UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Strategies to bridge yield gaps in equatorial African upland rice (*Oryza sativa* L.) production systems

by

Isaac Newton Alou

Submitted in partial fulfilment of the requirements for the degree

Philosophiae Doctor (Soil Science)

In the Faculty of Natural and Agricultural Sciences

Department of Plant and Soil Sciences

University of Pretoria

Supervisor: Prof JM Steyn

Co-Supervisors: Prof JG Annandale & Prof Michael van der Laan

February 2020

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DECLARATION

I, Isaac Newton Alou, declare that this thesis, which I hereby submit for the degree Doctor of Philosophy (Soil Science) at the University of Pretoria, is my own work, and has not previously been submitted by me for a degree at this or any other tertiary institution. The thesis is from research work of my own efforts except where acknowledged.

SIGNATURE: ___________________________

Isaac Newton Alou

DATE: ____________________________

FEBRUARY 2020

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DEDICATION

This piece of work is dedicated

to

The Almighty God, Elohim (YHWH)

And my beloved wife, Pauline Christine and daughters Hattie Patience and Goshen Ahuva

ACKNOWLEDGEMENTS

"I can do all things through Jesus Christ who strengthens me" (Philippians 4: 13).

This work was funded under the Agricultural Technology and Agribusiness Advisory Services (ATAAS) Project through the National Agricultural Research Organisation (NARO) and partly by the University of Pretoria.

I would like to thank God for allowing the following persons to come into my life.

Prof JG Annandale, while serving as the Head Plant Production and Soil Science Department, played a key role in finding a supervisor prior to my admission to the study programme. I thank Prof JM Steyn for the open acceptance to supervise me and warm welcome to South Africa. Prof M van der Laan and Prof JG Annandale willingly accepted to co-supervise. My supervisors were not only academic mentors; they were guardians who supported me and my family during perilous and needy moments. Special thanks to Mrs. Joey Herman, Mr. Burger Cillie and Mr. Lucas Nonyane for administrative and technical support.

I thank God for sending us a vindicated true prophet, William Marion Branham, in this age. His biblical teachings shaped my spiritual life. Thank you, Pastor George Jeriel Martin of Willows Assembly Pretoria and Pastor Amiti Tom of Entebbe Local Assembly for spiritual guidance.

I acknowledge the contribution of Dr Goto Akio, Dr Geoffrey Onaga, Dr Kayuki Crammer Kaizzi and NARO institutes for availing weather data and secondary data on rice production.

My beloved wife, Mrs. Pauline Christine Alou, my daughters Hattie Patience and Goshen Ahuva, and the extended family; you gave me time, moral support and inspiration to study.

God bless, God seën (*Afrikaans*), Mungu akubariki (*Swahili*)

TABLE OF CONTENTS

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

LIST OF TABLES

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

LIST OF FIGURES

PREFACE

Many agricultural-based economies in Africa have recently embraced rice (*Oryza sativa* L.) for transformation of livelihood due to the strategic significance of the crop for food and income. Production of rice in uplands is gaining popularity for reasons including, reduced water requirements and labour inputs, and low emissions of greenhouse gases compared to lowland rice. Unfortunately, yields are often low and farmers continue in leaping production despite several research efforts. Potential yield of upland rice and yield gaps have not been quantified, and management opportunities for different categories of farmers to narrow yield gaps need to be investigated. Better understanding diverse upland rice cropping systems using a systematic approach (from plant to field to agroeological level) will advise infield and regional strategies to boost production and improve sustainability in different agroecological zones (AEZ).

This thesis is prepared in accordance with formatting guidelines provided by the *South African Journal of Plant and Soil*. It is organised into seven Chapters; four are results Chapters, which were prepared in article style. Where the same methodology was used for different studies, it is not repeated. The thesis opens with an introduction to the topic in Chapter One, and examines the literature on: (i) diversity of rice ecotypes and production systems, (ii) significance and potential of the crop as a major food crop and the need to improve resource-use efficiency in rice production systems, (ii) why water and fertilisers (especially nitrogen) are critical and challenging to manage in rice production, and (iii) the need to alleviate the inherent relatively low efficiency of the crop to utilise these resources. An exegesis of recent studies on nitrogen (N) and water stress (WS) is interpreted to highlight information gaps on the impact of N and WS on rice growth and yield.

Among the unique attributes of rice, a diverse cropping system ranging from hydromorphic cultures to dryland and high genetic diversity, are described in Chapter Two. This Chapter describes features of upland rice system in smallholder agriculture in equatorial Africa and opportunities that exist to enhance yields. The Chapter closes with procedures in crop modelling, specific on the Soil Water Balance model (SWB-Sci) and why this crop model was used. A generic, mechanistic approach to nutrient and water modelling emerges as the priority feature of the model, which suits the conditions of the study.

Chapter Three reports the response of upland rice to WS at different stages of development. It analyses why development is delayed in rice under WS, how sink-source relations are critical at each stage in yield determination, and unique WS adaptations such as recovery growth. The practical significance of water savings while minimising yield penalty is discussed for both rainfed and irrigated rice farmers.

The double challenge of matching crop N demand with supply and speculated high water requirement of rice is the topic of Chapter Four. The Chapter reports reasons for different rice growth between seasons despite optimised management of water inputs. Traits that are required for ensuring high nitrogen use efficiency (NUE) in rice, influence of N on irrigation requirements and relationships between NUE and water use efficiency (WUE) are described.

Chapter Five establishes crop parameters of two upland rice varieties of different maturity period, performance of SWB-Sci to predict growth, yield and water uptake under well-watered and stress conditions. This Chapter identifies different parameters for different varieties, which must be measured (in the case of limited empirical data) in rice modelling. The strengths and limitations of using the model to predict upland rice growth and yield under WS and N deficiencies are discussed.

Chapter Six concerns the validation of the model using independent data from different research experimental sites in Uganda. Relevance of the calibrated model to answer key agronomic questions is part of the major and most useful applications in the Chapter. Yield gaps of both varieties are quantified over 10 growing seasons using weather data for the period 2008–2012 from different AEZs of Uganda. Management scenarios and rice cropping systems are evaluated in the AEZs. The results suggest the strategic tactics required to increase yield and annual production in different AEZs.

Chapter Seven deals with general conclusions and recommendations. It highlights the hypothesis rejected and not rejected, answers to the questions raised in Chapter One. Future studies to improve predictions of the model under unique soil and water conditions are proposed, which was noted in odd simulation sites. Practical measures to increase availability, detail and scope of weather data and reporting of crop management data in studies are also proposed.

LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOLS

ARC	Africa Rice Centre
CAADP	Comprehensive Africa Agricultural Development Programme
CGIAR	Consultative Group for International Agricultural Research
D	Drainage
D	Wilmott's degree of agreement
DAE	Days after emergence
DAS	Days after sowing
ET	Crop evapotranspiration
ETo	Reference grass evapotranspiration
FAO	Food and Agricultural Research Organisation
FAOSTAT	Food and Agricultural Research Organisation statistics data base
GLM	General Linear Model
GS	Growth stage
HI	Harvest index
I	Irrigation
IFA	International Fertiliser Agency
IRRI	International Rice Research Institute
ITCZ	Inter-Tropical Convergence Zone
LAI	Leaf area index (m^2 m^{-2})
MAAIF	Ministry of Agriculture Animal Industry and Fisheries
MAE	Mean absolute error
Mha	Metric hectares
N	Nitrogen
NaCRRI	National Crops Resources Research Institute
NARIC	Namulonge Rice varieties
NEMA	National Environmental Management Authority, Uganda
NERICA	New Rice for Africa
NUE	Nitrogen use efficiency (kg kg^{-1} N)
P	Phosphorus

r	Pearson correlation coefficient
R^2	Coefficient of determination
RMSD	Root mean squared deviation
RMSE	Root mean square error
R	Runoff
SAS	Statistical analysis system
SSA	sub-Saharan Africa
SWB-Sci	Soil Water Balance model (research version)
UBOS	Uganda Bureau of Statistics
UNRDS	Uganda National Rice Development Strategy
USDA	United States Department of Agriculture
WHO	World Health Organisation
WS	Water stress
WUE	Water use efficiency (kg ha^{-1} mm^{-1} or kg m^{-3})
Y_a	Actual yield
Y_p	Potential yield
Y_t	Attainable yield
Y_w	Water-limited yield
ΔS	Change in soil water storage
θ	Soil volumetric water content
Ψ	Water potential

ABSTRACT

Strategies to bridge yield gaps in equatorial African upland rice (*Oryza sativa* L.) production systems

by

Isaac Newton Alou

Supervisor: Prof JM Steyn

Co-supervisors: Prof JG Annandale & Prof M van der Laan

Department of Plant and Soil Sciences

University of Pretoria

The average rice (*Oryza sativa* L.) farmer in sub-Saharan Africa (SSA) harvests less than 1.5 t ha^{-1} of grain yield in uplands production systems, while the yield potential is substantially higher. There are large yield potential gaps due to nutrient (especially nitrogen [N]) and water stress (WS). The main study objectives were to determine the effects of WS imposed at different growth stages (GS) on upland rice performance, to evaluate and compare nitrogen and water use efficiencies, to calibrate and test a crop simulation model for predicting water uptake and yield under a wide range of agroecological conditions and to quantify rice yields, and yield gap for the equatorial climate in Uganda and propose adaptive management strategies for improving yields.

Field experiments were conducted between 2013 and 2016 using two upland rice varieties commonly grown in SSA. Crop parameters were estimated from measured data for modelling purposes. The SWB-Sci model was parameterised, calibrated and tested using independent data from two seasons and secondary data from Ugandan research sites. Simulation studies were then performed for diverse rice growing areas along the equator (lying 0.10^{o}S–3.28^{o} N and 31.13^{o} E–34.16^{o} E) over the period 2008–2012.

Grain yield measured under well-watered, adequately fertilised conditions for the medium-duration variety (Nerica 4) was 7.2 t ha^{-1}, and 4.5 t ha^{-1} for the short-duration variety (Nerica 10). When water was withheld during tillering (Ti), anthesis and grainfilling for Nerica 4 it resulted in severe WS, but yield penalties were minimal (<25%), compared to a 75% yield loss with stress during panicle initiation. Considerable water savings (176–245 mm) are possible with WS during the non-sensitive GS.

Increasing N level altered tiller development, reduced thermal time to key GS, increased water use by 17–33% and grain N uptake per unit water used of Nerica 10, compared to the zero-N treatment. Use efficiencies for input resources declined with N rates above 120 kg N ha^{-1}.

The calibrated SWB-Sci model generally predicted water uptake, growth and yield of both varieties under different treatment conditions well, with little error and bias, for both Hatfield and Ugandan research sites. The attainable (Y_t)/potential yield (Y_P) ratio ranged from 0.04 to 0.59 between locations. If N limitations are alleviated, water-limited yield (Y_w) /Y_P ratio values of Nerica 10 (0.37–0.98) were generally higher than for Nerica 4 (0.08–0.86) across agroecological zones (AEZs).

Yield gaps of upland rice varieties were variable and specific to AEZs. Inter-seasonal differences were very apparent in the bimodal and transition rainfall zones. The gaps were small for the Eastern Savannah Moist (Y_w/Y_P = 0.78 ± 0.03) and the Northern Moist Farming Systems (0.75 ± 0.03). Adaptive cropping tactics to increase yield and annual rice production for WS-prone zones were identified. The use of the model should be useful in future studies to identify specific agronomic practices to increase WUE. Information can be used to drive policy on upland rice, for instance government initiatives to intensify rice production.

