increase maize production while reducing leaching.

This study investigated the interactive effect of water and nitrogen on N leaching and maize production. Four levels of water and nitrogen application regime were studied. EU-Rotate_N model stimulated water and nitrogen movement through soil profile and was used to identify option of managing water and nitrogen to reduce nitrogen loss through leaching while increasing maize production.

8.2 Methods and Materials

8.2.1 Site description

The research study was conducted at Nkango Irrigation Scheme in Kasungu district. Data were taken in two irrigation growing seasons from 1st June to 8th September, 2012 during the first season, and from 10st September to 5th December, 2012 during the second season. Nkango Irrigation Scheme is an informal scheme which is owned and managed by the local communities and is situated at Latitude 12^{0}35' South and Longitudes 33^{0}31' East and is at 1186 m above mean sea level. The study area has a unimodal type of rainfall with rains between December and April. The mean annual rainfall is about 800 mm. The site lies within maize production zone of Malawi and has dominant soil type of coarse sandy loam. Smallholder farmers in the area practise irrigation and are conversant with water application regimes.

Soil samples were collected from the soil layers. There were 5 soil layers and each layer was 20 cm thick. Table 8.1 shows the initial soil properties after analysis of the samples. The analysis of soil samples was done at Bunda College Soil Laboratory. The average C/N ratio of the site was 10.48.

Table 8.1: Soil properties of the research site

Soil layers	FC	PWP	SAT	Clay content	Sand content	Bulk density	Soil pH	OM content	Soil moisture content	Mineral soil_N kg N/ha
1	0.21	0.12	0.43	0.17	0.68	1530	4.7	1.17	0.04	33
2	0.22	0.12	0.42	0.18	0.67	1490	4.4	0.95	0.07	26
3	0.23	0.14	0.44	0.20	0.60	1490	4.4	0.57	0.12	26
4	0.24	0.14	0.44	0.23	0.63	1450	4.5	0.45	0.15	24
5	0.25	0.14	0.42	0.24	0.63	1500	4.6	0.31	0.17	20

8.2.2 Experiemental design

The plot size was 5 m by 5 m and ridges were spaced at 75 cm. Three maize seeds of hybrid maize (SC 407) were planted per hole at plant spacing of 25 cm and row spacing of 75 cm. They were later on thinned to one seed per station 7 days after germination. The maize was planted on Julian day of 2012152 and harvested on Julian day of 2012250. Water and nitrogen were factors under study. Water had three regimes and were: full

(100%) water requirement regime (FWRR) of maize plant; 60% of FWRR; and 40% of FWRR. A full maize water requirement was determined using Penman-Monteith procudure described by (Allen *et al.,* 1998). The irrigation events were done at interval of 10 days on the following Julian days of 2012152, 2012160, 2012170, 2012180, 2012190, 2012200, 2012220, 2012230, and 2012240.

The three nitrogen application regimes under study were: 125% of TNPRA (115 N kg/ha); 100% TNPRA (92 N kg/ha) and 75% of TNPRA (69 N kg/ha). The Typical Nitrogen Placement Rate in the area (TNPRA) as recommended by (MoAFS, 2011) is 92 N kg/ha. The plots were basal and top dressed on Julian days of 2012159 and 2012195 respectively. The basal dressing fertiliser was 23:21:0+4s while the top dressing fertiliser was Urea which has 46% of Nitrogen. EU-Rotate-N model was run to quantify nitrogen leached below 90cm of the soil profile.

8.2.3 Data collection

The Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia), was used to measure total nitrogen concentration at lateral distances. The measurement of the sensor are in Volumetric ion concentration (VIC), by using standazation equation the concentration of total nitrogen on each point was known. The lateral distances were as follows: at point of application (represented by 0 cm), at 5 cm away from the plant (represented by -5 cm), at 5 cm towards the plant, 10 cm towards the plant (this point was maize planting station), and 15 cm after maize planting station. The lateral distances were measured on the basis of spreading and elongation pattern in rhizospere of maize plants. The lateral reading of nitrogen were respecively taken at five soil depths of 20, 40, 60, 80, and 100 cm. The soil depths were selected based on maize roots growth habits which extend down to 100 cm (FOASTAT, 2000).

8.3 Results and Discussion

This section presents the findings of the study. Comparison of observed data obtained from field survey was compared against the simulated data obtained by running EU-Rotate_N model. The discussion on the findings of the study has also been done in this section. Figure 8.1 shows the comparison of temporal distribution of nitrogen below 90 cm in a treatment that received full water requirement regime (84 mm) and 125% of the Typical Nitrogen Placement Rate in the Area (TNPRA). The comparison is between nitrogen data obtained from the field to nitrogen data generated by EU-Rotate_N model. The Mean Absolute Difference (MAD) and Root Mean Squared Difference (RMSD) of the simulated and observed data for this treatment were 0.27 and 0.38 respectively.

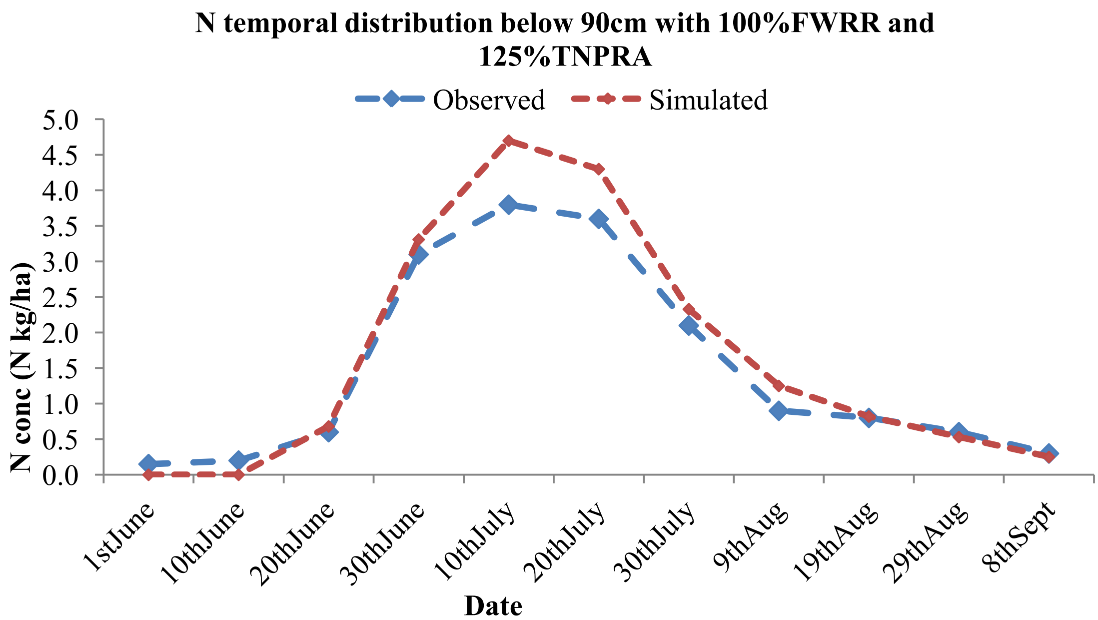


Figure 8.1: Temporal distribution of nitrogen below 90 cm with 100%FWRR and 125%TNPRA

As can be seen in Figure 8.1, the nitrogen data from both sources have similar trend of rise and fall throughout the whole growing season. From 1st to 10th June, 2012, the model predicted zero N leaching while data from the field indicated that there was some level of nitrogen content below 90 cm (specifically the measured depth for field study was 100cm). EU-Rotate_N model defines leaching as any additional nitrogen that moves down below 90cm. the model does not take into account the resident nitrogen content below 90cm and this is a reason that from 1st June to 10 June, 2012, the model only predicted zero nitrogen leaching. The Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia) which was used to measure nitrogen content at 100 cm had measured nitrogen content. It is therefore important to note the EU-Rotate_N model is measuring leached nitrogen below 90 cm while The Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia) is measuring prevailing nitrogen content at any given point. This might explain the reason why field data is reporting high nitrogen content than model from 1st to 10th June, 2012. From 20th to 30th June, 2012, there is very close corollation of field and model-generated data, from thereafter to 19th August, 2012, model-generated data is higher than from the field data. The reason to explain this discrepancy might be that EU-Rotate_N model calculates N leaching by multiplying nitrogen concentration with deep-percolated water. In this case, N leaching is dependant on amount of water moving down 90cm but in reality wetting fronts of water do not have the same concentration of nitrogen as preceeded water. Nitrogen moves slowly through soil profile than water. It is also important to note that soil complex can physically filter solute dissolved in water. The model is giving probable exact approxiamation of N leaching in the soil to the actual reality. The other reason to consider is that the Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia) provides nitrogen content of the soil at that particular time of measurement. The sensor has capability to provide data for every 15 minutes but due to constraint of time and resources, this research was only able to collect data every 10 days. So the gap in time of data collection might contribute to lower nitrogen content from field data. The miaze yield 6,940 kg/ha. This was the highest yield obtained in the study.

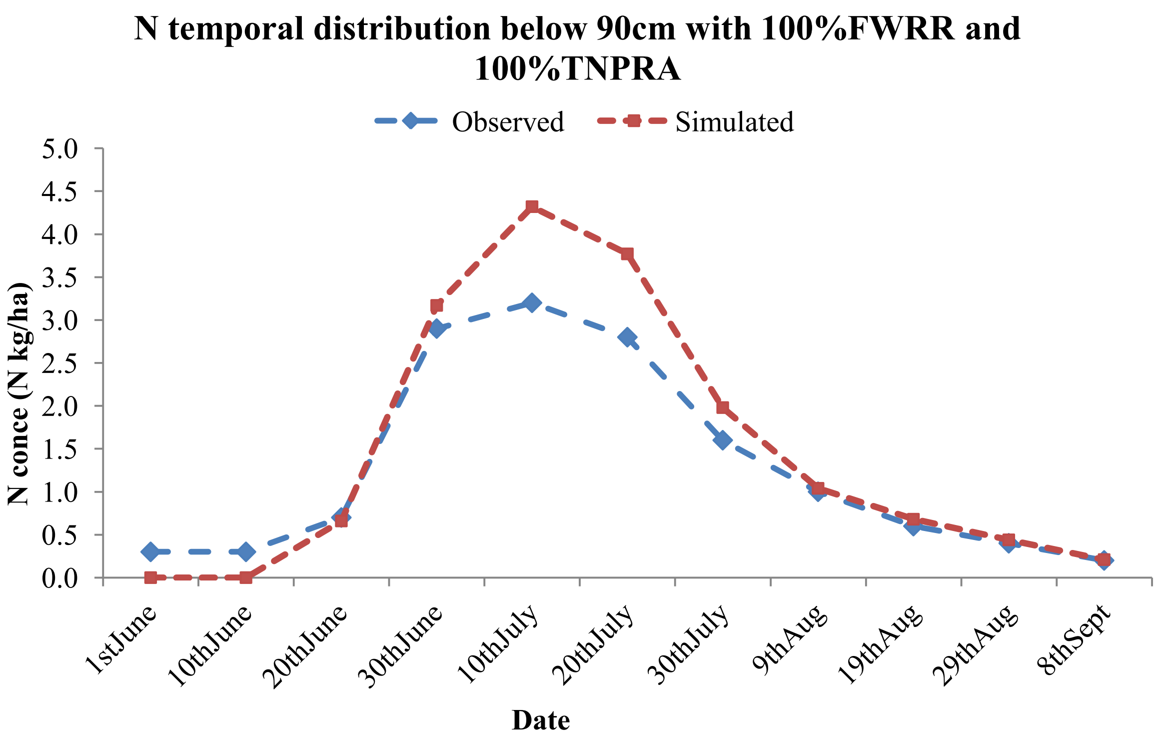


Figure 8.2: Temporal distribution of nitrogen below 90cm with 100%FWRR and 100%TNPRA

Figure 8.2 shows the temporal comparative nitrogen contents below 90cm from the treatment that had full water requirement regime with nitrogen application regime as recommended by Malawi Government. The MAD and RMSD of the simulated and observed data for this treatment were 0.32 and 0.49 respectively. The typical recommended nitrogen application regime in the area for maize production is 92 N kg/ha (MoAFS, 2011). Figure 8.2 indicates that from 1st to 10th June, 2012, the observed data were slightly above simulated data. Thereafter, observed data were less than simulated data until at the end of the growing season on 8th September, 2012. However, the important thing to observe is that the graph trend on the rise and fall of graph lines are very similar. In this case, the similarity of trends suggests that EU-Rotate_N model while over-predicting N leaching below 90 cm but can be powerful tool on devising management options to reduce N leaching. The management options to reduce N leaching can be to reduce amount of applied water when maize reach mid-stage, change of method of applying water to crops, or applying nitrogen in small amounts spread over the during of mid-stage. The maize yield from this treatment was 6,450 kg/ha.