CHAPTER 1

GENERAL INTRODUCTION

1.0 Rice (*Oryza* spp.) diversity, importance, production systems and main constraints

Rice (*Oryza* spp.) belongs to division Magnoliophyta, class Liliopsida, order Poales, family Poaceae, and genus *Oryza*. There are 22 species, 20 are wild and two are cultivated. *Oryza sativa* and *Oryza glaberrima* Steud are the two species of cultivated rice, with primary centers of origin in south eastern Asia and tropical Africa (West Africa), respectively (Chang 1976; Oka and Chang 1959). *Oryza sativa* is grown worldwide in over 110 countries in humid tropical and subtropical climatic conditions, from 35 ^{o}S in Argentina to 50 ^{o}N in China (Kapoor et al. 2011). Cultivated rice, including all rice accessions or progenies are named as *Oryza* spp. There are over 115,000 accessions of cultivated rice, making the crop the most diverse (IRRI 2012; FAO 2014; H.M. Lam, personal communication, January 18, 2017) and this depicts a long evolutionary pathway. It is thus not surprising that genetic classification of rice is still confusing, since earlier works to date (Kato et al. 1928; Dingkuhn et al. 1989; Vaughan and Morishima 2003). Nevertheless, sativa varieties are grouped into three categories: indica (tropical and subtropical ecologies), japonica (temperate distribution), and javanica (tropical component of japonica grown in Indonesia), based on morphological characteristics (Matsuo 1952; Oka and Chang 1959; Dingkuhn et al. 1989). Glaszmann et al. (1984) and Glaszmann et al. (1985) re-classified rice into six genetic groups: group I and VI (most indica and japonica, javanica rices), group II (AUS varieties from Bangladesh, most short duration). Group I are short, higher tillering indica suitable for lowland cultivation. Groups III, IV and V share common differences (satellites groups) from the other groups, V is from India subcontinent, and III and IV are deep water rices from Bangladesh and Northeast India (Glaszmann 1987). Ecophysiological adaptation of rice is thus widening and recently, New Rice for Africa (NERICA®) progenies from interspecific crossing between African indigenous rice (*O. glaberrima* Steud) and Asian varieties (*O. sativa* Japonica) were developed for both lowland and upland production systems (Jones et al. 1997). These progenies are widely adopted in sub-Saharan Africa (SSA) and are ascribed for increased growth of upland rice cultivation (Africa Rice Centre 2007). Although rice is ratooned, most species are grown as annuals (Oka and Chang 1959).

Rice is the most important food crop and is the world's second most important cereal, a staple to 50% of the human population, and accounts for 29% of the global output of grain crops (RICE 2017). In developing countries, rice accounts for 27% of dietary energy and 20% of protein intake and contributes essential micronutrients (1.10-2.64 mg/100g Fe and 3.14-5.89 mg/100g Zn) (Gina et al., 2002) which are considered the most deficient nutrients in human diets. Per capita consumption of rice in 2012 was estimated at 103 kg person^{-1} year^{-1} for Asia and 27 kg person^{-1} year^{-1} for Africa on average (van Oort et al. 2015). Although relatively low, per capita rice consumption was estimated to increase at 5.5% per year (2000–2010 average) in Africa and is the fastest growing, compared to that of other food staples such as cassava, finger millet and sorghum (Saito et al. 2015). Unfortunately, many rice growing countries in Africa are heavily reliant on imports to meet domestic rice demand (Saito et al. 2015).

Given the significant position of rice (*Oryza sativa* L.), increasing rice yields in different production systems should be a priority. Rice cropping systems can be broadly classified into irrigated (lowland and upland), rainfed upland, rainfed lowland and deep water or floating rice (Kato and Katsura 2014). The crop can be grown in cool climates, high altitude mountains of Nepal and India (Shrestha et al. 2011) to sea level, hot semi-arid or deserts of Egypt, Iran and Pakistan under irrigation, to monsoon rainfall areas of Bangladesh (Akinbile et al. 2011). It is an upland (non-saturated, aerobic soil) crop in many parts of Africa, SSA and Latin America (Fageria et al. 2010; Koné et al. 2014; Amarasingha et al. 2015), where it thrives entirely on rainfall. Hydromorphic systems or floating rice are common in seasonally deep flooded areas such as the Mekong river basin in Vietnam, Chao Phraya in Thailand and Ganges-Brahmaptura in India (Zeigler and Puckridge 1995; Tuong et al. 2004; Fukai and Ouk 2012).

Although rice is uniquely adapted to such diverse habitats and water regimes, the crop performs best in lowlands and often, rice is regarded as a semi-aquatic crop (Parent et al. 2010). The highest grain yields have been recorded in latitudinal regions (50^{o}N and 40^{o}S) of maximum solar radiation (R_s) and as such, rice is also regarded as a macro-thermal (high temperature requirement) crop (Akinbile et al. 2011; Kato and Katsura 2014). Rice yields in Egypt (9.4 Mg ha^{-1}) are among the world's highest (FAO 2017). On average, grain yields of rainfed lowlands are generally high in Asia (2.5–4.5 Mg ha^{-1}) and improving over time, compared to yields in rainfed upland (1.5–2.5 Mg ha^{-1}), which have stagnated for some decades in SSA (ARC 2007). It is not surprising that yields are low in uplands, because extensive research has been conducted on lowland rice (anaerobic and puddled soils), compared to upland rice (non-puddled and unflooded soil) (Kato and Katsura 2014). Low yields of upland rice may explain why, in several rice growing areas, the cropping system is perceived as a subsistent system with low production potential (Saito et al. 2005). It is important to clarify and change general perceptions about the significance of upland rice to food security through improved practices that should result in high yields and production. Furthermore, there is a growing tendency for transition from flooded lowland to aerobic rice cultivation, primarily to save water (Tuong et al. 2004). In addition, increasing concerns on greenhouse gas emissions and environmental pollution from chemicals, make uplands an alternative system to sustain rice production. Furthermore, upland rice cultivation has been viewed as one practice to mitigate Malaria, (a leading killer disease in SSA, transmitted by *Anopheles* mosquitoes), which is prevalent in lowland rice growing communities, through reducing breeding grounds for the vector (WHO 2003; Nanfumba et al. 2011).

At least 70% of the total rice area (lowland inclusive) in SSA depends on rainfall and approximately 63% is grown in uplands (Africa Rice Centre 2007; Diagne et al. 2013). Upland rice is grown under diverse conditions in Africa, on soils with inherent limited nitrogen supply because soil organic matter is generally low, and under variable rainfall patterns and seasons (Kamara et al. 2010; Koné et al. 2011; Kaizzi et al. 2014). In most upland rice growing areas, seasonal water shortages due to low rainfall and uneven distribution are prevalent (Kijoji et al. 2014), but also runoff and low water storage capacity of soils, aggravate water deficits. The cropping system is either a monocrop or in rotation with other cereals and tubers, and bush burning and shifting cultivation are common (Koné et al. 2011; Minyamoto et al. 2012).

Coupled with a shallow root system (Kato and Okami 2010) and poor management practices, the crop is exposed to high risks of N deficiency and water stress (WS). Nitrogen is the principal nutrient limiting growth and yield of rice, according to several pot and field studies (Fageria and Baligar, 2005; George et al. 2002; Sanchez, 2002; Kaizzi et al. 2014). In lowlands, rice removes very high N in grain (1.4–1.7% N) and in straw (0.5–0.8% N) dry matter yield (Dobermann and Fairhurst, 2002). In upland rice, fertiliser use is limited and N application rates are low (< 46 kg N ha^{-1} on average) on farms. These practices can result in high N removal at harvest and severe N deficiencies in rice (Sanchez 2002; Minyamoto et al. 2012). In contrast to conventional methods, which focus on supply of N (Peng et al. 2002), nutrient management practices that aim at matching crop demand for N with supply, are important in improving the use efficiency of applied N. Previous studies mentioned above on N response of upland rice did not consider water requirements when comparing different treatments and yet water availability affects N uptake and use. Current guidelines developed for fertiliser use in upland rice (ARC 2007; Kaizzi et al. 2014) were not based on the yield potential (Y_P, yield under non-limiting conditions) of specific varieties. If fertiliser recommendations are based on correct information, such as kg of N depleted t^{-1} grain yield and N yield response (yield increase per kg N applied), then more efficient and profitable use of fertilisers may be achieved. Such information is of paramount importance to rice farmers in maximising profits from fertiliser usage efficiency. The potential benefits of fertiliser use and increasing rates in smallholder farms in upland rice production are high, based on the results of some studies. For example, Kaizzi et al. (2014) reported that upland rice compared to most key food crops in SSA, fetches the highest net returns on investment with benefit: cost ratio greater than 2.0.

1.1 Exegesis on nitrogen and water limitations and their role in determining rice yield gaps

Gains in crop yields per unit area will have to increase above the current levels to meet the food and nutrition demand of the increasing global population. The world population is estimated to increase annually by more than 2% and will reach eight billion by 2025 (WHO 2018). Increase in crop productivity will come with increases in level of production inputs, among others, water and nutrients (http://www.agra.org), which are scarce in agriculture (Tuong et al. 2004). Rice (*Oryza sativa* L.), as one of the strategic crops in Africa's quest for a 'green revolution' (http://www.agra.org), is produced under high input of water, fertilisers and labour, notably so when grown on lowlands (Peng et al. 2002), although such production systems are not very efficient (Tuong et al. 2004). Fertilisers are generally costly inputs in crop production, especially in Africa compared to USA or Europe (Sanchez 2002). Indeed, the average farmer is mostly concerned with fertiliser usage and rarely with water management (because water is not costed) and yet, water inputs and management have hidden cost on nutrient usage.

Literature assumes that when pests and diseases are effectively controlled, through agronomic practices or eliminated using disease tolerant genotypes, rice yields in either lowland or upland will be principally limited by water unavailability and nitrogen deficiency (Timsina and Humphreys 2003). This assumption commonly held among rice agronomists could be typical of most rice growing areas in SSA, based on successful stories on rice breeding in Africa (Jones et al. 1997; Africa Rice Centre 2007). In this sub-region, improved and widely adopted rice germplasm, New Rice for Africa (NERICA®), has also been evaluated on farms and found highly competitive against weed pressure and tolerant to common rice diseases (Dingkuhn and Asch (1999); Cissoko et al. 2011; Maji et al. 2011). Short-term studies suggest that yield loss related to WS in rice is very variable (30–100%), depending on crop growth stage (GS), intensity and duration of the stress (Farooq et al. 2009; Heinemann et al. 2011). In terms of water availability conditions for rice growth, threshold levels of soil water potential (Ψ_{soil}) are quite well understood for lowland rice. Stress develops at Ψ_{soil} of approximately -86 kPa in the surface layers under anaerobic conditions (Lilley and Fukai, 1994; Bouman et al. 2001). However, sensitivity to WS was investigated from a limited, narrow range of soil water conditions, between Ψ_{soil} -14 and -200 kPa (Kato et al. 2009). For upland rice, such information is not documented and water availability levels for optimal growth of rice in uplands are not established (Belder et al. 2005). Even if the same genotypes were grown in both ecosystems, water availability conditions in hydromorphic soils (lowland rice) are atypical of upland soil. The surface layer of an upland soil is often drier than its sub-soil.

Interpretation of WS severity and impact thereof on yield reductions is subject to indicators that are used to measure stress. Studies have used proxy measurements such as depth of standing water, days of no irrigation, relative transpiration and biomass reduction or drought index to indicate level of WS (Ebaid and El-Refaee 2007; Kato et al. 2006 a, b; Kato et al. 2009; Heinemann et al. 2011). These indicators were interpreted singly or in isolation of others. Asch et al. (2005), in contrast to O'Toole et al. (1982), reported different response of root length to forms of WS. High rice genotypic diversity and different experimental environments and conditions also explain differential growth and yield response to WS (Dingkuhn et al. 1989; Parent et al. 2010). Imanywoha et al. (2004) and Asch et al. (2005) for instance, reported that significant decreases in top biomass occurred under different forms of stress in upland rice (cv. Nerica). Kato et al. (2006a) found no significant effects of late vegetative stress, around panicle initiation, on top dry matter yield of cv. Japonica. Moreover, several days with no irrigation in the study by Kato et al. (2006a), were during a stage regarded as the most sensitive to WS (Allen et al. 1998). Number of days with no rainfall and irrigation were used to indicate WS in studies by Imanywoha et al. (2004), Asch et al. (2005) and Kato et al. (2006a, b). In addition, upland rice genotypes were found to be more sensitive to WS during vegetative than the reproductive stage, based on decline in relative transpiration, but was ascribed to differences in duration of stress (Heinemann et al. 2011).

Yield loss at plant level is dependent on GS and level of plant available water (Allen et al. 1998). At field and regional scales, sensitivity to WS and yield loss is complex. Adaptations of a crop to WS under field conditions is governed by interactions in the soil-plant-atmospheric continuum. For instance, Oikeh et al. (2009) reported that water shortage during a year of relatively low rainfall did not affect upland rice grain yield, but did affect growth (plant height), as compared to another year. Such an unexpected response could be a result of seasonal differences in atmospheric demand and availability of nutrients. Likewise, mild effects of WS on some rice yield components and severe effects on others have been reported (Hsiao and Xu 2000).

Water stress and N deficiency *per se* are primary limitations from single and short-term experiments. Nevertheless, the relative contributions of these factors to yields and yield gaps have not been quantified well in aerobic rice systems. At crop level, yield gaps are rarely well quantified for most crops (van Ittersum et al. 2013), partly because several investigations from agronomic stand point isolated biophysical factors, against the fact that biophysical factors (crop, pest and diseases, nutrients, soil properties, water, weeds and weather) interact in an interwoven manner. In addition, limited application of sensitive analytical tools to spatial variations like boundary line analysis in single factor experiments (Shatar and McBratney 2004) conceals contribution of factors to crop growth and yield.

1.2 Overview of rice production in the tropics - the case of Uganda

Equatorial climatic (5° –10° N or S) areas are endowed with favourable conditions for, not only rice production, but for most crops. The climate in many areas allows two main rice crops per year under rainfed conditions (George et al. 2002). The dominant rainfall pattern along the equator is bimodal. This pattern is a result of the sun passing overhead biannually, or the Inter-Tropical Convergence Zone (ITCZ) (Philips and McIntyre 2000). This is typical of Uganda, which lies between 1°30′S–4°N and 29°30′E–34°E. The rainfall pattern is also modulated by the interaction of topography and surface water bodies in the East African region (Nsubuga et al. 2014). Consequently, some regions in the country are characterised by a unimodal rainfall pattern. Due to the complex interaction of ITCZ and landscape factors, rainfall distribution in Uganda thus follows two unique patterns: in the northern hemisphere, a unimodal regime and in the southern hemisphere and close to the equator, a bimodal regime (Mubiru et al. 2012). The unimodal pattern further north (about 2^{o}N) in the country is characterised by a short dry period, because rainfall starts earlier, normally in August, than for the bimodal regime (Mubiru et al. 2012). Some areas fall in a transition zone between the two rainfall patterns. The distinct rainfall patterns result in differences in planting windows and lengths of the growing season for crops (Mubiru et al. 2012), rice inclusive. Annual long-term rainfall varies from 500 to 1800 mm on average, with a mean of 1180 mm (NEMA 2008). Rainfall looks abundant, even if evaporative may be high, but is usually torrential and with dry spells in-between.

Unlike in Asia, where ‘off-season rice’ production under irrigation in the dry season is common (George et al. 2002), this system is not practiced in African equatorial climatic zones (~23.5^{o}N to ~23.5^{o}S), because in contrast to Asia, investment in irrigation infrastructure has been neglected. Farmers depend entirely on rainfall for crop production. Like in similar areas on the continent, upland rice in Uganda is grown in two seasons, also referred to as the wet seasons (March–June and August–November), but the majority of famers restrict upland rice cultivation to the second season (August–November) (NEMA 2003). Statistics by Uganda Bureau of Standards (UBOS 2010) and MAAIF (2010) show that 75% of the rice is produced in the second season. It is believed farmers' choice of seasons is because the first season (March–June) is normally short (NEMA 2003), meaning there is a higher risk of WS, which may negatively affect rice growth. However, experience shows that farmers are constrained with storage facilities to keep grains in desirable condition for a long period before disposing it to the market (Kijima et al. 2008). It is thus likely that growing most rice in the second season allows farmers to sell the produce shortly after harvest, and meet high prices pre-festive season or Christmas, thereby alleviating the burden of grain storage. Preference for seasons is, therefore, either due to a biophysical constraint, in this case water supply, which requires investigation, or other non-related constraints.

There is a high potential to diversify rice cropping systems. In view of low rice productivity, low annual production and speculations on possible reasons for farmers' preference to seasons, it is necessary to explore the current rice cropping system. Available options to famers to practice either double or single rice cropping per year require comprehensive analysis using sound tools such as crop simulation models. The argument for a fallow and one long duration variety with high yield potential (a proposed system), against the argument of a short one, followed by long-duration variety in different seasons annually (uncommon traditional system), can be investigated for different agro-ecological zones. Suitability of a system can be assessed in terms of production costs, compared to total yield per year. If answers to these key agronomic questions are found, information generated may be useful in boosting annual rice production in such areas and consequently reduce rice imports.

1.3 Why crop simulation models to estimate yields and diagnose yield gaps

Comprehensive diagnosis and understanding of complex interactions between factors causing differential crop growth responses under limiting and non-limiting conditions require crop simulation models (Passioura and Angus 2010). Spatial and temporal variability limit the application of findings from a study to elsewhere, but such variability can be accounted for in a crop model. The use of crop models in upland rice is important because production risks under rainfed conditions are very high (Wopereis et al. 1996), more so in uplands where there is high evaporative demand and some soils have poor water storage capacity (Parent et al. 2010). The use of crop models is also important because yield loss can be highly site-specific, meaning that multiple field studies in different sites are required for spatial assessment and this is not cost effective. It is noteworthy that crop models in rice cropping systems are important not only for drought prone conditions, but also in high rainfall zones to quantify components of the soil water balance. Kuo et al. (2006) argued that rice suffers from WS, even in high rainfall areas in Asia that receive on average 2000 mm of rain over a period of five months. In Asian areas, high rainfall conditions can result in flooding and the form of WS is due to too much water.

Crop yields in Africa and in the developing world at large are generally low (Tittonell and Giller 2013), despite research efforts that have resulted in among other breakthroughs, development of new crop varieties and hybrid seeds (http://www.agra.org). The average farmer harvests grain yields of around 1 t ha^{-1} or less from cereal crops such as rice, maize, sorghum and millet (FAOSTAT database in Tittonell and Giller 2013). Upland rice yields in Uganda highly vary (0.3–5.72 t ha^{-1}) across agro-ecological or regions and seasons (Kijima et al. 2008; Alou et al. 2012; Onaga et al. 2012; Kaizzi et al. 2014). Achievable rice yield (Y_t, yield without fertilisation under rainfed conditions) is less than 1.0 t ha^{-1} on average but Y_t approximating 2.0 t ha^{-1} have been reported (Kaizzi et al. 2012). A wide yielding gradient across the country indicates site differences in production potentials which are not well quantified. Low yields undermine the significance of staple crops to food and income security in African countries. The concern today is not only about the low crop yields but the perceived widening yield gaps across Africa (Tittonell and Giller 2013), which are often not quantified. Reference yields are commonly described as potential, achievable, attainable or actual yields, but some modifications in terminology such as water-limited or nutrient limited yields also exist (De Wit and VanKeulen 1987). The definitions below of reference yields are collectively based on the work of Ladha et al. (2003), Passioura and Angus (2010), Tittonel and Giller (2013) and van Wart et al. (2013):

(a) Potential yield (Y_P) is defined as the maximum yield of a genotype restricted by only the season-specific climatic conditions and it is attained when all inputs, pest and diseases are effectively controlled and cultural management are not limiting.

(b) Water-limited yield potential or water-limited yield (Y_w) is the 'relevant measure of maximum yield attainable in rainfed systems'. In this thesis, the assumption of optimum soil water storage for determining Y_w (van Wart et al. 2013) does not hold during model simulations of this reference yield. Furthermore, Y_w will be defined as the maximum measured yield achieved under rainfed conditions and with no nutrient and other limitations.

(c) Attainable yield (Y_t), also called locally attainable yield, corresponds to water and nutrient limited yields (De Wit and VanKeulen 1987) that can be measured from the most productive fields. In a review by Tittonel and Giller (2013), this reference yield is achieved when management is optimised on farms or for on-farm trials managed by researchers, and where pest and disease levels are negligible. Generally, on-farm crop yields vary with the level of crop management, therefore Y_t in this thesis refers to rice yield with no fertiliser (especially N) inputs from researcher-managed trials (usually pests and weeds are well controlled as compared to on-farm trials) under rainfed conditions.

(d) Actual yields (Y_a) is the best or average yield in the farmers' field. Actual yields are very variable in space and time. Yield on farms is limited by many abiotic (nutrient and water stresses, erosion) and biotic factors (diseases, pests, weeds, variety), which interact in an interwoven manner. Actual rice yields in this thesis refer to on-farm yields measured from yield surveys. In common cases, actual yields are measured yields averaged across, or aggregated at administrative (district or village) level, rather than site-specific data.

Ideally, $Y_a \leq Y_t \leq Y_w \leq Y_p$, but where crop yield is less-responsive to inputs (De Wit, 1992) due to environmental and management factors, it can be difficult to accurately separate Y_a from Y_t (Passioura and Angnus 2010). Water-limited yield also can be close to Y_t, as can be observed during unfavorable rainfall seasons (Oikeh et al. 2008). This means that at least two yield gaps can be calculated: between Y_w and $Y_{t,,}$ between Y_t and Y_a (Tittonel and Giller 2013), and between Y_P and Y_a. Arbitrary, Y_t on farms is approximately 80% of Y_P (World Bank 2008; Passioura and Angus 2010), but since 2008, technological advances in crop production have occurred, meaning changes in production levels as well. In principal, the gap ($1-Y_a/Y_P$) is very wide, many factors are involved, and identifying opportunities for famers may be difficult using only Y_a/Y_p. Measurement of Y_P for rice like for most crops is rare and the ratio of Y_w / Y_P is therefore difficult to assume. However, as Y_P is a key pillar for ecological intensification (Tittonel and Giller 2013), accurate estimation of the relative yield can inform us about agro-ecological zones with the most favourable conditions for high rice productivity.