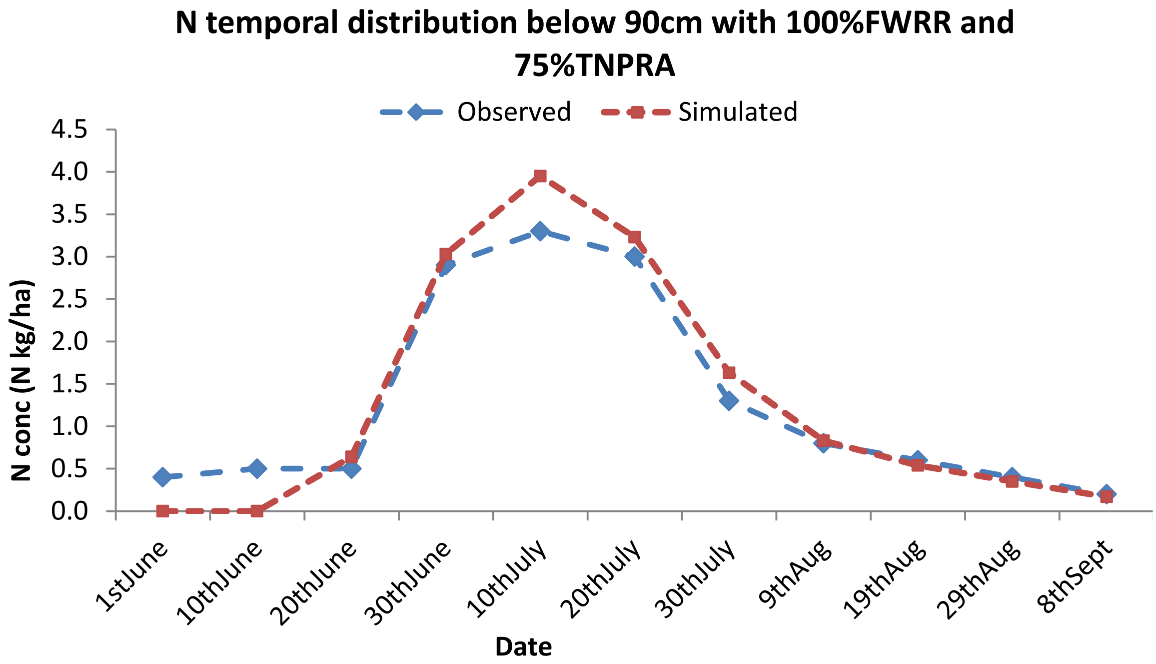


Figure 8 3: Temporal distribution of nitrogen below 90cm with 100%FWRR and 75%TNPRA

Figure 8.3 shows temporal comparative nitrogen distributions below 90 cm from a treatment that received full water requirement regime and 75% of the typical recommended nitrogen application rate in the area. The simulated data were generated using EU-Rotate_N model and observed data was collected using The Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia). The MAD and RMSD of the simulated and observed data for this treatment were 0.21 and 0.31 respectively. The simulated are shown to nearly fitting the observed data with expection of 1st and 10th June, 2012. This perfectly fitting relationship indicates that in some cases EU-Rotate_N Model can strongly predict the temporal N leaching. This is very essential in minimising N losses through leaching which would contaminate groundwater and decrease economic returns of the farmer. The maize yield of this treatment is 4,670 kg/ha. This maize yield is 73% of the yield obtained in a treatment that received recommended nitrogen application rate in the area. If N leaching is compared of these treatments, it will be noted that the difference was very small when observed data are used to compare at the peak of lossing nitrogen.

Figure 8.4 shows temporal comparative nitrogen distributions below 90 cm from a treatment that received 60% of full water requirement regime and 115% of the typical recommended nitrogen application rate in the area. The MAD and RMSD of the simulated and observed data for this treatment were 0.28 and 0.36 respectively. Figure 8.4 shows that N leaching of simulated data was zero from 1st June to 10th July, 2012. The simulated nitrogen contents started to increase meaning that N leaching started to occur on when maize was in late mid-stage.

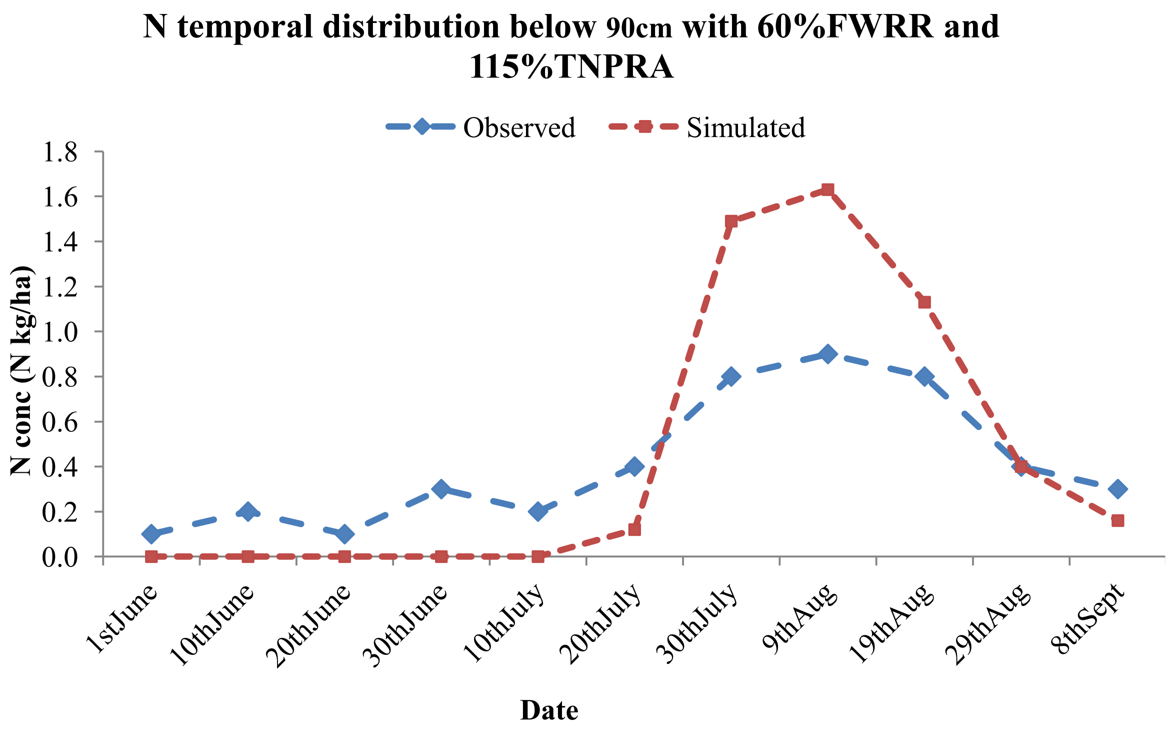


Figure 8.4: Temporal distribution of nitrogen below 90cm with 60%FWRR and 115%TNPRA

From 20th July to 29th August, 2012, N leaching was higher than observed data. The model was found to be able to successfully simulate the concentration of nitrogen at different depths in soil. The highest N leaching was reported on 19th August, 2012, the simulated N leaching was 1.6 N kg/ha and observed N leaching was about 0.9 N kg/ha. On 19th August, was just twenty days to harvest, this N leaching would have therefore been avoided without affecting maize yield. The maize yield of this treatment is 5,600 kg/ha which is above treatments represented by Figure 8.3. This shows that in water scarcity periods, reduction of water applied to water and increase application of nitrogen can result into increased yield. When nitrogen lost through leaching is compared with Figure 8.3, it can be shown that the Figures 8.3 and 8.4 above registered high N leaching than Figure 8.4. This further demonstrates that Figure 8.4 might be a good choice when water is scarce.

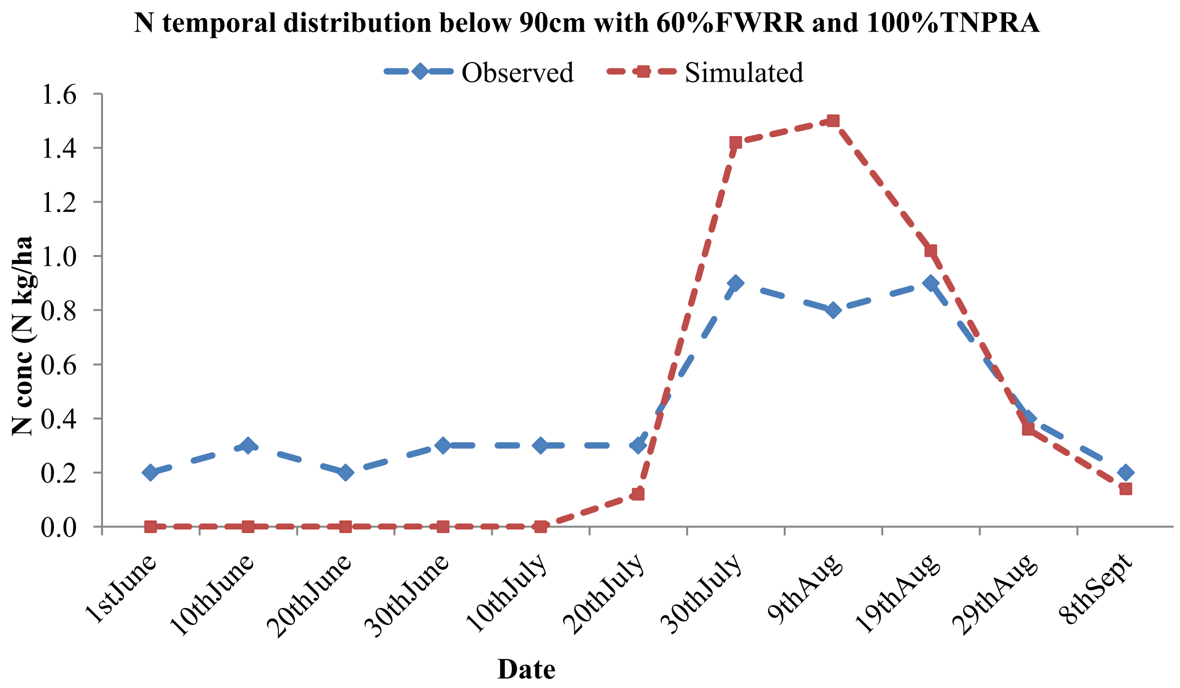


Figure 8.5: Temporal distribution of nitrogen below 90cm with 60%FWRR and 100%TNPRA

Figure 8.5 shows temporal comparative nitrogen distributions below 90 cm from a treatment that received 60% of full water requirement regime and 100% of the typical recommended nitrogen application rate in the area. The MAD and RMSD of the simulated and observed data for this treatment were 0.27 and 0.33 respectively. Simulated data shows that there was no N leaching from 1st June to 10th July, 2012, while observed data shows that nitrogen content was consistently below 0.4 N kg/ha from 1st June to 20th July, 2012. Both graph lines started to rise after 20th July and declined from 19th August, 2012. Mthandi *et al.* (2013) concluded that Maize roots over time reduce their ability and capacity to absorb nitrogen from surrounding soil masses. The reduced capacity of roots to absorb nitrogen induces maize plant to start re-mobilizing nitrogen from old leaves to new leaves. In this case, it means nitrogen content was still high in the soil even though maize was toward harvesting hence continued application of water resulted into increasing N leaching. In Figure 8.6, the lost nitrogen through leaching towards the end of season would have improved resident nitrogen level in the soil and ensures that is used by the plant in the following season. The maize yield of this treatment was 4,980 kg/ha. When compared with a treatment that received same amount of nitrogen of 100% TNPRA (Figure 8.2), the difference of maize yield is 1,470 kg/ha which is representing about 30% reduction of maize yield. This means that reduction of water requirement by 40% resulted into reduction of maize yield by 30%. In areas where water scarcity is high, farmers can be advised to reduce water requirement and still be able to harvest maize yield within acceptable range. The other benefit is reduction of leached nitrogen, in Figure 8.6, the maximum nitrogen loss from the observed data is 0.9 N kg/ha while in Figure 8.2 the maximum nitrogen loss from observed data is 4.25 N kg/ha. This demonstrates that in terms of management of water and nitrogen resources treatment (Figure 8.5) pose as best option when is compared with treatment represented by Figure 8.2. When the maize yield of this treatment is compared yield to the treatment (Figure 8.4), the difference is only 620 kg/ha representing only 13% reduction of maize yield. In this case, option of treatment represented by Figure 8.5 may also be good choice if compared with treatment represented by Figure 8.4. The maize yield obtained from this treatment was 4,980 kg/ha. Figure 8.6 represents the temporal distribution of nitrogen below 90cm deep on a treatment that received 60% of the full water requirement regime and 75% of the typical nitrogen application rate in the area.

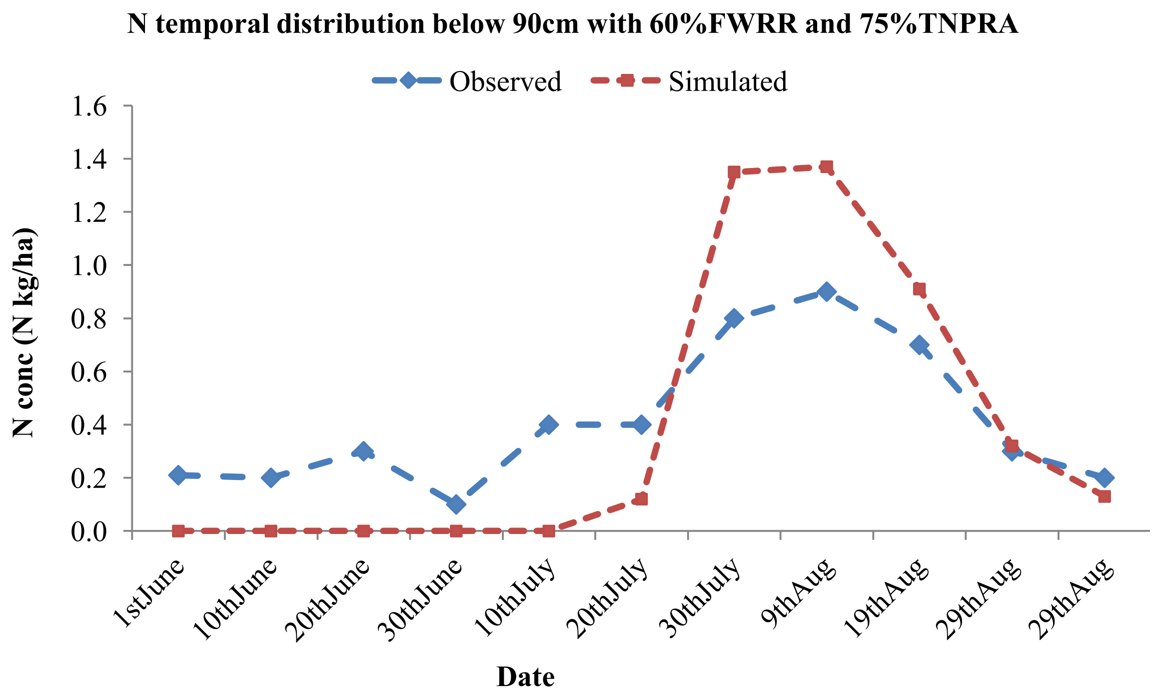


Figure 8.6: Temporal distribution of nitrogen below 90cm with 60%FWRR and 75%TNPRA

The model is perfectly fitting the observed data. The MAD and RMSD of the simulated and observed data for this treatment were 0.26 and 0.30 respectively. Figure 8.6 shows that the first five nitrogen leaching from the simulated data were zero indicating that there was no nitrogen leaching while observed data measured nitrogen contents at 100 cm. Observed data consistently nitrogen contents were very 0.4 N kg/ha from 1st June to 20th July, 2012 and after that nitrogen content started to rise just like from the simulated data, and they both started to fall on the same date on 9th August, 2012. This suggests that even though EU-Rotate_N model did not perfectly predicted N leaching but can be powerful tool to use in managing nitrogen at field level. Xu *et al.* (2013) reported that models can be useful models to predict the risk of nitrogen contamination to surface water and groundwater. EU-Rotate_N model can thus be very useful in predicting nitrogen losses.

The predicted N losses through leaching did not perfectly match the observed data. However, it has to be noted that leaching is continuous process it starts when soil can no longer hold excess water and stops when excess water has completely drained. In this case, while data in the specific time on the measured days are perfectly fitting each other, the case might not be the same in other times or other days. The maize yield from this treatment was 3,910 kg/ha. When compared with yields from other treatments, the maize yield of this treatment represents about 56% of the maize yield obtained from a treatment that received 125% of TNPRA with the same water application regime (Figure 8.1). In terms of nitrogen fertilizer economic returns, 75% cost of buying fertilizer was saved to obtain 56% of maize yield. Economically this is huge savings of money to buy nitrogen fertilizer, but huge benefits were also realized in savings to hazardous environmental impacts that would have occurred due to N leaching. Maize yield obtained from this treatment was 3,460 kg/ha.

Figure 8.7 represents the temporal distribution of nitrogen below 90cm deep on a treatment that received 40% of the full water requirement regime and 115% of the typical nitrogen application rate in the area. The MAD and RMSD of the simulated and observed data for this treatment were 0.17 and 0.18 respectively. Figure 8.7 indicate that there was no leaching from simulated data by EU-Rotate_N model. The graph line has remained at zero leaching throughout the maize growing season.

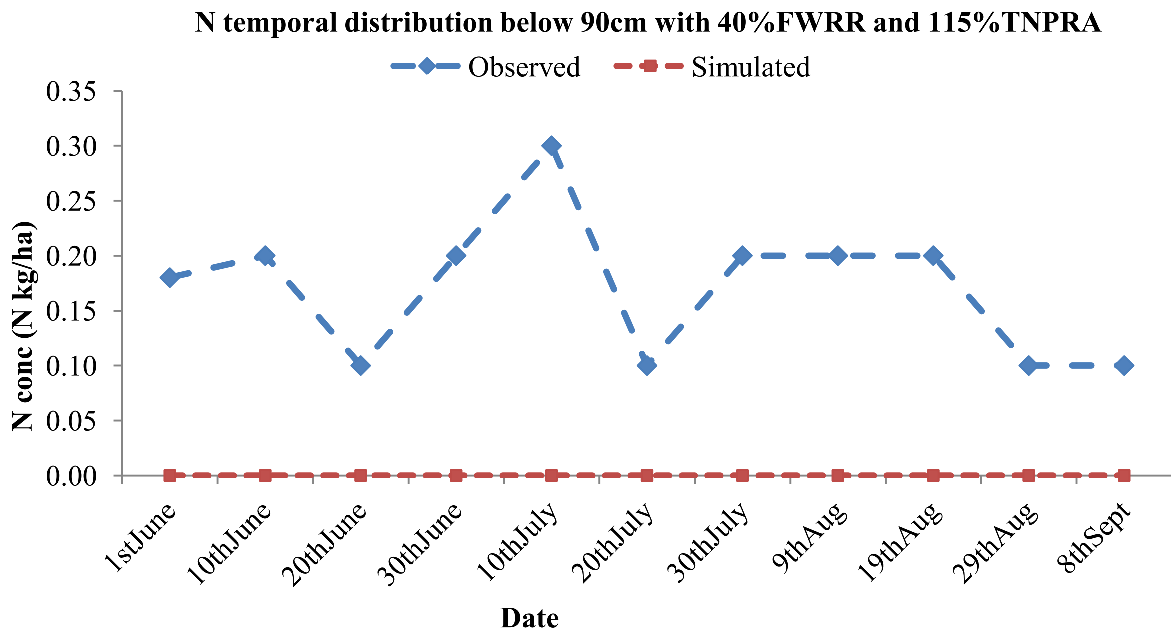


Figure 8.7: Temporal distribution of nitrogen below 90cm with 40%FWRR and 115%TNPRA

While for observed data indicates that 100cm, some nitrogen level were measured by the Triscan Sensor (EnviroScan, Sentek Pty Ltd, Stepney, Australia). However, this has reamined considerably low, the highest was observed on 10th July, 2012 and 0.3 N kg/ha. This shows that this was resident nitrogen content at this point, so there was no additional nitrogen added by percolating water. EU-Rotate_N model simulated nitrogen lost through leaching only and do not take into consideration the the native nitrogen content of the soil layer. The maize yield of the treatment was 3,690 kg/ha which was 53% and 66% reduction if compared to treatments represented by Figures 8.1 and 8.4 respectively which received some amount of nitrogen with different applied water contents. This treatment therefore does not offer good choice when water for maize production is limited. When compared to treatments that received same amount of water (40% of FWRR), the difference present only 12% and 18% to treatments that received smae water content but different nitrogen regime, with later receiving 100% of TNPRA and the other one receiving 75% of TNPRA. So while there was no N leaching but does not offer optimal option that can increase maize yield.

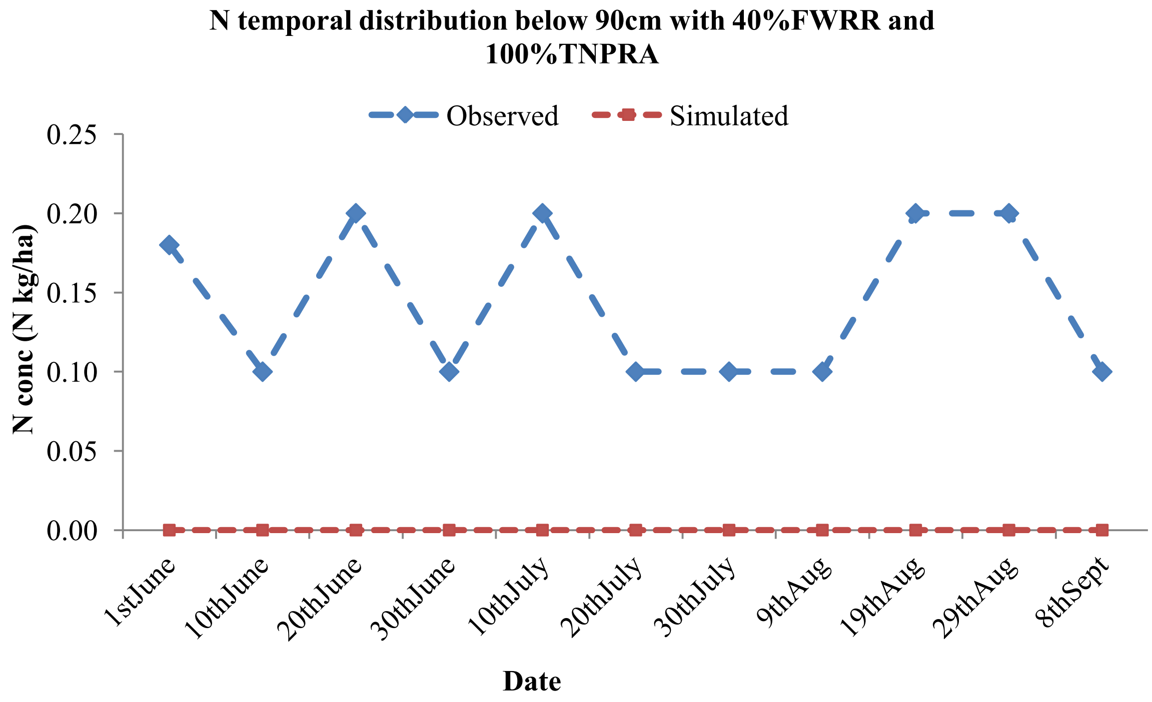


Figure 8.8: Temporal distribution of nitrogen below 90cm with 40%FWRR and 100%TNPRA

Figure 8.8 represents the temporal distribution of nitrogen below 90cm deep on a treatment that received 40% of the full water requirement regime and 100% of the typical nitrogen application rate in the area. The MAD and RMSD of the simulated and observed data for this treatment were 0.14 and 0.15 respectively. Observed data of Figure 8.8 shows that nitrogen contents at 100cm deep was consistently below 0.2 N kg/ha throughout the growing season. Simulated data of Figure 8.8 indicates that there was no nitrogen leaching throughout the growing season. The maize yield of the treatment was 3,470 kg/ha. This yield when compared to treatment represented by Figure 8.7 above, the difference in maize yield was 720 kg/ha which represent 12% reduction in maize yield. Reduction of nitrogen application regime by 25% resulted into reduction of maize yield by 12%.

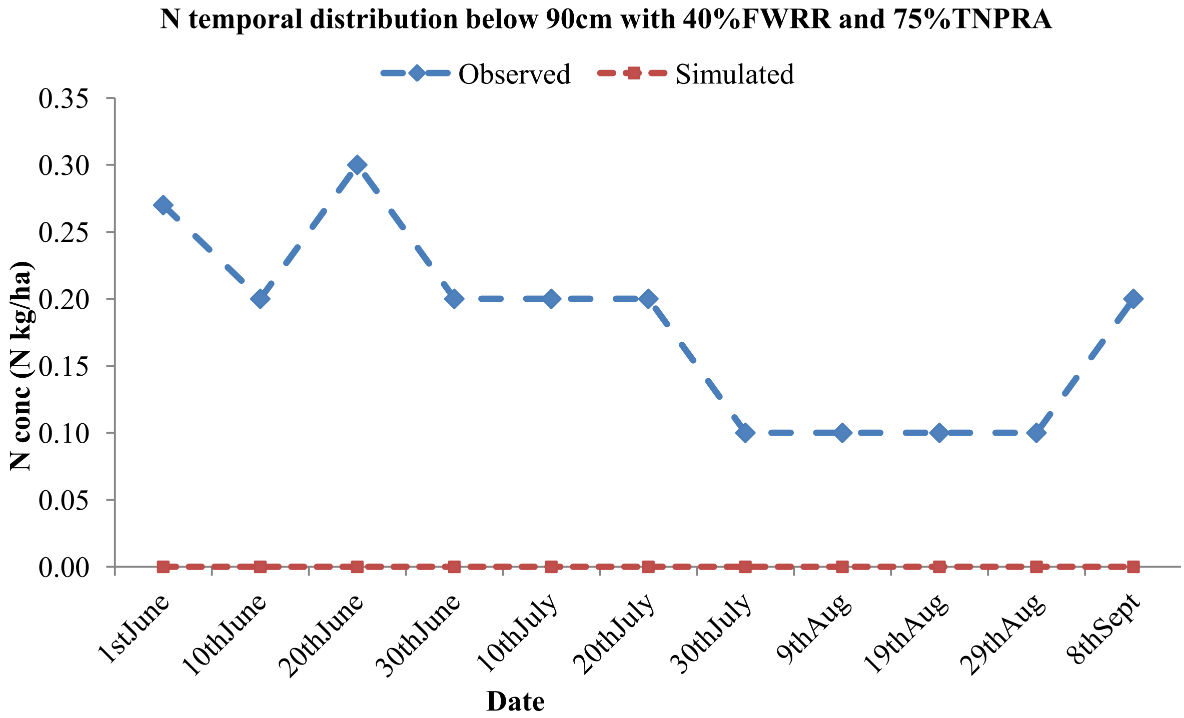


Figure 8.9: Temporal distribution of nitrogen below 90cm with 40%FWRR and 75%TNPRA

Figure 8.9 represents the temporal distribution of nitrogen below 90cm deep on a treatment that received 40% of the full water requirement regime and 75% of the typical nitrogen application rate in the area. The MAD and RMSD of the simulated and observed data for this treatment were 0.18 and 0.19 respectively. The simulated data from the model indicate that there was no leaching and observed data indicates that nitrogen content increased at the beginning and started to decline towards the end of growing season. Mthandi *et al.,* (2013) reported that plant roots develop surviving strategy to respond to the degree of water availability. They reported that plant roots develop of long roots so that it can tap water at lower depths but when soil moisture is available plant roots will convert the energy saved into yield and roots do not grow longer. So this may be the reason why nitrogen content is declining instead of increasing at 100 cm – the plant roots have developed so deep that they are able to tap water together with nitrogen at that level. The maize yield of this treatment was 3, 240 kg/ha which is only 18% reduction of yield obtained in a treatment that received same amount of water and 125% of TNPRA. This means that 50% reduction in applied nitrogen resulted into 18% reduction in maize yield. When N leaching Figure 8.9 is compared with Figure 8.8, it shows that in both treatments there was no N leaching when simulated data are used. When observed data are used to compare the two, it will be shown that both had their nitrogen contents declined meaning that maize developed long roots to be able to tap water at deeper depth.

8.4 Conclusion and Recommendations

8.4.1 Conclusion

The paper presents the findings of observed and simulated N temporal distribution below 90 cm of soil depth. Three water application regimes used in the study area were 84, 51, and 32 mm of water which was applied at interval of 10 days. The nitrogen application regimes used in the study were 115, 92, 69 N kg/ha. The EU-Rotate_N model was used to simulate temporal N distribution.

The study concluded that observed and simulated data had similar trends in plots that received 84 and 51 mm of water, but had completely different trend in plots that received 32 mm of water. It was observed that the model did not register N leaching in plots that received 32mm of water while observed data showed that no leaching occurred in these plots. It was explained that EU-Rotate_N model only considers the additional N added to the layer below 90 cm and resident N in the soil layers below 90cm is not considered as N leaching. The observed data on the other hand registered nitrogen concentration which was noted as N leaching from upper layers.

The study observed that EU-Rotate_N model can be adequately be used to predict nitrogen loss through leaching only when the simulated data are not showing zeros. This model is therefore powerful decision support tool which can be used to minimise N losses.
Great caution should be taken though. The focus should not only be aimed at having zero N leaching. The optimal amount of water and nitrogen should be applied to maize to maximise its production while reducing N leaching. The treatments that received 40% of FWRR did not experience N leaching (predicted by the model), yet had lowest maize yield.