Of practical relevance, frameworks on assessment of yield gaps in the African agriculture context and a delineated atlas have been proposed (van Ittersum et al. 2013). However, achievement of yield gap maps globally is a long-term venture which will require a series of studies with highly-specific information at crop, landscape and regional levels for accurate delineation. This PhD research can thus be viewed as a contribution towards such a goal.

1.4 Objectives

The overall objective of this study was to assess and identify key management strategies to improve upland rice productivity and production through the quantification and estimation of yield gaps and the contribution of water and nitrogen limitations to actual yields.

The specific study objectives were:

i) To determine the effects of WS imposed at different phenological stages on growth, phenology, recovery of source size, yield and water use efficiency (WUE) of upland rice.

ii) To evaluate nitrogen and water use efficiencies and clarify synergisms on N and water use of upland rice under water non-limiting conditions.

iii) To adapt and evaluate the Soil Water Balance and Nutrient (SWB-Sci) model in order to predict the effects of WS, nitrogen and water interactions on crop performance of two upland rice varieties.

iv) To estimate rice yields, quantify yield potential and yield gaps, and assess WUE of upland rice for an equatorial tropical climate using a calibrated crop model.

v) To propose adaptive cropping tactics for improving upland rice systems by predicting yields and annual production for different crop management scenarios.

1.5 Research questions and hypotheses

Research questions and hypotheses tested towards answering each question were:

a) How are sink-source relations and yields affected by WS, when the soil dries out gradually during different phenological stages and how does WS impact on water use and WUE of upland rice?

Hypotheses:

i) Recovery from WS results in the same source size, measured as leaf area index, fractional interception and above-ground biomass, per development stage as that for a well-watered control, because while development is delayed under stress, growth continues at a decreasing rate.

ii) Delay in the period to reach reproductive stage due to WS increases with tiller abortion and / or inhibition severity – i.e. the more tillers abort, the more thermal time is required to reach reproduction with stress during vegetative growth because of tiller regeneration.

b) What is the minimum water requirement for optimal yield of upland rice, and does it change under varying nitrogen supply under well-watered field conditions?

Hypotheses:

i) Nitrogen fertilisation increases crop water demand under water non-limiting conditions because N stimulates canopy growth.

ii) Nitrogen fertilisation has a negligible influence on depth of water extraction as water is not limiting growth of especially roots.

iii) The point for maximum WUE and NUE, use of N and water (agricultural use efficiency intersection with WUE) is attained at the highest N rate in each growing season.

c) What are the achievable and potential yields of upland rice, and yield gaps under different rainfall distribution and production systems in equatorial areas- the case of Uganda?

Hypotheses:

i) Grain yields in most rice growing areas are largely limited by water and nutrient stresses - the ratio of Y_t / Y_p is greater than 50% in at least 66% of the sites.

ii) Simulated Y_w of upland rice in the equatorial tropical areas are specific to regional rainfall regimes?

iii) There is no yield and production merit of growing a short-duration (for drought escape) over medium-duration (high yielding, no drought escape) variety in short rainfall seasons.

d) What agronomic options can be advised from modelling experiments to improve annual rice production efficiency in agro-ecological zones where unfavourable rainfall patterns hinder double rice crops in a year?

Hypotheses:

i) Introducing a fallow period during the short rainy season prior to the cropping of a high yielding rice variety in the long rainy season (a fallow–rice system) will improve annual yield as compared to a double rice crop (short–long duration variety rice system).

ii) In a fallow– rice system in low rainfall areas, sowing time during the long rainfall season is not critical in determining Y_w and chances of yield differences between sowing dates are small because soil profile water builds during fallow, under equal fallow length over a simulation period.

iii) Modelled water-limited yield gap (1- Y_w /Y_P) is specific to growth duration of a genotype in a rainfall regime. Otherwise, in a typical unimodal rainfall scenario, the ratio of modelled Y_w to Y_P of a short-duration variety should be different between growing seasons (because simulated Y_P is quite similar among seasons) in real and statistical sense over a simulation period.

1.6 Motivation for the study

Low rice yields in uplands undermine the significance of the crop as a major food and income enterprise. Production over seasons leaps and is mostly attributed to water shortages as the crop is sensitive to WS. Fertiliser usage (particularly N) is limited among subsistent producers, who are the majority. Unravelling productivity targets of the system and yield gaps is very important in the wave of paradigm shifts in rice cultivation. There is increasing recognition for alternative rice production systems that save water, reduce labour and minimise environmental pollution from agrochemicals in lowland rice (Bouman et al. 2007). Production of rice in uplands is gaining popularity in developing countries which are not endowed with inland valleys (Saito et al. 2015). The prospects are that cultivated rice area in uplands will expand and commercial upland rice production will grow, and markets will emerge. Unfortunately, research during the last decades has focussed on lowland, intensive rice systems, with much emphasis on raising yields through variety development. Little research has focussed on improving WUE from an agronomic perspective. Field level studies on water management of upland rice in equatorial tropics, especially in Africa, are generally lacking and yet water shortages are prevalent. Consequently, seasonal rainfall in many cases (meteorological perspective) have been used to recommend water management practices in SSA and for nutrients, green house and pot studies are common (NaCRRI 2010; Matsumoto et al. 2014). Empirical basic information on crop model parameters, phenology, the water and N balances, and crop yield is required for development of prudent management strategies of N and water. With small-scale irrigation gaining momentum is Africa as well (Stirzaker et al. 2017), this research will contribute towards solving problems in water and nutrient management in rice.

Most guidelines on N fertilisation in upland rice are developed under rainfed conditions. More information, aside from yield response, is needed on nitrogen use efficiency (NUE) of upland rice under stress-free growth conditions. Relations between NUE and WUE, and influence of N on the water balance can be used in recommending best management practices and in modelling frameworks to close rice yield gaps. Alternate approaches that consider the complex interactions in the soil-plant-atmospheric continuum (Passioura and Angus 2010) are needed to seek agronomic solutions on water and N stresses, yield loss and low productivity in upland rice in temporal and spatial scales. The use of crop simulation model approaches is scarce in upland rice, partly due to a lack of basic information needed for modelling. Diagnosis of principal yield limitations at field, regional and national level will generate information on strategies for achieving local and sub-regional rice potential to benefit small-scale and commercial rice farmers. This study will contribute to solving main problems in upland rice production by delineating a working yield gap map for Uganda, devise strategies for improving these cropping systems, and to generate information for rice crop modelling elsewhere.

CHAPTER 2

LITERATURE REVIEW

2.1 An overview of rice (*Oryza sativa* L.) production and consumption

Cultivation of rice differs between ecosystems (lowlands, uplands and mangrove) in many respects, but different moisture regimes and soil are the most distinct. Rice cultivated in a standing water body where water may be drained at some stage of crop development is called lowland or anaerobic rice, while non-flooded aerobic soils is termed upland rice (Tuong et al. 2004). Rice cultivation is evolving and new terms to describe systems are being introduced into scholarly literature. Bouman et al. (2002) coined the term 'aerobic rice' to refer to high yielding rice varieties under irrigation and fertilisers in aerobic soil, which is distinguished from traditional upland rice where low yielding varieties are grown under rainfed conditions. Other authors, for instance Lampayan et al. (2010), have used upland and aerobic rice synonymously and define aerobic rice as a system where the crop is grown under non-flooded conditions as opposed to saturated soil. Belder et al. (2005) have used aerobic rice technology in lowland rice experiments with no ponding, a practice which is being adapted in the Philippines. The definition by Bouman et al. (2002) shows that there is an overlap between aerobic and upland rice. In this thesis, the term upland rice will be used for grown under non-flooded conditions, irrespective of whether irrigation was supplemented or not, in the different trials conducted. The aspect of 'high or low yielding' is not considered, because low or high yields is relative and requires a benchmark for a given environment and region.

The cultivated area under rice in rainfed conditions is approximately 20% of the global area under rice production. Rainfed lowlands account for 30% (about 46 Mha) and irrigated rice share is 75% of the total rice cultivated area (FAO 2014). The remaining fraction (about 4%) is likely the share for floating rice. Anaerobic rice systems (irrigated, rainfed and flooded prone systems) represent approximately 73.6% (about 128 Mha) of the cultivated area. The share of global rice area in uplands, although small, is likely to increase because of the significance of the system in saving water and reducing environmental pollution (IRRI 2006; Bouman et al.

2007). Production of rice in uplands is forecasted to increase the contribution to world-wide rice market (CGIAR Science Council 2006). Statistics by Africa Rice Centre (2007) estimated a 7% per annum increase in rice production, which accrues from expansion in rice cultivated area. Forecasts of FAO (2013) showed a rapid annual growth rate of 4.3–7.8% in paddy area, especially in East Africa, excluding Madagascar. In this sub-region, virgin lands are converted into cultivated area, through bush burning (Imanywoha 2001). Such practises are detrimental to the land and soil resource base. Sustainable solutions are required to address these emerging challenges.

Global rice production is estimated to be 700 million tonnes annually on average in over 122 countries, representing about 29% of the global grain production (IRRI 2002; FAO 2014). For instance, FAO data showed that in mid-2016 746.8 million tonnes (496.0 MT of milled rice) was produced and 502.9 million tonnes (403.9 MT of milled rice) was utilised as food. Nearly 75% of the global grain basket comes from Asia under anaerobic irrigated systems (Dobermann and Fairhurst 2000). Asia is the leading rice producing and consuming region, with more than 90% of the global production share. The leading rice producing countries are China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines and Japan (not necessarily in that order) (IRRI 2002). Rice grain yields ranging from 6.3 to 9.9 t ha^{-1} have been recorded in sub-tropical or temperate regions in Asia (Akinbile et al. 2011). In contrast, countries in sub-Saharan Africa (SSA) are not self-sufficient in rice production and thus rely on imports from Asia to meet domestic demand (FAOSTAT 2013).

Most countries in Africa produce rice but in a few of these (Cape Verde, Comoros, Gambia, Guinea, Guinea Bissau, Liberia, Madagascar, Egypt, Senegal and Sierra Leone), rice is a staple food (FAOSTAT 2012). West Africa contributes 75% of Africa's rice under upland systems in countries such as Sierra Leone, Guinea, Nigeria, Ivory Coast and Liberia (Africa Rice Centre 2005). It is noteworthy that these countries have a long history of rice cultivation, with diverse ecosystems that boost diversity because West Africa is one of the primary centres of rice origins. Other countries like Cote d'Ivoire, Mali, Mauritania, Niger, Nigeria and Tanzania consider rice as an important food crop. Madagascar, followed by Tanzania, are the leading producers of rice in the Eastern and Southern African region (FAOSTAT 2012). Uganda is an emerging rice producing country with large production on uplands (FAO 2013; Kaizzi et al.

2014). Average grain yield (<1.5 t ha^{-1}) and production is low in Africa because rice production is heavily dependent on rainfall, with minimal use of mineral fertilisers and a large area share (approx. 63%) is rainfed (Africa Rice Centre 2007). For instance, about 20 million tonnes is annually produced on about 9 million hectares (Africa Rice Centre 2006).