8.4.2 Recommendations

This section presents the management options that can be used to reduce N leaching from irrigated maize production. These options have been identified using the field work and from the N leaching simulation by using EU-Rotate_N model.

i. Amount of water applied to maize should tally with what is needed by plant roots, for example during development stage, less amount of water applied to maize crop can be useful to its development while reducing N leaching. The study concluded that water application regime has huge influence on N leaching, the higher the amount of applied, the higher N leaching will occur.
ii. Apply N fertilizer in small bits than applying twice at basal and top dressing. The study noted that applying high amount of N fertilizer at once result into more

losses through leaching. Plant roots will only absorb nitrogen it requires leaving excess N to be leached by water below the active rooting zone.

iii. N leaching is simply defined as N which is below active root zone of a crop. This means that for shallow-rooted crops, N leaching can be below few depth of soil while deep-rooted crops, N leaching can be below far deeper. In this case, N leaching can be managed by rotating shallow- and deep-rooted crops. Intercropping of shallow- and deep-rooted crops can also manage N leaching. This is because deep-rooted crops can be efficiently absorb nitrogen which has 'leached' from shallow-rooted crops.

References

FOASTAT. 2000. Maize. http://www.fao.org/nr/water/cropinfo_maize.html accessed on 14th May, 2013

Holland, H. K., and Schepers, S. J. 2010. Derivation of a Variable Rate Nitrogen Application Model for In-Season Fertilization of Corn. Published in Agronomy Journal. 102: 1415 -1427 (2010)

Jansen, B. H. 1999. Efficient use of nutrients: An art of balancing. Field Crops Research 56: 197-201.

Kanyama-Phiri, G. Y., and Snapp, S. S. 1998. Developing improved organic matter technologies in partnership with smallholder farmers in southern Malawi. A paper presented at the First All Africa Crop Science Congress Africa Crop Science, 13–17 January 1997. Pretoria, South Africa

Malhi, S. S., Johnston, A. M., Gill, K. S., Pennock, D. J. 2004. Landscape position effects on the recovery of 15N-labelled urea applied to wheat on two soils in Saskatchewan, Canada. Nutrient Cycling Agro ecosyst. 68: 85-93.

Ministry of Agriculture and Food Security (MoAFS). 2011. Annual reports and notes. Lilongwe, Malawi.

Mloza-Banda, H. R. 1994. Principles and practices of crop management. A field study guide.- Bunda College of Agriculture, Lilongwe, Malawi.

Morin, J. 1993. Soil Crusting and Sealing in West Africa and Possible Approaches to improved management. In: Soil tillage in Africa: needs and challenges. FAO Soils Bulletin: 65: 95-128.

Mthandi, J., Kahimba, F. C., Tarimo, A. K. P. R., Salim, B. A., Lowole, M. 2013. Temporal Distribution of Total Nitrogen Concentration in Rootzone of Maize (*Zea mays L.*). Journal of Experimental Biology and Agricultural Sciences, September - 2013; Volume – 1(4). http://www.jebas.org. ISSN No. 2320 – 8694

Nielsen, D. R., van Genuchten, M. T., and Biggar, J. W. 1986. Water flow andsolute transport processes in the unsaturated zone. Water Resour. Res. 22: 89108.

Nyiraneza, J., N'Dayegamiye, A., Gasser, O. M., Giroux, M., Grenier, M., Landry, C., and Guertin, S. 2010. Soil and Crop Parameters related to corn nitrogen response in Eastern Canada. Published in Agronomy Journal 102: 1478 -1490 (2010)

Randall, G. W., and Mulla, D. J. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. *J. Environ. Qual.* 30(2): 337-344

Saito, M. 1990. Mineralization of soil organic nitrogen and its movement in an Andisol under field conditions. Bulletin of the Tohoku Natl. Agric. Exp. Stn. 82: 63

Sørensen, J. 2010. Nitrogen distribution and potential nitrate leaching in a combined production system of energy crops and free range pigs. Master of Science Thesis. Aarhus University. Department of Agroecology and Environment. The Faculty of Agricultural Sciences Department of Biology. Faculty of Science.

Stevenson, F. J. 1986. Cycles of Soil, carbon, nitrogen, phosphorus, sulfur, micronutrients. New York: Willey. 1986.

Thiombiano, L., Bationo. A., Hartemink, A., Lungu. O., Naimi, M., Okoth, P. 2006. African Soils: Their Productivity and Profitability of Fertilizer Use. Background Paper presented for the African Fertilizer Summit. June, 2006 Abuja, Nigeria.

Xu, Y., Chin, M., Zhou, X. 2013. A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems. Global Ecology and Biogeography 22:737-749.

Zotarelli, L., Scholberg, J. M., Dukes, M. D., Mun˜oz-Carpena, R. 2007. Monitoring of nitrate leaching in sandy soils: comparison of three methods. J. Environ. Qual. 36 (4), 953–962.

Zumani, W. U., Arshad, M., Saleem, A. 2001. Distribution of Nitrate-Nitrogen in the soil profile under different irrigation methods. International Journal of Agriculture and Biology. 1560-8530/2001/03-2-208-209. http://www.ijab.org.

CHAPTER THREE

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

The aim of the study was to develop management options for optimizing water and nitrogen utilization for enhanced maize crop productivity. The specifically objectives were: To evaluate the agronomic response of maize to different water and N application regimes; To determine the lateral and vertical movement of nitrogen under different irrigation regimes; and To model the distribution pattern of nitrogen in the maize root zone. The study was conducted in Nkango Irrigation Scheme in Kasungu district, Malawi. The general conclusions of the study are as follows:

To increase WUE, maize should receive more water during its reproductive stage, which is mid-growth stage than during its vegetative growth stage, and again decrease amount of water in its late-stage. To increase NUE, it is very important to know when to apply nitrogen to maize plants in coarse-textured soils, high amount of N should be applied few days after the start of its reproductive stage to minimise chances of being leached because N moves quickly with water flow.

In fine-textured soils, high amount of N should be applied few days before the start of maize reproductive stages so that it can move down and be absorbed by maize roots before the end of its reproductive stage. Vertical movement of nitrogen is influenced by water flux, while direction of flow is greatly influenced by absorption rate of plant roots due to gradient created by absorption.

When supply of nitrogen is low due to high absorption of plant roots, especially during the period when plants require large quantities of nitrogen, the lateral movement of nitrogen towards plant roots is greatly influenced by diffusion. To minimize losses of nitrogen through leaching and ensure that nitrogen is deposited within active root zone, a plant should not receive water after physiological maturity. The study established the fact that when the plant leaves are not fully developed water loss is greatly influenced by evaporation from the uncovered soil surfaces. This loss of water therefore reduces ability to dissolve and move nitrogen.

When plant leaves are fully developed and soil surface is covered, an evaporation loss is minimized and high losses of N are through leaching. The pulling effect by plant roots is created by negative gradient due to water uptake. Nitrogen therefore moves towards the plant roots through water flux. However, when the plant demand of nitrogen is surpassing availability of nitrogen in the soil, plant roots create an environment which facilitates movement of nitrogen through diffusion. In this case, nitrogen will still move towards plant roots even though the region next to roots has high concentration of nitrogen.

Maize roots over time reduce their ability and capacity to absorb nitrogen from surrounding soil mass. The reduced capacity of roots to absorb nitrogen induces maize plant to start re-mobilizing nitrogen from old leaves to new leaves as evidenced from literature. The soil moisture redistribution in the root zone is directly related to the amount of applied irrigation water and spatial distribution of soil moisture content was primarily influenced by roots water uptake and evaporation.

In irrigated maize production, N leaching can be reduced if water applied to maize crop is reduced. The study found that treatments that received 60% of required crop water reduced N leaching by 20% compared to treatments that received 100% of required crop water, even though yield difference of two (in treatments that received same N dosage of 92 kg N/ha) was 11%.

3.2 Recommendations

i. The study was conducted in sandy loam soils. Further study needs to be done in different types of soil to establish the maize responses to different levels of water and nitrogen for different types of soils.

ii. While it was not economicaly viable to apply 125% of TNPRA in the study, technically the treatment gave very good insight of behaviour of nitrogen in the soil when its content is 'high'. It is therefore recommended that further study needs to be done in which two or more treatments with high nitrogen application levels than TNPRA will be tested so as to know behaviour of nitrogen in soil when its application content is high.

iii. Further study needs to be done on the pulling effect of plant roots. Maize at different stages has different pulling effects. The study needs to unearth whether the pulling effect is also influenced by soil types, soil moisture contents, availability of nitrogen in the soil etc., and to what extent does pulling effect affects the movement of solutes in the soil.

iv. Amount of water applied to maize should tally with what is needed by plant roots, for example during development stage, less amount of water applied to maize crop can be useful to its development while reducing N leaching. The study concluded that water application regime has huge influence on N leaching, the higher the amount of applied, the higher N leaching will occur.

v. N leaching is simply defined as N which is below active root zone of a crop. This means that for shallow-rooted crops, N leaching can be below few depth of soil while deep-rooted crops, N leaching can be below far deeper. In this case, N leaching can be managed by rotating shallow- and deep-rooted crops. Intercropping of shallow- and deep-rooted crops can also manage N leaching. This is because deep-rooted crops can be efficiently absorbing nitrogen which has ‘leached’ from shallow-rooted crops.

vi. Maize have fibrous root system and most of the active roots (from literature review about 40% of active roots) are concentrated within top layers above 20 cm, meaning that most of maize roots active absorption takes place in top layers. This means that once N has gone below this layer, it has more chances of not being absorbed by maize roots. In this case, intercropping of maize with deep-rooted crops such as pigeon peas can maximise use efficiency of applied N and reduce contamination of groundwater.

APPENDICES

Appendix A 1: Primary Data of Phosphorus and Nitrogen taken on 27th May, 2012

Smple#	Sampled Points	Field point use	Depth of sampling	pH	P (abs)	P (ppm)	Total N abs	Total N (ppm)	Total N (%)	K *μeq g-1*	Mg *μeq g-1*	Ca *μeq g-1*
1	P1	cultivated	0-20	5.2	263	33.206	46	7.360	0.046	1.215	28.964	19.254
2			20-40	4.0	109	14.864	29	5.336	0.029	1.023	29.147	19.647
3			40-60	4.0	82	11.648	33	5.812	0.033	0.854	26.470	16.540
4			60-80	4.7	40	6.646	24	4.740	0.024	0.800	31.295	10.254
5			80-100	5.2	25	4.859	15	3.668	0.015	0.410	36.415	10.235
6	P2	cultivated	0-20	4.9	708	86.208	81	11.529	0.081	2.024	45.987	36.257
7			20-40	4.1	441	54.407	61	9.147	0.061	2.113	55.461	35.981
8			40-60	4.0	371	46.070	58	8.790	0.058	1.065	41.324	29.547
9			60-80	5.0	200	25.703	54	8.313	0.054	0.664	40.369	24.160
10			80-100	4.0	159	20.819	17	3.907	0.017	0.548	35.642	16.798
11	P3	cultivated	0-20	5.0	125	16.770	29	5.336	0.029	1.029	22.354	16.001
12			20-40	5.0	117	15.817	28	5.217	0.028	1.345	26.145	11.336
13			40-60	4.0	72	10.457	27	5.098	0.027	1.110	26.789	9.254
14			60-80	4.1	26	4.979	27	5.097	0.027	1.564	31.546	9.021
15			80-100	4.9	24	4.740	18	4.025	0.018	0.466	33.589	5.327

16	P4	Forest/Virgin	0-20	4.5	165	21.534	59	8.909	0.059	0.996	52.634	26.548
17			20-40	4.5	126	16.889	49	7.717	0.049	0.698	48.951	21.647
18			40-60	5.2	63	9.385	49	7.717	0.049	0.624	54.876	12.540
19			60-80	4.5	30	5.455	43	7.003	0.043	0.425	44.657	12.032
20			80-100	4.1	36	6.170	56	8.551	0.056	0.512	42.658	9.112
21	P5	Forest/Virgin	0-20	4.0	148	19.509	56	8.551	0.056	0.789	41.620	15.475
22			20-40	4.3	41	6.765	35	6.050	0.035	0.725	38.542	13.334
23			40-60	5.0	40	6.646	33	5.812	0.033	0.358	42.375	4.614
24			60-80	4.1	17	3.907	25	4.859	0.025	0.314	29.789	4.019
25			80-100	failed to sample due to too much water								

Appendix A 2: Primary Data of Organic Carbon taken on 27th May, 2012

Smple#	Sampled points	Field point use	Depth of sampling	1st read (mls)	2nd read (mls)	Titre (mls)	Norma	K2Cr07 used	Carbon (%)	C/N ratio	OM (%)
1	P1	cultivated	0-20	33.00	50.00	17.00	8.50	1.50	0.599	13.011	1.0773
2			20-40	15.70	33.20	17.50	8.75	1.25	0.499	17.198	0.89775
3			40-60	40.20	58.60	18.40	9.20	0.80	0.319	9.673	0.57456
4			60-80	3.90	22.40	18.50	9.25	0.75	0.299	12.469	0.53865
5			80-100	21.00	39.90	18.90	9.45	0.55	0.219	14.630	0.39501
6	P2	cultivated	0-20	0.00	15.70	15.70	7.85	2.15	0.858	10.591	1.54413
7			20-40	0.00	16.70	16.70	8.35	1.65	0.658	10.793	1.18503
8			40-60	17.10	35.60	18.50	9.25	0.75	0.299	5.159	0.53865
9			60-80	39.90	59.20	19.30	9.65	0.35	0.140	2.586	0.25137
10			80-100	16.70	36.10	19.40	9.70	0.30	0.120	7.041	0.21546
11	P3	cultivated	0-20	0.00	17.00	17.00	8.50	1.50	0.599	20.638	1.0773
12			20-40	35.60	53.00	17.40	8.70	1.30	0.519	18.525	0.93366
13			40-60	3.00	21.30	18.30	9.15	0.85	0.339	12.561	0.61047
14			60-80	26.00	44.50	18.50	9.25	0.75	0.299	11.083	0.53865
15			80-100	9.20	28.50	19.30	9.65	0.35	0.140	7.758	0.25137
16	P4	Forest/Virgin	0-20	16.10	33.00	16.90	8.45	1.55	0.618	10.482	1.11321
17			20-40	8.60	26.00	17.40	8.70	1.30	0.519	10.586	0.93366
18			40-60	28.50	47.00	18.50	9.25	0.75	0.299	6.107	0.53865
19			60-80	17.00	35.60	18.60	9.30	0.70	0.279	6.495	0.50274

20			80-100	2.00	21.00	19.00	9.50	0.50	0.200	3.563	0.3591
21	P5	Forest/Virgin	0-20	0.00	17.10	17.10	8.55	1.45	0.579	10.331	1.04139
22			20-40	22.40	40.20	17.80	8.90	1.10	0.439	12.540	0.79002
23			40-60	35.60	53.90	18.30	9.15	0.85	0.339	10.277	0.61047
24			60-80	33.20	52.00	18.80	9.40	0.60	0.239	9.576	0.43092
25			80-100								

Appendix A 3: Primary Data of Soil Texture taken on 27th May, 2012

Smple#	Sampled points	Field point use	Depth of sampling	Sand (mls)	Silt (mls)	Sand (%)	Silt (%)	Clay (%)	Textural Class
1	P1	cultivated	0-20	10.5	2.5	70	17	13	Sandy Loam
2			20-40	10.0	2.5	67	17	17	Sandy Loam
3			40-60	10.0	2.0	67	13	20	Sandy Loam
4			60-80	9.0	2.0	60	13	27	Sandy Clay Loam
5			80-100	10.0	1.0	67	7	27	Sandy Clay Loam
6	P2	cultivated	0-20	10.0	2.5	67	17	17	Sandy Loam
7			20-40	10.0	2.0	67	13	20	Sandy Loam
8			40-60	10.0	1.0	67	7	27	Sandy Clay Loam
9			60-80	8.5	2.0	57	13	30	Sandy Clay Loam
10			80-100	8.0	2.5	53	17	30	Sandy Clay Loam
11	P3	cultivated	0-20	10.5	2.0	70	13	17	Sandy Loam
12			20-40	10.5	2.0	70	13	17	Sandy Loam
13			40-60	10.0	2.0	67	13	20	Sandy Loam
14			60-80	10.0	2.0	67	13	20	Sandy Loam
15			80-100	10.0	2.0	67	13	20	Sandy Loam
16	P4	Forest/Virgin	0-20	10.0	2.5	67	17	17	Sandy Loam
17			20-40	10.0	2.5	67	17	17	Sandy Loam
18			40-60	9.5	3.0	63	20	17	Sandy Loam
19			60-80	10.0	2.0	67	13	20	Sandy Loam
20			80-100	10.0	2.0	67	13	20	Sandy Loam

21	P5	Forest/Virgin	0-20	10.0	2.0	67	13	20	Sandy Loam
22			20-40	10.0	2.0	67	13	20	Sandy Loam
23			40-60	10.0	2.5	67	17	17	Sandy Loam
24			60-80	10.0	2.0	67	13	20	Sandy Loam
25			80-100						

Appendix A 4: Primary Data of Soil Moisture Content taken on 27th May, 2012

Sample#	Sampled points	Field point use	Depth of sampling	Tin wt.(g)	Tin wt. + moist soil	Tin wt. + dry soil	Wt of moist soil	Wt. of dry soil	Wt. of moisture	Moisture content(%)	moisture content mm/m	moisture content mm/mm	Soil color using munsell chart	Structure (wet condition)	Consistence (wet conditon)	Plasticity (wet condition)
1	P1	cultivated	0-20	1.24	28.26	27.18	27.02	25.94	1.08	4.163	41.635	0.042	Olive gray	Granular	Loose	None sticky
2			20-40	1.25	24.18	22.29	22.93	21.04	1.89	8.983	89.829	0.090	Olive gray	Granular	Loose	None sticky
3			40-60	1.23	29.03	25.64	27.80	24.41	3.39	13.888	138.878	0.139	Light brownish grey	Granular	Loose	None sticky
4			60-80	1.24	27.53	23.99	26.29	22.75	3.54	15.560	155.604	0.156	Light brownish grey	Slightly blocky	Slightly firm	Slightly sticky
5			80-100	1.25	38.58	32.55	37.33	31.30	6.03	19.265	192.652	0.193	Light brownish grey	Slightly blocky	Slightly firm	Slightly sticky
6	P2	cultivated	0-20	1.26	25.02	24.56	23.76	23.30	0.46	1.974	19.742	0.020	Dark gayish brown	Granular and massive	Loose and friable	None sticky

7			20-40	1.25	22.11	21.33	20.86	20.08	0.78	3.884	38.845	0.039	Dark gray	Granular and massive	Loose and friable	None sticky
8			40-60	1.24	28.20	26.09	26.96	24.85	2.11	8.491	84.909	0.085	Dark gray	Slightly blocky	Slightly firm	Slightly sticky
9			60-80	1.25	38.81	34.22	37.56	32.97	4.59	13.922	139.217	0.139	Light brownish grey	Slightly blocky	Slightly firm	Slightly sticky
10			80-100	1.25	48.39	41.25	47.14	40.00	7.14	17.850	178.500	0.179	Light brownish grey	Slightly blocky	Slightly firm	Slightly sticky
11	P3	cultivated	0-20	1.24	33.01	32.54	31.77	31.30	0.47	1.502	15.016	0.015	Light gray	Granular	Loose	None sticky
12			20-40	1.25	31.00	30.31	29.75	29.06	0.69	2.374	23.744	0.024	White	Granular	Loose	None sticky
13			40-60	1.29	37.04	32.76	35.75	31.47	4.28	13.600	136.003	0.136	White	Granular	Loose	None sticky
14			60-80	1.26	37.18	32.79	35.92	31.53	4.39	13.923	139.232	0.139	White	Granular	Loose	None sticky
15			80-100	1.23	39.28	34.13	38.05	32.90	5.15	15.653	156.535	0.157	White	Granular	Loose	None sticky
16	P4	Forest /Virgin	0-20	1.24	25.24	24.33	24.00	23.09	0.91	3.941	39.411	0.039	Light gray	Massive	Loose	None sticky

17			20-40	1.25	31.19	29.69	29.94	28.44	1.50	5.274	52.743	0.053	Light gray	Massive	Loose	None sticky
18			40-60	1.26	32.47	29.50	31.21	28.24	2.97	10.517	105.170	0.105	White	Granular and massive	Loose and friable	None sticky
19			60-80	1.25	32.83	29.22	31.58	27.97	3.61	12.907	129.067	0.129	White	Granular and massive	Loose and friable	None sticky
20			80-100	1.25	36.03	31.78	34.78	30.53	4.25	13.921	139.207	0.139	White	Granular and massive	Loose and friable	None sticky
21	P5	Forest /Virgin	0-20	1.25	30.88	29.10	29.63	27.85	1.78	6.391	63.914	0.064	Grayish brown	Granular and massive	Loose and friable	None sticky
22			20-40	1.25	34.38	30.77	33.13	29.52	3.61	12.229	122.290	0.122	Light yellowish brown	Granular and massive	Loose and friable	None sticky
23			40-60	1.24	37.18	32.91	35.94	31.67	4.27	13.483	134.828	0.135	White	Granular and massive	Loose and friable	None sticky
24			60-80	1.25	41.87	36.08	40.62	34.83	5.79	16.624	166.236	0.166	White	Granular and massive	Loose and friable	None sticky
25			80-100													

Appendix A 5: Primary Data of Particle Density taken on 27th May, 2012

Smple#	Sampled points	Field point use	Depth of sampling	Wt. of flask (g)	Flask wt.+ soil	Flask + soil+water	Flask wt+ water only	Particle density (g/cm3	Bulk density (g/cm^3)	Total porosity (%)	Field capacity (%)	Wilting point (%)
1	P1	cultivated	0-20	60.47	110.43	191.08	160.12	2.629	1.59	40	20	10
2			20-40	47.34	97.34	177.00	146.62	2.548	1.44	43	21	11
3			40-60	59.08	109.13	189.80	158.68	2.644	1.47	44	23	13
4			60-80	57.63	107.62	188.20	157.60	2.578	1.44	44	24	16
5			80-100	43.19	93.26	173.97	142.93	2.631	1.46	45	25	16
6	P2	cultivated	0-20	64.90	114.90	195.16	164.14	2.634	1.60	39	21	12
7			20-40	53.55	103.56	184.00	153.21	2.602	1.57	40	23	13
8			40-60	65.46	115.54	196.52	165.11	2.682	1.56	42	25	17
9			60-80	66.83	116.68	197.58	166.72	2.625	1.44	45	27	17
10			80-100	68.48	118.48	199.70	168.77	2.622	1.56	41	27	18
11	P3	cultivated	0-20	54.78	104.82	185.70	154.26	2.690	1.45	46	21	12
12			20-40	66.38	116.38	196.70	165.53	2.655	1.47	45	21	12
13			40-60	54.91	104.90	185.77	154.44	2.679	1.44	46	23	13
14			60-80	55.93	105.93	186.32	155.76	2.572	1.43	44	23	13
15			80-100	60.47	111.34	190.86	159.74	2.576	1.44	44	24	13
16	P4	Forest/Virgin	0-20	47.34	97.92	178.06	146.57	2.650	1.45	45	22	13

17			20-40	54.78	105.61	184.76	153.83	2.554	1.45	43	23	11
18			40-60	57.63	107.92	188.06	156.62	2.668	1.45	46	21	12
19			60-80	43.19	93.96	174.01	142.34	2.658	1.52	43	22	12
20			80-100	64.90	115.76	194.33	163.59	2.528	1.52	40	23	13
21	P5	Forest/Virgin	0-20	53.55	104.34	185.21	152.86	2.754	1.54	44	22	14
22			20-40	65.46	116.15	195.75	165.72	2.454	1.53	38	23	14
23			40-60	66.83	117.59	197.90	166.31	2.648	1.52	43	23	14
24			60-80	68.48	119.44	199.94	168.40	2.624	1.44	45	23	14
25			80-100									

Appendix B 1: Raw Data of Total Nitrogen collected during first Growing Season of 2012

N applied of 15 June

Planting on 1st June,2012

N applied on 11 July

		Total N%				**10-Jul**					**20-Jul**				
Plots	**Depth (cm)**	**1-Jun-12**	**10-Jun-12**	**20 June,**	**30 June,**	Lateral Distance (cm)					Lateral Distance (cm)				
						15	10	5	0	5	15	10	5	0	5
T1	20	0.046	0.05	0.03	0.03	0.06	0.30	0.50	0.46	0.16	0.08	0.10	0.20	0.13	0.16
	40	0.029	0.03	0.04	0.03	0.09	0.02	0.14	0.32	0.12	0.05	0.16	0.09	0.09	0.07
	60	0.033	0.04	0.04	0.03	0.03	0.06	0.09	0.08	0.09	0.04	0.08	0.10	0.06	0.02
	80	0.024	0.03	0.04	0.03	0.05	0.06	0.04	0.06	0.12	0.03	0.04	0.06	0.03	0.02
	100	0.015	0.02	0.03	0.02	0.06	0.06	0.60	0.05	0.07	0.02	0.03	0.01	0.07	0.08
T2	20	0.081	0.08	0.08	0.07	0.24	0.12	0.10	0.28	0.12	0.22	0.20	0.25	0.26	0.18
	40	0.061	0.07	0.06	0.04	0.19	0.11	0.09	0.23	0.10	0.21	0.18	0.23	0.25	0.16
	60	0.058	0.07	0.05	0.06	0.11	0.10	0.08	0.16	0.10	0.20	0.17	0.20	0.20	0.14
	80	0.054	0.05	0.04	0.06	0.10	0.10	0.07	0.12	0.09	0.18	0.14	0.20	0.17	0.13
	100	0.017	0.04	0.03	0.05	0.10	0.07	0.06	0.10	0.08	0.13	0.14	0.18	0.18	0.11
T3	20	0.029	0.03	0.04	0.04	0.08	0.10	0.17	0.29	0.18	0.11	0.12	0.20	0.24	0.14
	40	0.028	0.03	0.04	0.03	0.07	0.09	0.14	0.21	0.17	0.10	0.14	0.19	0.25	0.18

	60	0.027	0.02	0.04	0.02	0.06	0.08	0.11	0.09	0.10	0.09	0.10	0.19	0.22	0.16
	80	0.027	0.03	0.03	0.03	0.05	0.06	0.10	0.08	0.10	0.08	0.09	0.10	0.11	0.10
	100	0.018	0.02	0.03	0.03	0.05	0.07	0.10	0.07	0.09	0.07	0.10	0.10	0.09	0.08
T4	20	0.059	0.07	0.07	0.05	0.16	0.14	0.12	0.15	0.15	0.14	0.08	0.21	0.17	0.09
	40	0.049	0.06	0.06	0.04	0.18	0.16	0.17	0.15	0.17	0.15	0.10	0.18	0.14	0.07
	60	0.049	0.07	0.07	0.05	0.18	0.18	0.16	0.17	0.19	0.15	0.12	0.19	0.13	0.09
	80	0.043	0.05	0.03	0.02	0.14	0.14	0.11	0.14	0.18	0.15	0.17	0.18	0.14	0.11
	100	0.056	0.07	0.06	0.04	0.11	0.13	0.15	0.10	0.18	0.15	0.15	0.13	0.10	0.09
T5	20	0.056	0.07	0.07	0.08	0.13	0.14	0.12	0.23	0.15	0.11	0.12	0.18	0.17	0.17
	40	0.035	0.04	0.04	0.03	0.10	0.07	0.07	0.12	0.08	0.09	0.10	0.09	0.15	0.15
	60	0.033	0.05	0.03	0.02	0.09	0.06	0.05	0.09	0.07	0.09	0.07	0.07	0.13	0.10
	80	0.025	0.03	0.04	0.03	0.04	0.05	0.04	0.07	0.05	0.08	0.06	0.06	0.08	0.09
	100					0.05	0.05	0.03	0.05	0.04	0.08	0.05	0.05	0.06	0.06
T6	20	0.034	0.03	0.04	0.03	0.09	0.11	0.09	0.20	0.19	0.15	0.16	0.20	0.18	0.15
	40	0.056	0.06	0.06	0.05	0.09	0.10	0.01	0.20	0.13	0.13	0.18	0.14	0.16	0.15
	60	0.026	0.04	0.04	0.03	0.08	0.09	0.11	0.16	0.11	0.12	0.19	0.19	0.14	0.14
	80	0.028	0.04	0.03	0.02	0.08	0.09	0.10	0.13	0.10	0.11	0.18	0.16	0.17	0.12
	100	0.017	0.02	0.03	0.02	0.07	0.08	0.06	0.10	0.08	0.09	0.14	0.13	0.18	0.10
T7	20	0.045	0.05	0.05	0.04	0.07	0.09	0.10	0.25	0.11	0.08	0.10	0.10	0.23	0.14