Improving rice production is key to food security and income, given the dynamics in socio-economic trends worldwide. Firstly, rice growing areas are generally overpopulated and are some of the world's most impoverished communities (CGIAR Science Council 2006), and rice is a key crop to raising their living standards. Secondly, consumption patterns of major staple food crops are changing. For example, according to USDA (2013), consumption of rice in Africa was the highest (5.5 kg per person per year between 2000 and 2010) among coarse grains such as sorghum (*Sorghum vulgare* L.), millet (*Pennisetum glaucum* L.) and starchy crops such as taro (*Colocasia esculenta* L.) and cassava (*Manihot esculenta* Crantz) (Seck et al. 2013). Increasing consumer preference for rice to traditional staples shows a high potential of the crop as a major source of dietary calories, which is already evident in some countries (Kaizzi et al. 2014; Saito et al. 2015). Increasing demand for rice from mostly urban markets is driven by changes in production patterns and rapid population growth (Africa Rice Centre 2005; FAOSTAT 2012). Unfortunately, growth in rice production in Africa is limited because cultivation is largely on rainfed uplands (Africa Rice Centre 2007) and rainfed rice is highly vulnerable to drought (Wopereis et al. 1996).

Increase in rice production in Africa has been met through expansion in cultivated area, largely in uplands (Africa Rice Centre 2007). Despite expansion in cultivated area, production remains low in SSA and thus increasing rice production must be met through increasing productivity per unit land or per unit input. Water management is among areas which should receive considerable attention in boosting rice yields, based on several studies as opposed to conventional practices. For example, in Asia Kato et al. (2009) showed that under adequate water supply through supplementary irrigation attainable rice yields in uplands could match potential yields. Furthermore, water availability during a season has been viewed to drive rice production trends between years and inter-seasonal yield fluctuations (Kato et al. 2009;

Akinbile et al. 2001; FAO 2017). In fact, FAO statistics (2017) showed that seasonal rainfall has not only an impact on yield per unit area, but also on recovery in paddy areas.

2.2 Characteristics of rice production systems in sub-Saharan Africa – a case of Uganda

Rice cultivation in most growing areas worldwide occurs in smallholder systems (George et al. 2002; Saito et al. 2005; Koné et al. 2014), on less than 1.0 ha of cropland per household (Africa Rice Centre 2007; Kijima et al. 2008). Upland production is the dominant rice system in Africa (Africa Rice Centre 2007). In uplands, rice is either grown as a monocrop (single species) or as an intercrop with crops like maize (*Zea mays* L.), sweet potatoes (*Ipomoea batatas*) and cabbages (*Brassica oleracea)* in small proportions of land (Minyamoto et al. 2012). Legumes are rarely included in a rice cropping system and this contributes to soil nutrient depletion (Minyamoto et al. 2012). This is also typical of Uganda where rice production is characterised by limited use of inorganic fertilisers, poor crop rotations, and heavy dependence on rainfall, no water harvesting technologies and limited recycling of rice residues (Kijima et al. 2008; Minyamoto et al. 2012). In some major rice growing areas, farmers can afford some inorganic fertilisers, but N application rates as low as 46 kg N ha^{-1} are common (Minyamoto et al. 2012). In other cases, long-term rice-rice sequences are common and in addition to residue burning, the practices accelerate nutrient loss, particularly N (Donova and Casey 2000; Imanywoha 2001). Farmers thus tend to convert more woodlands to rice fields through slash-burn systems in an attempt to ensure productive lands (FAOSTAT 2004; Saito et al. 2005; Kamara et al. 2010).

Like in most farming communities in Africa, rice is not a traditional crop in Uganda, compared to crops such as bananas (*Musa* spp.) and cassava (*Manihot esculenta* Crantz) (Oonyu 2001). Rice was introduced by Indian traders as early as 1904, but cultivation only picked up in the 1950s (Wilfred 2006), where after the crop became popular. Most rice is rainfed (90%), only 5% is irrigated and 10% is under flooded conditions (APEP 2005). Commercial schemes, namely Kibimba, Doho and Olweny were established in lowland ecosystems by the government in 1970 (Oonyu 2001) to meet a small domestic market at that time, which comprised of schools, hospitals, prisons and world war veterans. Rice only became significant to the country's food and income security situation in the most recent two decades (MAAIF 2012) with production spreading to almost every region of the country.

Breeding programmes worldwide have developed and released rice varieties with shorter duration than traditional ones, which were grown around mid-20th century (Jones et al. 1997; Lamo et al. 2010). A short crop duration not only confers a merit of drought escape, especially late in the growing season, but also reduces seasonal water use; the latter merit is most important in irrigation. In Uganda, several upland varieties, among others IRAT 112, Supa-v-88, NARIC 2 and NARIC 3, were released by breeding programmes over time. However, of all these, the New Rice for Africa (NERICA) varieties were most responsible for geographic shift in rice production (Lamo et al. 2016). The different varieties were released by Institut de Recherbe Agronomiques de Malagasy (IRAT), Africa Rice Centre (ARC), and National Crop Resources Research Institute (NaCRRI) in Namulonge (NARIC stands for Namulonge rice). The crop cycle for NERICA varieties is short (105–120 days) in the tropics compared to the other varieties under rainfed conditions, but crop phenology can vary due to water stress (WS) (Prasertsak and Fukai 1997; Lamo et al. 2010). New rice for Africa varieties, although tolerant to most abiotic and biotic stresses, have been reported susceptible to WS (Africa Rice Centre 2007; Oikeh et al. 2008; Kaizzi et al. 2014). Upland varieties Nerica 1, Nerica 4 and Nerica 10 were released around 2002 due to good yield attributes and market qualities, and are the most popular varieties in Uganda (Lamo et al. 2010). Promotion of upland rice cultivation is one of the Uganda government's means to conserve wetland resources and the environment (NEMA 2003), because lowland rice accounts for more greenhouse gas emissions due to methanogenesis process and redox reactions (Bouman et al. 2007).

Rice productivity in Uganda, like elsewhere in SSA, is generally low, with an average grain yield of 1.0–1.5 t ha^{-1} (Kaizzi et al. 2014). A combination of poor cultivation practices, nutrient deficiency and WS due to erratic rainfall and uneven distribution is causing low rice yields (Kijima et al. 2008; Goto et al. 2012). Rice crops are at risk of WS, even in high rainfall zones in equatorial tropics, partly because farmers do not harvest or conserve rainwater (Kijima et al. 2008). The risks are evident in Uganda where farmers try to cope with water and nutrient stresses by opting to: (i) plant one rice crop annually (only in a 'good' rain season), (ii) fallow or shift cultivation to woodlands, (iii) slash and burn bushes (iv) frequent rice monocrops and (v) rotate with maize, but less often with legumes (NEMA 2004; Kijima et al. 2008). Most farmers are resource-constrained to invest in irrigation facilities in uplands (APEP 2005). There is a growing recognition for irrigation-based agriculture and about 190 irrigation projects are to be established across Uganda (New Vision 2019). Opportunities exist to mitigate WS related production challenges. For example, simple water conservation structures like bunds are rarely practiced in uplands but are easy to construct (Goto et al. 2012). Furthermore, upland rice genotypes are diverse in terms of crop duration and morphologies (Dingkuhn et al. 1989; Jones et al. 1997), which can be selected to make optimal use of growing seasons in the tropics.

With such a diverse upland rice system, there is a need to identify and or evaluate which options will be most appropriate in which areas for improvement of yield and crop water productivity in uplands. Shifting cultivation for instance is often perceived where rice farmers search for fertile soils due to nutrient depletion (Minyamoto et al. 2012) and yet the practice can be evaluated as a fallow to build soil profile water reservoir. In addition, best options to fit varieties of different phenologies to the variable inherent soil productivity and rainfall distribution in-season and inter-season varies should be explored. With more breeding effort, more varieties can be released and adopted in farming systems. Studies are needed to find answers to queries like (i) should farmers revert to specific rice varieties and of what crop duration? and (ii) what variety–variety combinations may suit specific agro-ecological conditions best in view of boosting annual yield? These are some relevant issues to consider in equatorial systems at large given rice cultivation is possible (but not feasible in all cases) throughout the calendar year.

Campaigns among African governments to promote upland rice production are increasing. Policy incentives are one of the driving factors to trends in rice production in SSA countries (USDA 2013; Saito at al. 2015). The Comprehensive Africa Agricultural Development Programme (CAADP) endorsed by African Heads of State and Governments (CAADP-NEPAD 2003) prioritised rice in the agenda with the aim of rural transformation. Thus, several African governments, among others Uganda, have put more emphasis on the promotion of upland rice. The Uganda National Rice Development Strategy was created (UNRDS 2009) and rice is also mainstreamed in the national agricultural research system (MAAIF 2009). Recently, rice was considered among the 10 priority agricultural commodities owing to high returns on investments and huge potential (MAAIF 2012). Profitable crop productivity in Africa is generally hampered by high costs of inputs, particularly fertilisers and other production costs (Sanchez 2002; Jansen et al. 2013). Fortunately, that is not typical for upland rice because higher profitability (benefit: cost ratio > 2) was reported, compared to most traditional crops (Imanywoha 2001; Kaizzi et al. 2014). Upland rice is thus one of the key enterprises that can help to improve farm productivity and livelihoods of farmers in Africa at large.

Incentives to increase local upland rice production also exist in the form of taxes on rice imports. Statistics from FAO (2013) and PMA (2009) show that Uganda is a net importer of rice, for instance 42–48% of the national rice consumption was met by imports between 1990 and 2010. A high tariff of approximately 75% or US$ 250 per tonne was imposed on rice imports into the East African region in the 2016–2017 fiscal year (FAO 2017). The tax policy can be viewed as an incentive for expanding rice production locally. A combination of government policy and improved technology, particularly NERICA varieties among other factors, therefore, explain the rapid growth of the rice industry in Uganda. For instance, grain production increased by 52% and area under rice cultivation by 46% over a period of seven years (MAAIF 2010). Per capita consumption was projected to increase from 7 kg in 2005 to 10 kg in 2018 (Lodin 2005; MAAIF 2009). Rice production was projected at 233,000 metric tonnes in 2018 (MAAIF 2009), which is realistic, given the production figures in recent years. For instance, grain production in 2004 was 121,000 metric tonnes of milled rice from an area of 93,000 ha and in 2010/2011 it was 218,000 metric tonnes from an area of 149, 000 ha (UBOS 2012). The period between 2004 and 2011 experienced a tremendous increase in grain production, which was attributed to higher production in uplands and an increase in the number of rice farmers from about 4,000 to over 35,000 (MAAIF 2009; UBOS 2012). The share of total rice area under uplands has increased from 55% in 2005 to 71% in 2011, but unfortunately, part of the expansion was into marginal lands (Lodin 2005; Gitau et al. 2011), which needs to be averted. Farmers in Uganda are thus gradually shifting rice cultivation from lowlands to uplands (Imanywoha 2011).

The overall analysis on rice production in SSA is that growth in grain production is achieved from expansion of cultivated land area (extensive production) and rarely a result of increase in yield per unit area (intensification). Cultivation into fresh woodlands compensates for low yields from soils that are exhausted. Indeed, analysis of yield trends (1961–2010) by Saito et al. (2015) in some SSA countries revealed that rice yields are stagnating and has collapsed in many cases. Saito et al. (2015) used segmented linear regression to analyse year averages of yields. Due to the limitation of the technique, their findings do not inform us on the underpinning biophysical factors that affected yields in the different years. Studies that account for within-spatial variation (landscape, regional or national level) in key biophysical factors through the application of crop-soil simulation models (Timsina and Humphreys 2003) will be useful in future.

2.3 Rice yield limitations in uplands: soil water and nitrogen relations

Upland is regarded as an unfavourable habitant for rice growth as the crop is inherently semi-aquatic (Parent et al. 2010). The maximum yield for upland production has been documented at 30% lower than for flooded or lowland rice under similar crop management conditions (Kato et al. 2009). Grain yield under rainfed production in uplands (1.5–2.5 t ha^{-1}) are also lower than for lowlands (2.5–4.5 t ha^{-1}) (Africa Rice Centre 2007; Kato et al. 2014). However, in extremely wet seasons (1000 mm rainfall in five months), George et al. (2002) reported grain yields in the range of 3.4–4.1 t ha^{-1} in rainfed uplands in the Philippines. Record yields are rarely reported in the tropics because measurement of rice yield under non-limiting conditions is generally lacking. In many breeding studies, production potential of rice under rainfed conditions is never established (Kijoji et al. 2014) and therefore it is difficult to assess the impacts of WS on yields. Peng et al. (1999) estimated the yield potential of rice in the tropics on about 10 t ha^{-1} using models. For uplands, it remains to be established if rice yields above 80% of potential yield are achievable and under what crop management conditions. Kato et al. (2009) showed that under adequate water supply (850 mm on average) yield (7.2–9.4 t ha^{-1}) of upland *japonica* rice matched that of lowland rice (6.4–8.0 t ha^{-1}) in most seasons. Their findings however could not inform on threshold levels of water inputs for optimum rice yields in uplands.

From comprehensive reviews, aspects and conditions of rice cultivation in uplands for achieving optimal yields have not been established (Kato et al. 2014). The primary constraints, however, have been identified and investigated. Soil WS, soil infertility and weeds have been cited in most studies as primary constraints to upland rice productivity worldwide (Fageria and Baligar 2001; Fageria et al. 2010). These biophysical factors interact in an interwoven manner in field or under uncontrolled conditions (von Liebig 1863). In terms of yield loss, weeds are not as a serious problem as the other two constraints for upland NERICA (Maji et al. 2011). Furthermore, Alou et al. (2012) reported small yield depressions with delayed and reduced frequency of weeding in low input upland NERICA.

Nitrogen deficiency tops the list of soil fertility constraints in rice production, based on extensive yield response, nutrient balance, and nutrient recovery studies (Sanchez 2002; Saito et al. 2005; Fageria et al. 2010). Fageria et al. (2009) found that N was the most limiting nutrient to growth of potted-grown upland rice genotypes in Brazil. In field studies in Uganda, grain yield (1.2 t ha^{-1}, averaged across varieties) without N fertilisation under rainfed conditions did not change in the absence of P, K or both nutrients (Kaizzi et al. 2014). Nitrogen fertiliser in northern Laos, Philippines increased grain yields of traditional and improved upland genotypes under rainfed conditions by 19% and 29%, respectively, while P fertilisers did not result in a response. The addition of P fertilisers to N caused a small increase in rice yield (Saito et al. 2005). Phosphorus and potassium are therefore applied at relatively low rates compared to N, depending on the soil fertility class (Africa Rice Centre 2007). Fertiliser rates commonly used are: 15–60 kg P_2O_5 ha^{-1} and 15–30 kg K_2O ha^{-1}, 46–120 kg N ha^{-1} for significant yield increases in rainfed upland rice (Africa Rice Centre 2007; Oikeh et al. 2008, Oikeh et al. 2009, Minyamoto et al. 2012; Onaga et al. 2014). It is noteworthy that these are typical nutrient recommendations and are not site-specific.

Most studies cited above frequently used grain yield response to N applied as a basis for guiding fertiliser use and yet nitrogen use efficiency (NUE) has many interdependent metrics (Cassman et al. 1996). Nitrogen use efficiency can be defined as the maximum economic yield produced per unit N applied, absorbed, or utilised by the plant to produce grain and straw (Fageria 2003). The definitions of NUE in the literature denote the ability of a system to convert inputs into outputs. The terms are classified as either agronomic efficiency (AE), physiological efficiency (PE), agro-physiological efficiency, apparent recovery efficiency (AR), or utilisation efficiency (UE) (Fageria 2001; Fageria and Santos 2003). Agronomic efficiency is the increase in grain yield per unit input N applied, while partial factor productivity of applied N is the grain yield produced per unit N applied (kg kg^{-1}). Apparent N recovery or recovery efficiency of fertilizer N is the ratio of increase in plant N accumulation at maturity per unit N applied. Internal NUE is the ratio of grain yield to total N uptake (kg kg^{-1}). More metrics for assessment of NUE is needed, because N recovery is affected by fluctuations in soil water availability (Power 1983). For a shallow rooted crop such as rice (Okami and Kato 2010), risks of N loss beyond root zone can be high, compared to other upland crops. Comprehensive knowledge of NUE is required in reducing fertiliser costs and maximising profits. Furthermore, achieving maximum crop N uptake will ultimately increase rice yield while minimising N loss to groundwater. Nitrogen is exposed to losses through denitrification, leaching and volatilisation, depending on its available form (NH_4^+, NO_2 and NO_3^-).

Efficiency of N use of rice in lowlands is generally low. Wei et al. (2010) and Motior et al. (2011) reported about that only 30% of the N from sole fertiliser application was taken up. Jian et al. (2014) in China reported some of the highest recovery rates (63%) and internal efficiencies (58.6 kg kg^{-1} N) for N in rice (hybrid lowland cv. Yangliangyou-6) literature at a rate of 90 kg N ha^{-1}. The N rate used in that study is moderate when compared to rates of 150–230 kg N ha^{-1} where maximum yields have been achieved in lowland rice (Yun et al. 1997; Kondo et al. 2005; Kato et al. 2009). Given that in lowlands, association of free-living and symbiotic organisms make a significant contribution to biological nitrogen fixation (Motior et al. 2011), NUE in uplands may be lower. In fact, NUE in upland rice is a result of low N application rates and poor recycling of crop residues on farms (Fageria et al. 2010).

Water stress is assumed as the leading cause of low rice yields worldwide and high yield variability between seasons (Tuong et al. 2004; Oikeh et al. 2008; Oikeh et al. 2009; Akinbile et al. 2009; Matsunami and Kokubun 2011). Rice grown in upland is 'forced' to cope with more variable soil water conditions, which can manifest in intermittent WS (Parent et al. 2010). High evaporative demand and low soil water reserves, compared to a standing water surface in lowland rice, cause highly variable water conditions over a season (Shrestha et al. 2013). Intermittent WS affects growth and yield even in high rainfall rice growing areas in Asia (Kuo et al. 2006). Rice is sensitive to even mild soil water deficits (Lilley and Fukai 1994), which is unique from other upland crops. In terms of yield loss due to WS, findings are mostly from single-factor experiments that compare yields between seasons (Oikeh et al. 2009). Attempts to match seasonal rice yields with rainfall amounts are common, but this is insufficient because of a complex water balance in the soil-plant-atmosphere continuum.

Yield loss in rice due to drought or WS can range from 30 to 92% and depends on the severity thereof, growth stage of occurrence and duration of the stress (Wopereis et al. 1996; Lafitte et al. 2007). Investigations in anaerobic or lowland rice indicated that stress develops when $\Psi_{soil} < -86$ kPa (Wopereis et al. 1996; Devatgar et al. 2009). Soil water potential values between -60 and -140 kPa in the 0–25 cm soil layer was reported as optimum for rice growth (Wopereis et al. 1996; Bouman et al. 2001; Devatgar et al. 2009), but these conditions are atypical of upland production. In uplands, surface soil can be drier than -600 kPa and crop adaptations to WS have been shown to vary between rice cultures or growing environments (Asch et al. 2002; Kato et al. 2008; Parent et al. 2010; Rebolledo et al. 2013). Mechanisms regulating water use under drought or WS in growth chambers (Asch et al. 2005; Heinemann et al. 2011) can be different from uplands because soil evaporation is a significant process in the open field (Passioura and Angus 2010), and yet evaporation is often assumed to be negligible and controlled in indoor studies. Other morphological adaptations such as enhanced rooting system, carbon trade-offs and stomatal sensitivity to evaporative demand during WS are often controlled in indoor experimental designs (Rebolledo et al. 2013).

Water and N interaction effects on rice yields are apparent, even in single-factor studies (Fukai and Ouk 2012), but this phenomenon is rarely considered in study designs. The effect of water availability on nutrient uptake in crops is well established. Soil water content below 14.5% plant available water, which mostly occur in the topsoil after several days of withholding water, was reported to lower nutrient uptake in upland rice (Prasertsak and Fukai 1997; Kijoji et al. 2014). Water supply and availability in seasons result in considerable differences in rice yields, even when nutrient application rates and crop management are similar among seasons. For example, findings by Oikeh et al. (2008) suggested grain yield differences of 105% between adjacent seasons at high N and P fertiliser rates in upland NERICA. In contrast, Onaga et al. (2012) suggested a smaller yield difference of 25.2% between successive seasons, which was higher without N fertiliser (0 kg N ha^{-1}) compared with 120 kg N ha^{-1}, under adequate P and K. Oikeh et al. (2010) consequently recommended 30 kg N ha^{-1} as the optimum rate for NERICA 1, 2 and 4 varieties in the acidic acrisols of West Africa, because grain yield was statistical similar with that at 60 kg N ha^{-1} (~ 0.7 t ha^{-1}) and lowest at 120 kg N ha^{-1} (~ 0.6 t ha^{-1}). In rainfed uplands in East Africa, Onaga et al. (2012) reported grain yields of 4.9 and 5.5 t ha^{-1} for successive seasons at 120 kg N ha^{-1}, which is about 11.3% yield difference.

In several single-factor studies mentioned above, it was assumed that the factor being investigated is only limiting growth while other factors were neglected or assumed optimal. Based on the law of the minimum, crop growth at large or yield is limited by the factor present in relative (minimum) level or amount to the other influencing factors (von Liebig 1841). This means that in field experiments where other potential limitations (which are manageable) to crop growth are not neutralised or buffered, a true response to the factor being investigated is not obtained. Ideal N responses in upland rice should be generated to improve our understanding of the optimal fertiliser ranges for maximising yield of the various rice genotypes.

2.4 Rationale for proper quantification of water and nitrogen use in rice production

Water scarcity and competition for use by different sectors is apparent worldwide. The human population continues to grow, and urbanisation and climate change will increase pressure on water resources (Tuong et al. 2004; United Nations 2011). Energy use in modern manufacturing technology of nitrogen fertilisers (Haber-Bosch process) is enormous and the main source, natural gas, is a non-renewable resource (IFA 2004). Unlike fertiliser usage, water is not cautiously used (less stringent practice) in rice production. “Farmers put 2 to 3 times more water in lowland rice fields than in those growing other cereals to produce 1 kg of paddy rice” (Tuong et al. 2004). Lack of judicious water management is partly because of the fact that in most countries no price is attached to water use for crop production and yet poor water management in one way increases fertiliser costs through leaching and drainage.