	40	0.019	0.03	0.03	0.03	0.06	0.08	0.08	0.20	0.10	0.07	0.09	0.01	0.22	0.13
	60	0.023	0.04	0.05	0.04	0.06	0.07	0.07	0.09	0.09	0.06	0.09	0.10	0.22	0.18
	80	0.036	0.04	0.03	0.03	0.05	0.06	0.07	0.08	0.06	0.05	0.08	0.09	0.08	0.09
	100	0.018	0.03	0.04	0.03	0.05	0.07	0.06	0.07	0.06	0.04	0.08	0.09	0.08	0.08
T8	20	0.047	0.05	0.05	0.04	0.15	0.13	0.11	0.20	0.16	0.15	0.15	0.12	0.17	0.12
	40	0.039	0.04	0.04	0.04	0.14	0.12	0.11	0.19	0.18	0.16	0.13	0.17	0.14	0.13
	60	0.053	0.06	0.05	0.04	0.09	0.10	0.10	0.08	0.15	0.15	0.14	0.16	0.12	0.12
	80	0.018	0.02	0.03	0.03	0.08	0.09	0.08	0.13	0.10	0.14	0.12	0.16	0.15	0.11
	100	0.024	0.03	0.03	0.02	0.11	0.07	0.08	0.09	0.07	0.11	0.12	0.13	0.11	0.09
T9	20	0.031	0.03	0.04	0.02	0.08	0.10	0.10	0.15	0.11	0.15	0.14	0.17	0.18	0.16
	40	0.054	0.06	0.06	0.05	0.08	0.09	0.10	0.12	0.08	0.12	0.13	0.14	0.15	0.14
	60	0.037	0.04	0.05	0.05	0.07	0.08	0.08	0.10	0.07	0.11	0.10	0.11	0.13	0.10
	80	0.029	0.03	0.04	0.03	0.06	0.07	0.08	0.08	0.05	0.09	0.09	0.10	0.09	0.09
	100	0.021	0.04	0.05	0.04	0.05	0.05	0.06	0.07	0.05	0.09	0.10	0.09	0.07	0.06
T10	20	0.053	0.06	0.07	0.05	0.09	0.12	0.14	0.18	0.13	0.13	0.12	0.17	0.16	0.14
	40	0.031	0.04	0.05	0.03	0.09	0.11	0.11	0.13	0.13	0.12	0.13	0.16	0.14	0.14
	60	0.037	0.04	0.05	0.03	0.10	0.10	0.12	0.14	0.12	0.13	0.14	0.14	0.14	0.15
	80	0.02	0.03	0.04	0.03	0.11	0.10	0.11	0.13	0.10	0.12	0.15	0.14	0.16	0.13
	100					0.11	0.09	0.09	0.10	0.10	0.12	0.14	0.13	0.13	0.16

T11	20	0.019	0.03	0.03	0.02	0.07	0.07	0.08	0.19	0.12	0.08	0.08	0.10	0.15	0.11
	40	0.017	0.03	0.03	0.04	0.06	0.07	0.07	0.09	0.10	0.07	0.10	0.12	0.16	0.11
	60	0.028	0.03	0.03	0.03	0.05	0.07	0.07	0.07	0.10	0.07	0.10	0.11	0.15	0.10
	80	0.033	0.03	0.04	0.03	0.05	0.05	0.06	0.06	0.09	0.07	0.10	0.10	0.11	0.10
	100	0.027	0.02	0.03	0.02	0.04	0.05	0.06	0.05	0.09	0.06	0.10	0.09	0.10	0.09
T12	20	0.089	0.04	0.04	0.03	0.15	0.13	0.15	0.16	0.12	0.15	0.14	0.12	0.15	0.12
	40	0.048	0.05	0.06	0.05	0.12	0.12	0.12	0.14	0.13	0.16	0.14	0.15	0.14	0.13
	60	0.059	0.06	0.05	0.05	0.11	0.10	0.11	0.11	0.10	0.10	0.13	0.14	0.14	0.14
	80	0.061	0.06	0.07	0.03	0.10	0.10	0.10	0.10	0.11	0.12	0.12	0.14	0.13	0.12
	100	0.042	0.05	0.05	0.04	0.11	0.09	0.10	0.10	0.10	0.12	0.11	0.12	0.12	0.11
T13	20	0.026	0.03	0.05	0.03	0.06	0.08	0.10	0.13	0.10	0.09	0.09	0.12	0.14	0.12
	40	0.039	0.04	0.04	0.03	0.05	0.07	0.09	0.12	0.10	0.09	0.09	0.12	0.14	0.11
	60	0.04	0.05	0.05	0.05	0.05	0.05	0.08	0.10	0.10	0.08	0.10	0.10	0.12	0.10
	80	0.026	0.03	0.03	0.02	0.05	0.05	0.07	0.99	0.09	0.07	0.01	0.10	0.10	0.10
	100	0.03	0.04	0.05	0.03	0.04	0.04	0.06	0.95	0.08	0.06	0.11	0.10	0.10	0.10
T14	20	0.051	0.05	0.05	0.03	0.05	0.06	0.10	0.10	0.10	0.06	0.07	0.10	0.11	0.10
	40	0.056	0.06	0.06	0.03	0.05	0.07	0.10	0.10	0.09	0.07	0.07	0.09	0.11	0.10
	60	0.049	0.06	0.07	0.04	0.05	0.07	0.09	0.10	0.09	0.08	0.07	0.10	0.11	0.10
	80	0.063	0.06	0.05	0.03	0.06	0.07	0.10	0.09	0.09	0.08	0.08	0.11	0.12	0.11
	100	0.021	0.03	0.03	0.02	0.06	0.08	0.09	0.09	0.08	0.08	0.09	0.11	0.13	0.12

T15	20	0.031	0.04	0.04	0.02	0.05	0.07	0.08	0.14	0.13	0.07	0.07	0.08	0.12	0.12
	40	0.028	0.03	0.03	0.03	0.05	0.06	0.07	0.09	0.12	0.07	0.07	0.07	0.12	0.12
	60	0.019	0.03	0.04	0.02	0.04	0.05	0.06	0.06	0.07	0.06	0.07	0.07	0.10	0.11
	80	0.021	0.03	0.03	0.03	0.04	0.05	0.06	0.05	0.06	0.05	0.06	0.06	0.07	0.09
	100					0.05	0.05	0.06	0.05	0.06	0.05	0.05	0.06	0.05	0.08
T16	20	0.017	0.02	0.02	0.04	0.07	0.05	0.08	0.12	0.12	0.07	0.08	0.07	0.01	0.01
	40	0.034	0.04	0.04	0.03	0.07	0.06	0.08	0.01	0.13	0.07	0.08	0.07	0.09	0.01
	60	0.041	0.05	0.05	0.03	0.07	0.07	0.07	0.02	0.10	0.08	0.09	0.06	0.19	0.10
	80	0.049	0.05	0.05	0.04	0.06	0.07	0.06	0.10	0.09	0.09	0.09	0.06	0.09	0.10
	100	0.059	0.06	0.06	0.05	0.07	0.08	0.06	0.10	0.09	0.09	0.10	0.05	0.09	0.10

Appendix B 2: Raw Data of Total Nitrogen collected during first Growing Season

		30-Jul					**9-Aug**					**19-Aug**				
	Depth															
Plots	**(cm)**	**Lateral Distance (cm)**					**Lateral Distance (cm)**					**Lateral Distance (cm)**				
		15	10	5	0	5	15	10	5	0	5	15	10	5	0	5
T1	20	0.25	0.19	0.27	0.18	0.14	0.19	0.18	0.18	0.17	0.13	0.16	0.16	0.15	0.17	0.12
	40	0.16	0.17	0.22	0.18	0.13	0.15	0.20	0.16	0.19	0.10	0.12	0.16	0.16	0.16	0.14
	60	0.15	0.18	0.21	0.15	0.11	0.16	0.18	0.15	0.16	0.11	0.14	0.14	0.17	0.16	0.15
	80	0.09	0.17	0.18	0.13	0.10	0.13	0.17	0.16	0.18	0.10	0.09	0.11	0.15	0.15	0.14
	100	0.08	0.10	0.10	0.08	0.08	0.10	0.14	0.14	0.11	0.10	0.07	0.76	0.14	0.14	0.14
T2	20	0.20	0.19	0.17	0.17	0.16	0.18	0.20	0.16	0.15	0.15	0.18	0.15	0.13	0.15	0.13
	40	0.19	0.17	0.21	0.18	0.15	0.17	0.19	0.17	0.18	0.16	0.18	0.13	0.15	0.16	0.16
	60	0.20	0.18	0.20	0.20	0.13	0.20	0.19	0.19	0.19	0.15	0.20	0.16	0.15	0.14	0.13
	80	0.22	0.20	0.18	0.20	0.14	0.19	0.20	0.20	0.20	0.15	0.19	0.19	0.14	0.16	0.19
	100	0.18	0.20	0.19	0.19	0.10	0.21	0.20	0.20	0.20	0.19	0.17	0.18	0.17	0.16	0.14
T3	20	0.12	0.12	0.17	0.23	0.12	0.15	0.17	0.21	0.21	0.12	0.17	0.16	0.20	0.22	0.13
	40	0.14	0.17	0.21	0.22	0.14	0.17	0.20	0.20	0.20	0.19	0.16	0.17	0.21	0.22	0.21
	60	0.11	0.13	0.20	0.19	0.16	0.14	0.15	0.17	0.18	0.18	0.18	0.14	0.20	0.20	0.17
	80	0.09	0.11	0.15	0.16	0.14	0.15	0.16	0.15	0.18	0.13	0.17	0.17	0.20	0.19	0.16
	100	0.08	0.09	0.10	0.10	0.11	0.11	0.09	0.12	0.13	0.11	0.14	0.16	0.19	0.20	0.15

T4	20	0.12	0.10	0.09	0.09	0.09	0.10	0.09	0.08	0.09	0.08	0.09	0.07	0.06	0.08	0.07
	40	0.14	0.08	0.10	0.09	0.08	0.10	0.09	0.09	0.09	0.07	0.08	0.10	0.08	0.06	0.09
	60	0.18	0.13	0.11	0.11	0.07	0.13	0.12	0.07	0.10	0.09	0.11	0.13	0.08	0.08	0.15
	80	0.19	0.18	0.11	0.11	0.07	0.13	0.12	0.15	0.10	0.10	0.17	0.14	0.14	0.11	0.13
	100	0.15	0.14	0.10	0.09	0.07	0.18	0.14	0.13	0.09	0.11	0.13	0.11	0.13	0.13	0.12
T5	20	0.23	0.18	0.21	0.16	0.13	0.17	0.18	0.14	0.17	0.13	0.12	0.13	0.12	0.15	0.13
	40	0.15	0.15	0.20	0.16	0.13	0.13	0.17	0.15	0.17	0.17	0.12	0.14	0.15	0.14	0.12
	60	0.12	0.13	0.20	0.15	0.14	0.12	0.14	0.15	0.14	0.14	0.13	0.13	0.15	0.13	0.12
	80	0.13	0.15	0.18	0.13	0.11	0.16	0.13	0.17	0.13	0.11	0.08	0.11	0.14	0.13	0.13
	100	0.07	0.02	0.08	0.10	0.09	0.10	0.13	0.02	0.03	0.09	0.10	0.10	0.13	0.12	0.10
T6	20	0.17	0.19	0.17	0.16	0.16	0.10	0.11	0.16	0.14	0.14	0.09	0.10	0.08	0.07	0.08
	40	0.16	0.18	0.20	0.16	0.18	0.08	0.19	0.17	0.16	0.13	0.08	0.09	0.09	0.08	0.10
	60	0.21	0.18	0.17	0.20	0.15	0.09	0.18	0.17	0.17	0.14	0.09	0.09	0.08	0.08	0.09
	80	0.19	0.17	0.18	0.19	0.14	0.17	0.18	0.19	0.16	0.15	0.10	0.08	0.08	0.08	0.08
	100	0.15	0.17	0.17	0.15	0.11	0.18	0.19	0.14	0.16	0.19	0.10	0.10	0.09	0.10	0.10
T7	20	0.10	0.12	0.16	0.20	0.13	0.12	0.17	0.20	0.20	0.14	0.11	0.15	0.19	0.19	0.11
	40	0.11	0.10	0.14	0.17	0.13	0.16	0.18	0.19	0.19	0.19	0.19	0.18	0.20	0.19	0.12
	60	0.09	0.10	0.12	0.16	0.15	0.14	0.17	0.18	0.17	0.17	0.17	0.14	0.19	0.18	0.11
	80	0.08	0.08	0.10	0.16	0.13	0.16	0.16	0.16	0.15	0.18	0.20	0.17	0.17	0.16	0.10

	100	0.08	0.08	0.09	0.10	0.11	0.10	0.10	0.12	0.12	0.12	0.15	0.17	0.15	0.14	0.10
T8	20	0.12	0.11	0.12	0.12	0.10	0.10	0.09	0.09	0.11	0.08	0.09	0.09	0.07	0.09	0.07
	40	0.14	0.14	0.13	0.14	0.13	0.12	0.12	0.10	0.13	0.10	0.10	0.11	0.09	0.11	0.09
	60	0.16	0.15	0.14	0.14	0.13	0.14	0.12	0.13	0.14	0.11	0.11	0.12	0.09	0.13	0.10
	80	0.15	0.15	0.14	0.15	0.14	0.15	0.14	0.14	0.15	0.13	0.12	0.13	0.12	0.13	0.10
	100	0.15	0.12	0.12	0.13	0.13	0.16	0.15	0.14	0.14	0.12	0.13	0.13	0.13	0.14	0.12
T9	20	0.14	0.13	0.16	0.17	0.14	0.14	0.12	0.14	0.15	0.12	0.12	0.11	0.12	0.13	0.11
	40	0.11	0.12	0.15	0.15	0.13	0.13	0.12	0.14	0.16	0.12	0.12	0.15	0.14	0.13	0.13
	60	0.10	0.12	0.14	0.12	0.12	0.12	0.13	0.14	0.17	0.13	0.13	0.15	0.14	0.13	0.14
	80	0.10	0.10	0.13	0.11	0.11	0.13	0.12	0.15	0.14	0.14	0.14	0.15	0.14	0.13	0.14
	100	0.07	0.10	0.10	0.10	0.10	0.13	0.14	0.13	0.13	0.13	0.14	0.16	0.15	0.14	0.15
T10	20	0.12	0.11	0.10	0.12	0.10	0.10	0.10	0.09	0.10	0.09	0.09	0.09	0.08	0.09	0.08
	40	0.12	0.11	0.12	0.13	0.10	0.10	0.11	0.10	0.10	0.10	0.09	0.10	0.10	0.09	0.10
	60	0.13	0.13	0.12	0.13	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	80	0.13	0.14	0.13	0.14	0.12	0.12	0.12	0.11	0.11	0.11	0.10	0.11	0.10	0.11	0.11
	100	0.14	0.14	0.14	0.15	0.13	0.13	0.13	0.12	0.12	0.12	0.11	0.12	0.10	0.12	0.12
T11	20	0.07	0.08	0.15	0.18	0.13	0.07	0.10	0.14	0.15	0.12	0.07	0.10	0.13	0.14	0.12
	40	0.07	0.09	0.17	0.16	0.13	0.05	0.10	0.14	0.15	0.12	0.07	0.11	0.14	0.14	0.11
	60	0.07	0.09	0.13	0.14	0.12	0.06	0.10	0.14	0.14	0.11	0.05	0.12	0.11	0.12	0.11

	80	0.06	0.09	0.12	0.13	0.10	0.07	0.10	0.11	0.10	0.14	0.08	0.12	0.10	0.11	0.10
	100	0.07	0.08	0.09	0.09	0.09	0.10	0.11	0.12	0.10	0.11	0.08	0.12	0.09	0.10	0.10
T12	20	0.13	0.13	0.12	0.12	0.10	0.12	0.11	0.12	0.10	0.11	0.11	0.10	0.10	0.11	0.10
	40	0.14	0.15	0.13	0.14	0.14	0.13	0.12	0.12	0.13	0.13	0.12	0.12	0.13	0.12	0.10
	60	0.14	0.14	0.14	0.14	0.14	0.13	0.11	0.13	0.13	0.12	0.13	0.13	0.13	0.13	0.12
	80	0.15	0.14	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.14	0.14	0.13	0.12	0.13	0.13
	100	0.15	0.14	0.12	0.13	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.14	0.14
T13	20	0.09	0.09	0.10	0.11	0.10	0.09	0.08	0.09	0.10	0.09	0.08	0.08	0.08	0.10	0.08
	40	0.10	0.09	0.10	0.11	0.10	0.09	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.10	0.09
	60	0.10	0.10	0.11	0.12	0.10	0.09	0.09	0.10	0.11	0.10	0.09	0.09	0.09	0.10	0.09
	80	0.10	0.10	0.11	0.13	0.11	0.10	0.09	0.11	0.11	0.10	0.09	0.09	0.10	0.10	0.09
	100	0.09	0.10	0.12	0.13	0.12	0.10	0.11	0.12	0.12	0.11	0.09	0.10	0.10	0.11	0.10
T14	20	0.08	0.08	0.10	0.12	0.11	0.07	0.07	0.09	0.09	0.09	0.07	0.07	0.07	0.08	0.08
	40	0.08	0.08	0.10	0.11	0.10	0.08	0.08	0.10	0.09	0.09	0.08	0.09	0.08	0.10	0.09
	60	0.09	0.09	0.11	0.10	0.10	0.09	0.09	0.10	0.10	0.09	0.08	0.09	0.09	0.10	0.09
	80	0.09	0.09	0.10	0.10	0.09	0.09	0.09	0.10	0.11	0.10	0.08	0.10	0.09	0.10	0.10
	100	0.09	0.10	0.09	0.10	0.09	0.10	0.09	0.10	0.11	0.10	0.09	0.11	0.10	0.11	0.10
T15	20	0.07	0.08	0.07	0.11	0.10	0.06	0.07	0.09	0.10	0.09	0.06	0.07	0.08	0.10	0.09
	40	0.07	0.08	0.07	0.13	0.10	0.07	0.07	0.09	0.10	0.10	0.06	0.08	0.09	0.09	0.10

	60	0.07	0.08	0.07	0.10	0.09	0.06	0.08	0.09	0.10	0.10	0.07	0.08	0.09	0.10	0.10
	80	0.07	0.08	0.08	0.10	0.10	0.07	0.08	0.10	0.10	0.09	0.07	0.09	0.09	0.10	0.10
	100	0.07	0.07	0.07	0.07	0.09	0.08	0.09	0.10	0.10	0.09	0.08	0.09	0.10	0.10	0.10
T16	20	0.09	0.08	0.08	0.12	0.10	0.08	0.08	0.08	0.10	0.09	0.08	0.07	0.07	0.10	0.09
	40	0.09	0.09	0.09	0.12	0.10	0.09	0.10	0.09	0.11	0.10	0.09	0.09	0.10	0.10	0.10
	60	0.09	0.10	0.10	0.12	0.10	0.09	0.10	0.10	0.11	0.10	0.10	0.09	0.10	0.12	0.10
	80	0.10	0.18	0.08	0.10	0.10	0.10	0.11	0.10	0.11	0.11	0.10	0.10	0.11	0.12	0.11
	100	0.10	0.09	0.09	0.10	0.01	0.09	0.11	0.11	0.12	0.12	0.11	0.11	0.12	0.13	0.12

Appendix B 3: Raw Data of Total Nitrogen collected during first Growing Season of 2012

Plots	Depth (cm)	29-Aug Lateral Distance (cm)					8-Sep Lateral Distance (cm)				
		15	10	5	0	5	15	10	5	0	5
T1	20	0.11	0.14	0.11	0.10	0.09	0.10	0.10	0.10	0.09	0.08
	40	0.10	0.10	0.11	0.11	0.08	0.10	0.11	0.10	0.08	0.09
	60	0.09	0.10	0.11	0.10	0.10	0.11	0.10	0.09	0.01	0.10
	80	0.09	0.08	0.11	0.12	0.08	0.11	0.09	0.08	0.11	0.09
	100	0.08	0.08	0.12	0.10	0.08	0.09	0.07	0.07	0.10	0.07
T2	20	0.12	0.13	0.12	0.13	0.10	0.10	0.10	0.09	0.08	0.09
	40	0.13	0.13	0.18	0.13	0.09	0.11	0.09	0.09	0.07	0.10
	60	0.14	0.13	0.15	0.15	0.10	0.10	0.17	0.10	0.10	0.10
	80	0.15	0.17	0.15	0.15	0.09	0.12	0.11	0.11	0.11	0.11
	100	0.17	0.16	0.13	0.17	0.11	0.15	0.18	0.14	0.12	0.12
T3	20	0.18	0.18	0.14	0.15	0.17	0.15	0.17	0.19	0.18	0.14
	40	0.17	0.22	0.20	0.20	0.20	0.17	0.17	0.20	0.21	0.16
	60	0.20	0.21	0.17	0.19	0.20	0.19	0.19	0.20	0.20	0.17
	80	0.19	0.11	0.19	0.17	0.17	0.17	0.20	0.19	0.20	0.17
	100	0.17	0.15	0.18	0.19	0.15	0.16	0.12	0.19	0.19	0.17
T4	20	0.06	0.07	0.05	0.06	0.06	0.05	0.07	0.07	0.07	0.08
	40	0.07	0.08	0.07	0.06	0.09	0.07	0.08	0.08	0.09	0.08

	60	0.09	0.08	0.08	0.07	0.09	0.08	0.09	0.08	0.08	0.07
	80	0.10	0.09	0.09	0.09	0.10	0.08	0.10	0.11	0.11	0.09
	100	0.09	0.09	0.07	0.09	0.13	0.10	0.10	0.13	0.12	0.11
T5	20	0.10	0.11	0.10	0.09	0.07	0.07	0.07	0.08	0.07	0.08
	40	0.09	0.11	0.10	0.09	0.07	0.07	0.08	0.09	0.09	0.07
	60	0.09	0.09	0.10	0.10	0.09	0.09	0.09	0.08	0.09	0.09
	80	0.08	0.07	0.10	0.11	0.09	0.09	0.08	0.08	0.07	0.09
	100	0.07	0.07	0.11	0.09	0.07	0.08	0.07	0.09	0.08	0.07
T6	20	0.08	0.09	0.08	0.10	0.09	0.08	0.09	0.09	0.07	0.08
	40	0.08	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.07	0.09
	60	0.08	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09
	80	0.09	0.10	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.10
	100	0.10	0.10	0.11	0.11	0.10	0.09	0.10	0.10	0.09	0.10
T7	20	0.14	0.12	0.16	0.12	0.13	0.09	0.10	0.12	0.18	0.12
	40	0.18	0.14	0.18	0.18	0.18	0.09	0.09	0.11	0.17	0.09
	60	0.17	0.16	0.15	0.19	0.15	0.12	0.15	0.18	0.17	0.08
	80	0.12	0.13	0.15	0.15	0.19	0.11	0.13	0.12	0.19	0.08
	100	0.12	0.12	0.12	0.09	0.13	0.10	0.12	0.18	0.18	0.07
T8	20	0.08	0.08	0.08	0.80	0.07	0.07	0.07	0.07	0.07	0.07
	40	0.09	0.09	0.09	0.09	0.07	0.07	0.07	0.07	0.09	0.08
	60	0.10	0.09	0.11	0.11	0.09	0.07	0.10	0.08	0.09	0.08
	80	0.10	0.10	0.11	0.12	0.10	0.10	0.09	0.11	0.09	0.10
	100	0.11	0.12	0.13	0.12	0.12	0.10	0.10	0.11	0.10	0.11

T9	20	0.10	0.10	0.11	0.12	0.10	0.10	0.09	0.09	0.10	0.10
	40	0.12	0.11	0.10	0.11	0.10	0.10	0.09	0.10	0.12	0.10
	60	0.13	0.12	0.12	0.10	0.12	0.10	0.11	0.11	0.13	0.11
	80	0.12	0.13	0.13	0.13	0.13	0.11	0.12	0.12	0.13	0.12
	100	0.12	0.14	0.14	0.14	0.13	0.12	0.12	0.13	0.13	0.14
T10	20	0.08	0.09	0.08	0.09	0.08	0.07	0.08	0.08	0.09	0.08
	40	0.08	0.09	0.08	0.09	0.09	0.08	0.08	0.09	0.09	0.08
	60	0.08	0.09	0.09	0.10	0.09	0.08	0.09	0.10	0.09	0.09
	80	0.09	0.10	0.09	0.10	0.10	0.09	0.09	0.09	0.10	0.09
	100	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
T11	20	0.07	0.10	0.13	0.12	0.10	0.06	0.10	0.12	0.12	0.10
	40	0.06	0.11	0.13	0.13	0.10	0.07	0.10	0.12	0.11	0.11
	60	0.08	0.12	0.12	0.12	0.10	0.07	0.12	0.13	0.12	0.12
	80	0.08	0.11	0.10	0.11	0.10	0.09	0.12	0.14	0.12	0.13
	100	0.09	0.11	0.12	0.10	0.09	0.09	0.12	0.14	0.13	0.13
T12	20	0.09	0.10	0.10	0.09	0.09	0.08	0.07	0.09	0.09	0.08
	40	0.10	0.10	0.12	0.10	0.11	0.09	0.09	0.09	0.09	0.09
	60	0.10	0.11	0.12	0.13	0.11	0.08	0.09	0.10	0.10	0.09
	80	0.10	0.12	0.13	0.13	0.13	0.09	0.10	0.11	0.10	0.11
	100	0.13	0.12	0.16	0.16	0.13	0.11	0.12	0.12	0.10	0.11
T13	20	0.07	0.07	0.07	0.08	0.06	0.06	0.06	0.06	0.06	0.05
	40	0.07	0.07	0.08	0.08	0.07	0.06	0.07	0.07	0.07	0.06
	60	0.08	0.08	0.08	0.09	0.08	0.07	0.07	0.09	0.07	0.06
	80	0.08	0.08	0.09	0.09	0.08	0.08	0.07	0.09	0.08	0.08

	100	0.09	0.09	0.09	0.10	0.10	0.09	0.09	0.10	0.08	0.08
T14	20	0.06	0.07	0.07	0.08	0.07	0.05	0.06	0.06	0.07	0.07
	40	0.07	0.07	0.07	0.08	0.07	0.05	0.06	0.06	0.08	0.07
	60	0.08	0.07	0.07	0.09	0.08	0.07	0.07	0.06	0.08	0.08
	80	0.09	0.08	0.09	0.09	0.09	0.07	0.08	0.10	0.08	0.09
	100	0.10	0.09	0.10	0.10	0.09	0.09	0.09	0.10	0.09	0.09
T15	20	0.06	0.07	0.08	0.09	0.09	0.05	0.06	0.07	0.09	0.09
	40	0.06	0.08	0.09	0.10	0.09	0.06	0.08	0.08	0.09	0.09
	60	0.06	0.09	0.09	0.10	0.10	0.06	0.09	0.09	0.10	0.10
	80	0.07	0.09	0.10	0.10	0.10	0.08	0.09	0.10	0.09	0.09
	100	0.08	0.10	0.10	0.10	0.10	0.08	0.10	0.10	0.10	0.09
T16	20	0.07	0.06	0.07	0.09	0.08	0.07	0.05	0.05	0.09	0.08
	40	0.09	0.08	0.09	0.10	0.09	0.07	0.06	0.06	0.09	0.09
	60	0.09	0.09	0.10	0.10	0.09	0.08	0.08	0.09	0.09	0.09
	80	0.10	0.09	0.10	0.11	0.10	0.09	0.08	0.10	0.10	0.09
	100	0.10	0.10	0.11	0.11	0.10	0.09	0.09	0.10	0.10	0.10

Appendix C. 1: Raw Data of Maize Yield Responses collected during first Growing Season