Enormous water levels applied to rice does not necessarily mean that the crop requires or uses a lot of water. Much of the water in flooded rice is lost through percolation and drainage (Tuong et al. 2004). Consequently, technologies aimed at reducing water use in rice production, namely aerobic cultivation, alternate wetting and drying, and saturated soil culture in puddled fields are being advanced to increase WUE (Tuong et al. 2004; Bouman et al. 2007) and possibly reduce impacts of agro-chemicals on water resources. Some rice scientists, however, suggest that rice has high water and fertiliser requirements and breeding efforts over decades have not solved this challenge (Matsumami and Kokubun 2011). The major success towards high rice yields through breeding has been improved input-responsive varieties and better harvest index than traditional ones (Saito et al. 2005). Water requirements may seem high but are not accurately quantified. For instance, Kato and katsura (2014) reported that even under aerobic rice cultivation, skilled farmers apply 1000 mm of irrigation water during growth to obtain grain yield of 6 t ha^{-1} in the Kanto region of Japan. During dry season in Los Baños, Philippines 744–924 mm of irrigation was used to achieve 4.0–5.7 t ha^{-1} of a high-yielding cv. Apo. Belder et al. (2005) also reported a similar range (778–826 mm) of seasonal water inputs for grain yields of 4.2–6.3 t ha^{-1} of the same variety in aerobic conditions in Los Baños. Although rice water requirements depend a lot on the climate in which the crop is grown, and aerobic systems have achieved a reduction in water inputs compared with conventional flooded rice (Bouman et al. 2006), the water input values cited in above studies can still be regarded as high.

The common practice in aerobic rice is to raise soil water content up to field capacity during irrigation (Bouman et al. 2005). Practically, ensuring such a soil water regime in an upland field can be difficult, because of high unproductive water losses (runoff and drainage) from erratic rainfall. Estimating water requirements and use requires proper quantification of the soil water balance. Optimum thresholds of soil water availability are yet to be determined for aerobic rice (Belder et al. 2005) and yet such information is important for optimising yield and WUE. Several studies on water use of rice, among others Tuong et al. (2004), Belder et al. (2005) and Vories et al. (2013), reported WUE as grain yield per irrigation amount rather than per crop water used (ET). Some of these studies were on flooded rice, perhaps justifying the use of the metric water productivity (calculated as yield per unit water applied) as opposed to WUE. Although flooding is perceived as a wasteful practice in rice, weeds are smothered under such conditions and this leads to effective weed control. In contrast, in upland rice, non-beneficial losses through weeds may affect water use if not well controlled. Further, plant density can affect water use, where high plant density may mean more water use. Plant density (rice plants per ha) needs to be clarified when reporting information on WUE. Estimates of WUE based on ET are needed to afford information on what the crop really uses. When expressed as yield per unit water applied usually for economic feasibility (technically not correct term for WUE), (Tuong et al. 2004), it is tricky to apply such findings to other locations, even for the same rice variety. Water management or irrigation systems differ in efficiency and thus, proportion of water used by a crop or lost will also differ.

2.5 Application of crop simulation models in yield gap analysis

Crop models can be used to separate the contribution of key biophysical factors to growth and yield because models integrate the bio-physical and ecological processes that govern plant growth (Passioura and Angus 2010). Crop models as important diagnostic tools in agriculture have three main applications namely: research, decision support, and education and training (Mathews et al. 2000). The five basic modules for yield estimation common to most crop models are: crop growth duration, biomass accumulation rate, partitioning of biomass between plants organs, soil water balance, and nutrient uptake and balance (Ritchie et al. 1990). Depending on nature of the model and available data, reference yields namely potential yield (Y_p), water-limited yield (Y_w) and attainable yield (Y_t) can be simulated from crop-soil simulation models (Tittonel and Giller 2013). Models are either process-based or mechanistic in simulation approach – some use complex functions to describe the dynamics in nutrient and water availability or response, radiation use and consequently yield, while others use parameters to estimate physiological processes.

Before application, a model should preferably be parameterised, calibrated, tested and corroborated, using adequate independent data sets. Model calibration refers to the adjustment of simulated values to closely match observed values (Timsina and Humphreys 2002). To gain confidence in the model's performance, independent data sets (not used in calibration) should be compared with simulated values – model corroboration. This allows testing the robustness of the model (Willmott 1981) over a range of conditions. Model performance is assessed using statistical indicators of error and bias, which should not be interpreted in isolation. Unexplained gaps are indicated by the R^2 value for goodness of fit. Other indicators used to assess model performance are: root mean square error (RMSE) or of deviations (RMSD), normalised RMSD, normalised objective function (NOF) and D-index (Ahuja et al. 2002). The D-index, or the coefficient of modelling efficiency (ME, $1 \leq D \leq 0$) is a measure of deviation between model predictions in relationship to scattering of the observed data.

Models have been applied to cropping systems since the last three decades. In rice, earlier works using CERES-Rice (Ritchie et al. 1990) and ORYZA2000 (Bouman et al. 2001) are some examples of successful stories on the use of crop models. Several other studies have applied crop models to rice cropping systems in Asian countries (Arora 2006; Bouman and van Laar 2006). Case studies where different crop models were applied have been reviewed by Timsina and Humphreys (2003) and revealed the following:

(i) Data bases of crop models are lacking parameters for commonly grown varieties and where information is available, it is for new cultivars not grown in farming systems. In the case of rice, little or few field-scale studies have been conducted on crop parameters (Campbell et al. 2001 cited by Boschetti et al. 2006), despite the position of the crop worldwide. Without variety-specific genetic coefficients, modelling exercises can become inappropriate to cropping systems. Generation of crop parameters of the variety is important, especially for upland rice where genetic diversity is high (Dingkuhn et al. 1989). Production risks are also high in rainfed rice (Wopereis et al. 1996), notably in uplands and this makes it very important to determine parameters as a basis for investigating potential production in the system.

(ii) Further, lack of adequate data for validation of the models was a frequent setback to confidence in model simulations (Timsina and Humphreys 2003). This limits application of a parameterised crop model to a wider range of ecological conditions. Some reviews showed studies where aggregated data as averages were used for model validation (Passioura and Angus 2010). However, considering that high spatial variability exists between fields, wrong conclusions can be made about the performance of a model to predict yield accurately. Some satisfactory model corroboration can be achieved using site-specific data points. The variability in observed data should be known to avoid misinterpretation of error of precision from the model. Unfortunately, this is not always the case because secondary data are often summarised.

(iii) Related to the above limitation, reasons for poor performance of simulation models were not mentioned in most studies. Some studies, for instance Arora (2006), suggested that some models may not perform well under upland conditions because of inherent model assumptions. Studies mostly aim at predicting final yields and seldom the time-course (in-season) of growth variables like biomass, fractional interception of R_s and leaf area index. Often, measured data is lacking and incomplete. In such a situation, it may be possible to simulate final yield correctly, but for a wrong reason and vice-versa.

(iv) Application of models to simulate growth under conditions of water and nitrogen stress was not successful in many studies (Kropff et al. 1994; Mall and Agarwal 2002). Grain yield of rice above 4 t ha^{-1} was not satisfactorily predicted in some cases (Mall and Aggarwal 2002), indicating lack of robustness in some models. However, with adequate data measured during crop growth, the reasons for poor performance of a model should be easy to explain.

Investigations on crop models, including commonly used rice models have been tested under continuously ponded cultures or lowland rice. The ability of crop models to predict the time-course of growth variables and yields in upland rice systems and under limiting conditions of N or water availability is yet to be investigated. Crop models have been widely applied in lowland rice in many studies reviewed by Timsina and Humphreys (2003), but rarely to assess rice yields and yield gaps in upland growing conditions. Such investigations are scarce, partly because most of the focus on increasing rice yields has been through drought studies (from a breeding perspective), as opposed to adapting the crop to water limitations (Kato and Katsura 2014).

Use of crop simulation models can also clarify arguments on rice yield loss and causes of yield reduction in different rainfall conditions. Further, proper application of a simulation model to a cropping system at regional scale or ecological zone can aid in strategic decision making. For instance, under what conditions can rice yields be maximised in a specific environment and to what magnitude; what opportunities and practices can result in improved yields; and how can yield gaps be narrowed to achieve maximum yields for smallholder farmers? Unfortunately, application of crop models to understand rice production systems has not been widely or spatially done. Investigations in aerobic or upland rice cropping systems are few in equatorial tropical areas (Fukai and Ouk 2012), because basic information on crop parameters required for modelling purposes is rarely documented.

2.5.1 The Soil Water Balance (SWB-Sci) model and case studies

The Soil Water and Nutrient Balance (SWB-Sci) model was developed from the NEWSWB model of G.S. Campbell (Washington State University, Pullman, WA, USA), an improved version of the wheat growth-water balance model published by Campbell and Diaz (1988). Several versions of the improved model were later released, for instance the user-friendly version by Benadé et al. (1997). Developed by the Department of Plant Production and Soil Science, University of Pretoria originally as a real-time tool for irrigation scheduling, the model also has other applications, for instance the simulation of P dynamics in soil (van der Laan 2009). The model is commercially named SWB and a detailed description of it is published by Annandale et al. (1999). SWB-Sci is a generic crop (specific parameters should be determined for each crop), daily time step model and uses a mechanistic modelling approach to irrigation scheduling, and nutrient and salt balances. The weather, soil, and crop management units allow for integration of dynamics in the soil-plant-atmosphere continuum. This framework overcomes limitations of most models for irrigation scheduling by solving the problem of taking irrigation frequency into account (Annandale et al. 1999) and thus the model can be applied to rainfed conditions.

Modelling N dynamics in the soil-crop-atmosphere system in the SWB-Sci follows similar approaches to that of Cropping Systems Simulation Model [CropSyst] (Stöckle et al. 2003). CropSyst and SWB have similar backgrounds, having both evolved from work done by Prof. Gaylon Campbell from Washington State University. The major N transformation processes (mineralisation, immobilisation, nitrification and denitrification) are described in Stöckle et al. (2003). The N balance in SWB-Sci includes N transport, N transformations, ammonium sorption and crop N uptake. Solute movement in the soil profile is based on incomplete mixing, an approach similar to that by Corwin et al. (1991). The coefficient of mobility represents the percentage of solute to be cascaded to the next layer (van der Laan 2009). Mineralisation of N from its organic state to inorganic form (NH_4^+ or NH_3) is driven by the need of microorganisms and carbon (Lutz 1965). The SWB-Sci calculates first net N mineralisation, and immobilisation is regarded to occur if net N mineralisation is less than zero. The C:N ratio of crop residues is a key parameter used in estimating mineralisation and immobilisation (van der Laan 2009). Parameterisation of crop residues for the fraction and three carbon pools (active, slow and highly resistant) and simulations on inorganic transformations in the model are described in van der Laan (2010) and Tesfamariam (2009). Crop N demand is estimated from input parameters of plant N concentration: N:P ratio, root N concentration (kg kg^{-1} DM), maximum grain N concentration (kg kg^{-1} DM) and grain N partitioning coefficient of 1.0 for small grains. Notwithstanding the different N concentrations of crops, N dilution curves (indicate mobilisation of N from leaves to grains) are grouped for C3 (0.45) and C4 plants (0.38) (van der Laan 2009). Crop N uptake is estimated as the minimum of crop N demand and potential N uptake (Stöckle et al. 1994). It is noteworthy that while this approach assumes a passive flow – uptake is a function of soil water content and concentrations of NO_3^- and NH_4^+, uptake of N is also active. The above approach is very likely to underestimate crop N uptake especially in the early growth stages, where roots are superficial. Nitrogen concentrations for critical, minimum and optimum growth of rice are not available in the model. Some of the N input parameters were determined from the experiments in the present study and others were derived from available literature (Fageria et al. 2010). Crop growth is limited by N when above ground N concentration is between the critical and minimum level (Stöckle et al. 2003).