Water regime		W (mm)	W (m^3)	N (kg/ha)	Y (kg/ha)	W productivity - (Y/W)	N Productivity - (Y/N)	Ears/plants (3replicates)			Kernel/ears (3replicates)			1,000 kernel weight (g) (3 replicates)		
								1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
FB	T1	590	5900	92	3850	7	42	1.02	1.03	1.03	419	418	420	185	187	173
	T2	430	4300	115	3670	9	32	1.03	1.04	1.03	427	426	426	189	183	196
	T3	840	8400	69	2560	3	37	1.01	1.03	1.02	401	340	322	175	183	167
	T4	650	6500	46	1040	2	23	1.04	1.02	1.02	356	332	330	139	128	148
40%	T1	330	3300	92	2640	8	29	1.04	1.01	1.03	356	343	348	176	179	163
	T2	330	3300	115	2890	9	25	1.03	1.02	1.02	344	349	342	179	185	175
	T3	335	3350	69	2130	6	31	1.02	1.02	1.03	336	338	342	167	163	169
	T4	330	3300	46	986	3	21	1.01	1.02	1.02	334	327	322	117	125	112
60%	T1	530	5300	92	3950	7	43	1.03	1.06	1.05	448	436	428	199	192	186
	T2	530	5300	115	4200	8	37	1.04	1.02	1.04	486	473	483	206	213	189
	T3	530	5300	69	2600	5	38	1.02	1.03	1.03	330	341	346	175	168	179
	T4	535	5350	46	1280	2	28	1.01	1.03	1.02	324	329	334	126	135	142
100%	T1	890	8900	92	5120	6	56	1.05	1.07	1.06	502	496	482	227	229	210
	T2	880	8800	115	5830	7	51	1.06	1.04	1.07	498	501	503	241	249	256
	T3	885	8850	69	3450	4	50	1.03	1.05	1.04	476	489	494	195	203	182
	T4	860	8600	46	1350	2	29	1.02	1.03	1.03	362	356	352	182	167	198

Appendix D 1: Main treatment effects

	Treatment levels	Maize yield (Kg/Ha)
Water :application regimes	100 % FWRR	4806
	40 % FWRR	2672
	60 % FWRR	3738
	FPR	3223
Nitrogen (Kgs/Ha)	46 Kgs N/Ha	2143
	69 Kgs N/Ha	3313
	92 Kgs N/Ha	4303
	115 Kgs N/Ha	4680
Grand mean		3609.9
LSD (0.05)		782.3
CV (%)		18.9

Appendix D 2: Water application regime effect on average maize yield

Treatment	Average maize yield (Kg/ha)
100 % FWRR	4805.8 *a*
60 % FWRR	3738.33 *b*
FPR	3223.3 *bc*
40 % FWRR	3672.2 *c*

Means followed by the same letter are not statistically significantly different

Appendix D 3: Interaction of water and nitrogen effect on maize yields

	Nitrogen levels (Kg/ha)			
Water application regimes	**46**	**69**	**92**	**115**
100 % FWRR	2840	4140	5950	6333
40% FWRR	1635	2923	2853	3277
60 % FWRR	2147	3103	4510	5193
FPR	1950	3087	3940	3917

Appendix D 4: Water application regime effects

Water application regime	Effect
100 % FWRR	1195.8
40 % FWRR	-937.8
60 % FWRR	128.4
FPR	-386.6

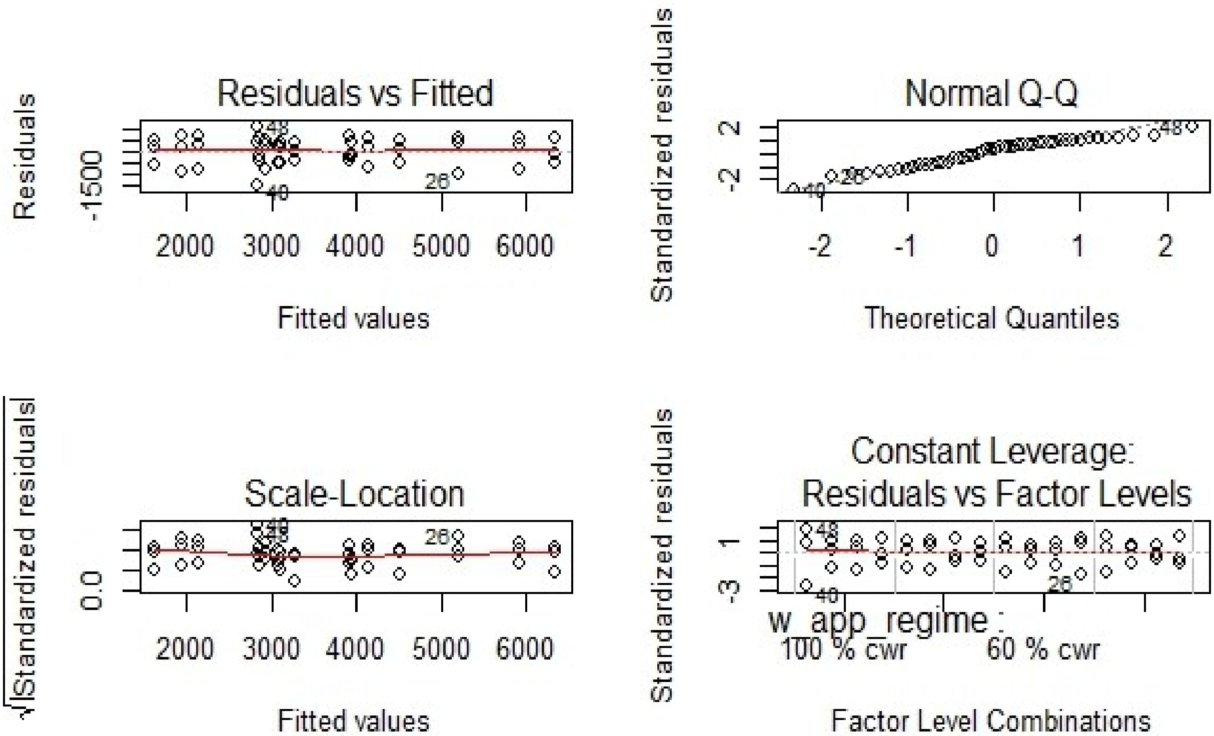
Appendix D 5: Nitrogen level effects

Nitrogen levels (Kg/ha)	Effect
46	-1466.9
69	-296.6
92	693.4
115	1070.1

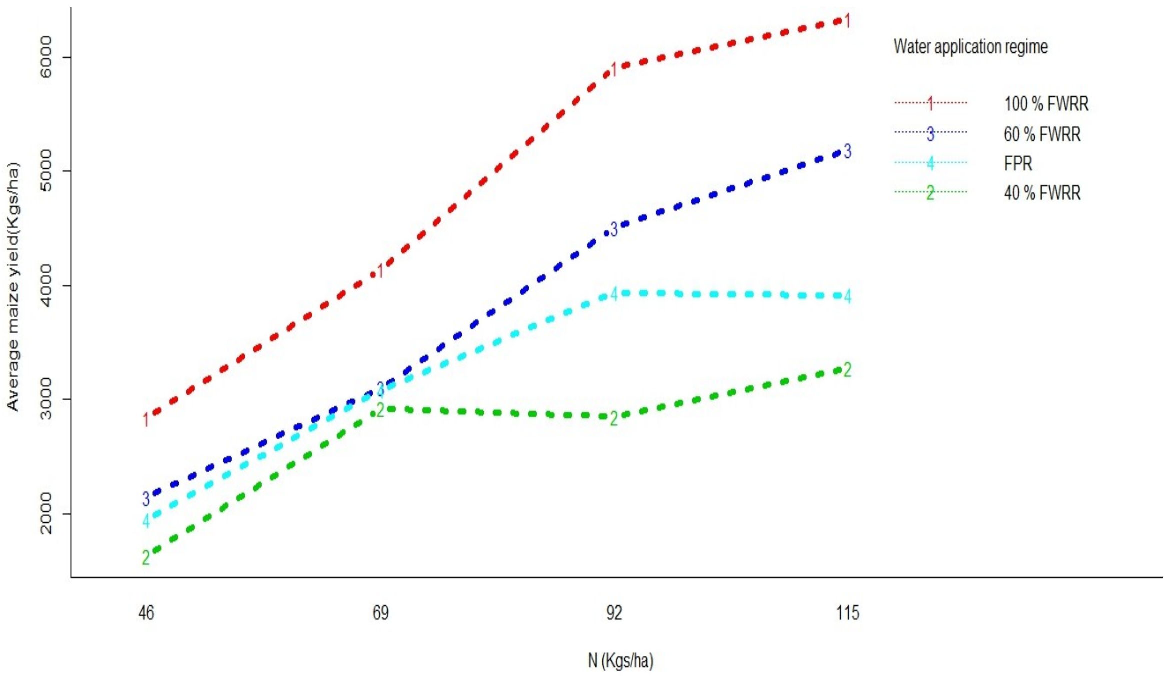
Appendix D 6: Interaction of Water application regimes and Nitrogen level effects

	Nitrogen levels (Kg/ha)			
Water application regime	**46**	**69**	**92**	**115**
100 % FWRR	-498.9	-369.3	410.8	457.4
40 % FWRR	430.1	547.7	-512.2	-465.6
60 % FWRR	-124.8	-338.4	78.3	384.9
FPR	193.6	159.9	23.2	-376.7

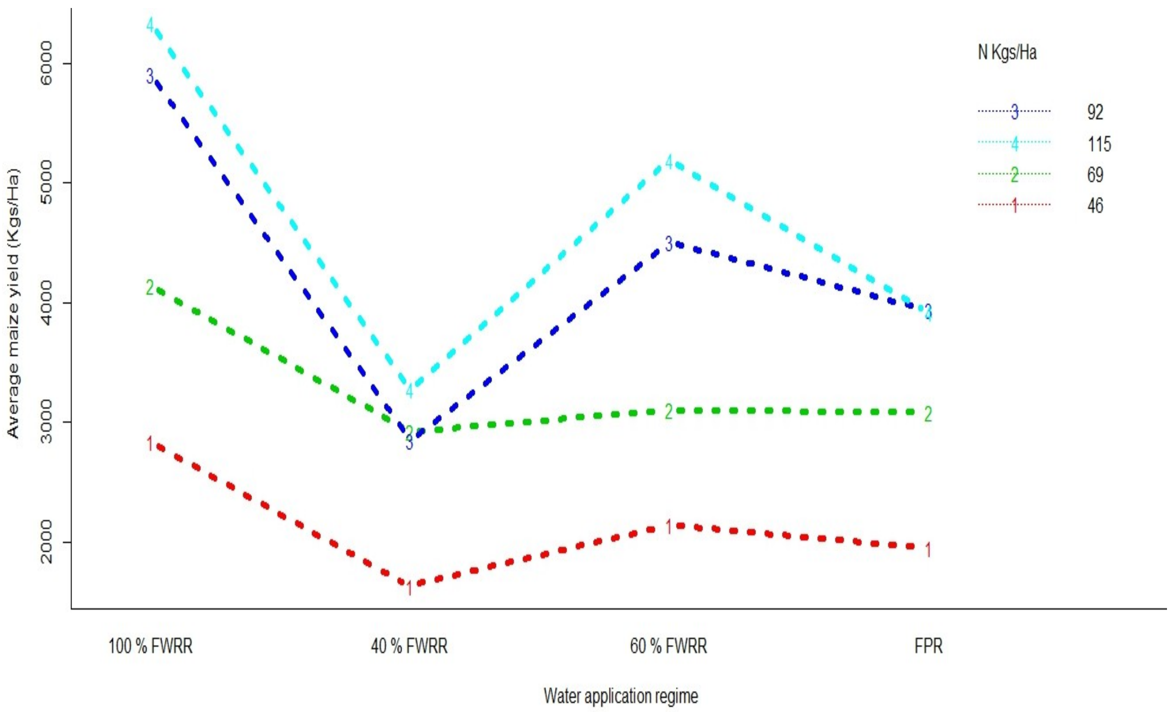
Appendix D 7: Model diagnostic plots



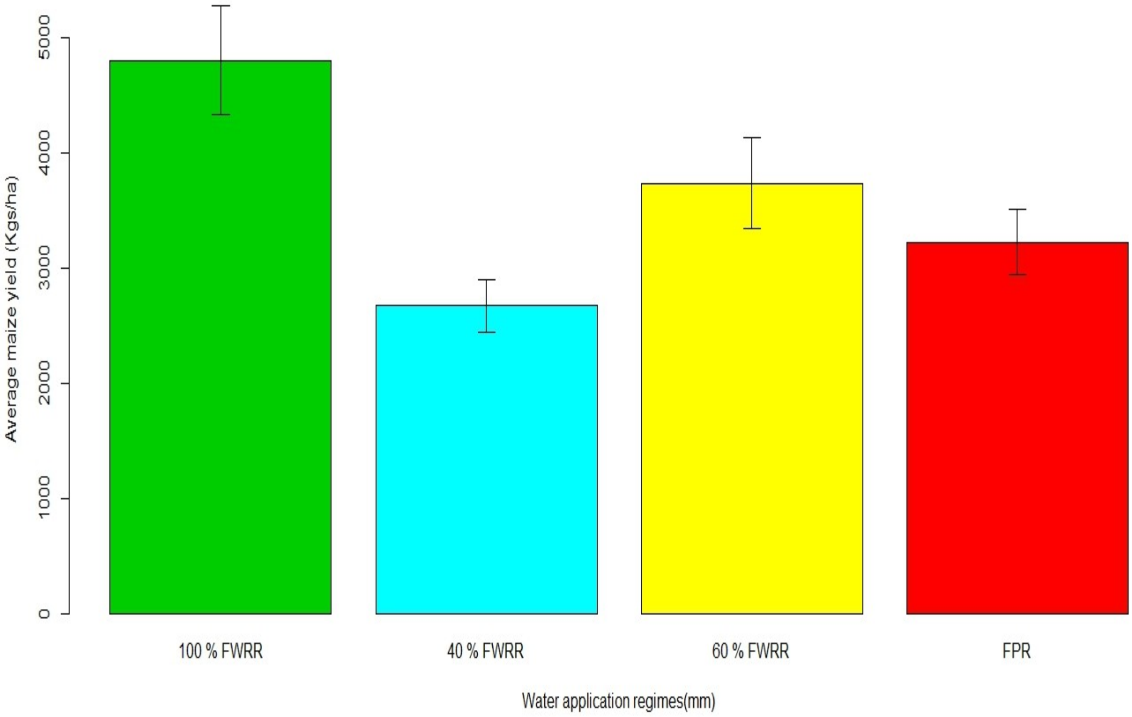
Appendix D 8: Nitrogen levels (kg/ha) effect on average maize yield



Appendix D 9: Irrigation water (mm) effect on average maize yield



Appendix D 10: Bar graphs with error bars showing impact o water application regime on maize yield (kg/ha)



Appendix D 11: Bar graphs with error bars showing impact of N application level on maize yield (kg/ha)