The model uses standard approaches such as those of Penman and Monteith (1977), and Tanner and Sinclair (1983) to determine if daily dry matter increment is transpiration- or radiation-limited and uses the lower value of the two. This permits simulation of crop growth and yield under both well-watered and water limiting conditions. Dry matter produced in a plant is partitioned to roots, stems, leaves and reproductive organs or head, depending on phenology. Partitioning of dry matter is influenced by WS and the model uses a stress index (ratio of actual to potential transpiration) to regulate allocation between plant organs. Crop development is governed by thermal time and growing degree days are calculated based on the crop base temperature, the measured average daily temperature and photoperiod (day length).

Movement of soil water in the profile is simulated using a cascading subroutine – water moves when a layer's soil water content is above the drained upper limit. Cascading is used once interception by the canopy surface and runoff are accounted for. The soil profile is divided into in 11 equal layers. This multilayer soil component of the model ensures realistic simulation of daily changes in water movement and uptake. Evaporation and runoff are outputs of the water balance in the topsoil layer (precipitation and irrigation are inputs), the thickness (0.03–0.05 m) depends on soil type. Drainage is estimated from drainage factor and daily water (mm) movement through the profile. Potential soil evapotranspiration (PET) is divided into potential evaporation (E) and potential transpiration (T) by calculating the canopy extinction coefficient for solar radiation (R_s) from the leaf area index (Ritchie 1972). Profile water uptake (U, kg m^{-2} s^{-1}) is calculated using a root density weighted soil water potential (Campbell and Norman 1988) as in equation 2.1.

$$U = \frac{(\Psi_s - \Psi_j)}{G_p} \quad \text{.......} 2.1$$

where Ψ_s (J kg^{-1}) is a profile root density weighted average soil water potential, calculated as the product of gravitational and matric potentials of a soil layer i, (Ψ_i), divided by the fractional root length of that layer, which decreases linearly with soil depth (Campbell and Diaz 1988). Ψ_l is the average canopy leaf water potential and G_p is the plant conductance (kg m^{-2} s^{-1}).

The minimum input requirements in the weather unit are precipitation and maximum and minimum temperatures. Rice has a base air temperature of 8–10^{o}C, an optimum range of 20^{o}C–30^{o}C and maximum temperature of 42^{o}C (Mathews et al. 1995; Bouman et al. 2001). Chilling conditions and high temperature affect rice spikelet sterility and grain yield, notably during panicle initiation and flowering (CGIAR Science Council 2006; Shrestha et al. 2011). However, when these cardinal temperatures are used as default in crop models, they may lead to some biased simulation of rice phenology, particularly in uplands. In uplands, soil temperature is subject to high variability in thermal regimes, which exposes growth of meristems to higher temperatures (Shrestha et al. 2013). In lowlands, growing points are submerged below water for most of the growing season (Shrestha et al. 2013), meaning that thermal time requirements to reach development stages of rice are different between the ecosystems.

The model uses the standardised FAO Penman-Monteith approach (Allen et al. 1998) to estimate reference evapotranspiration when measured data like R_s, vapor pressure and wind speed are absent. In the absence of crop-specific parameters, the FAO-based model, which makes use of crop factors in the database, can be used to simulate the soil water balance.

The SWB-Sci model has been shown to simulate the soil water balance, crop growth or plant productivity and nutrient dynamics reasonably well in several independent studies, among others Jovanovic et al. (1999), Jovanovic et al. (2000), Annandale et al. (2000), Annandale et al. (2011), Ghezehei et al. (2015), Tesfamariam et al. (2015) and Ogbazghi et al. (2016). These studies were done on different crops and soil water availability conditions. Overall judgment was that the model was successfully adapted and applied in the different cases.
Relevant to the present research, some studies which used the SWB-Sci crop growth model will be highlighted. In a study by Tesfamariam et al. (2015), the model simulated leaf area index amongst other parameters well, while the aboveground biomass and grain yield of maize and oats were simulated satisfactorily ($D > 0.85$; $MAE\% \leq 14$ and $R^2 > 0.8$). Dryland (rainfed) crops

or pastures comprised part of the independent data sets used for testing and validation results showed a slight overestimation of yield by 0.2–4 t ha^{-1}. Ghezehei et al. (2015) adapted the SWB crop growth model for predicting intercrop growth in rainfed silvopastoral systems. Crop yield (for independent data sets) of kikuyu (*Pennisetum clandestinum*) ($r^2 = 0.5$, MAE < 0.35) and cumulative yield of intercrop with *Jatropha ccurcas* ($r^2 > 0.5$, MAE < 0.57) were well predicted. Although Ogbazghi et al. (2016) used SWB-Sci to simulate N mineralisation from sludge, their findings on a significant influence of rainfall and temperature on the variable, moreover within an agro-ecological zone, highlights appropriateness of the model for scenario simulations. Detecting effects of spatial variability within a zone when often less anticipated is noteworthy. Rainfall and temperature are drivers of potential yields in crops and some of the key hypotheses of this thesis (in chapter six on yield gaps) are around rainfall regimes in the equatorial climate. Annandale et al. (2000) concluded that SWB was easily adapted to pea (*Pisum sativum* L.) under well-watered and deficit irrigation conditions and can be used to estimate water-use of the crop. Performance of the model was in accordance with growth analysis data, with the exception of one parameter, pod yield (RMSE of 1.5 t ha^{-1}) under stress conditions. Above all, SWB-Sci is robust and the success stories in rainfed conditions suggest that it should be suitable for simulation of upland rice, which is largely a rainfed crop in Africa.

CHAPTER 3

GROWTH, PHENOLOGICAL, AND YIELD RESPONSE OF UPLAND RICE (*Oryza sativa* L. cv. Nerica 4®) TO WATER STRESS DURING DIFFERENT GROWTH STAGES

I.N. Alou[ab], J.M. Steyn[a], J.G. Annandale[a] and M. van der Laan[a]

[a] Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, 0028 South Africa

[b] National Agricultural Research Organisation (NARO), Bulindi ZARDI, P.O. Box 101 Hoima, Uganda

This chapter is published in Agricultural Water Management as:

I.N. Alou, J.M. Steyn, J.G. Annandale, M.van der Laan, 2018. Growth, phenological, and yield response of upland rice (*Oryza sativa* L.) to water stress during different growth stages. Agric. Water Manage. 198, 39–52. https://doi.org/1016/j.agwat.2017.12.005.

Abstract

Rice (*Oryza sativa* L.) grown in uplands is exposed to variable soil water conditions and unpredictable periods of water stress (WS). The study was conducted to determine the impacts of WS imposed at different phenological stages on growth, phenology, recovery of source size, yield and water use efficiency (WUE) of upland rice. The popular cv. Nerica 4® grown in Africa was sown under a rain-out shelter for two seasons. Treatments included a well-watered control (CT) and stress imposed by withholding water for the duration of different stages: tillering (Ti), panicle initiation (PI), anthesis (AT) and grain filling (GF). Name codes used for treatments were thus: CT, STi, SPI, SAT and SGF. When water was withheld, soil water content in the 0–0.6 m soil layer dropped to approximately 50 % of plant available water, while stomatal conductance of the abaxial leaf surface and leaf area index decreased significantly, suggesting that severe stress was experienced. Growing degree days to reach the different growth stages were roughly equal in both seasons, even though sowing was in the mid and early summer of 2013/2014 and 2014/2015, respectively. Time to reach peak tillering could not be explained by temperatures and cumulative solar radiation during growth. The onset of reproduction was highly significant ($p < 0.0001$) delayed by WS, independent of whether tiller abortion occurred or not. Findings suggest that lower plant densities are recommended to cope with stress during PI, to reduce water loss and control unproductive tillers at harvest. It is concluded that stress during late reproductive stages, unlike during PI, does not alter crop duration and has a negligible effect on water loss and WUE. Farmers with limited irrigation water can try to avoid WS by making sure they irrigate during PI and save water during later reproductive stages.

Key words: Delayed development, plant available water, water stress, thermal time, water use efficiency, NERICA®

3.0 Introduction

About 11 percent of the global rice (*Oryza sativa* L.) cultivated area is in uplands (non-flooded, unsaturated soil) (IRRI 2002). Growing rice in non-puddled, unsaturated and well-drained soils (upland systems) (Kato and Katsura, 2014) is gaining popularity over flooded rice for various merits. This share is likely to increase, particularly because of growing recognition to save water in rice systems (Bouman et al. 2001; Kato et al. 2006). Growth in rice production and acreage in sub Saharan Africa (SSA) is estimated at 7.0% per annum and can ascribed to the release of improved New Rice for Africa (NERICA®) varieties (ARC 2007). These progenies are a result of interspecific crossings between African indigenous upland rice (*Oryza glaberrima* Steud) and Asian lowland rice (*Oryza sativa* L. Japonica) and were developed for low input systems (Jones et al. 1997). The yield of rice in rainfed conditions is comparatively lower in uplands (1.5–2.5 Mg ha^{-1}) than for lowlands (2.5– 4.5 Mg ha^{-1}) and approximately 30% lower under similar water supply conditions (ARC 2007; Kato and Katsura, 2014). This yield difference among Japonica rice varieties was marginal when water supply was unlimited (Kato et al. 2009), meaning that high potential varieties need full irrigation. Although water saving technologies, including aerobic systems, have reduced water inputs compared to conventional flooded rice (Tuong et al. 2004), levels of water application are still quite high. The irrigation strategy practiced in aerobic rice systems is to raise soil water content to about field capacity if rainfall is insufficient (Bouman et al. 2001). Investigations are therefore needed to determine the minimum water requirements for maximum rice productivity.

In most parts of Africa, upland rice is rainfed (Kijoji et al. 2014) and periods of WS are unpredictable due to poor rainfall distribution. Response of rice to WS generally varies with duration, intensity of stress (Heinemann et al. 2011) and most importantly, the growth stage when stress occurs. The three main growth phases of rice are the vegetative, reproduction and ripening stages, which are subdivided into 10 principle growth stages (Fageria 2007), and which overlap even within a single plant because the rice crop makes tillers of different chronological ages. Stress in rice plants was reported to develop at Ψ_{soil} < -86 kPa for lowland conditions (Bouman et al. 2001) and at Ψ_{soil} < -100 kPa in potted upland soil (Asch et al. 2005), but sensitivity of physiological processes such as transpiration and leaf expansion to WS differs along the crop cycle (Devatgar et al. 2009; Heinemann et al. 2011). Mechanisms to cope with WS in *Oryza sativa* L. are thus well documented for pot, screenhouse and lysimeter studies, although such conditions may not represent field conditions well (Parent et al. 2010; Kijoji et al. 2014). For instance, Ψ_{soil} between -60 and -140 kPa at 0–25 cm depth, which are reported as threshold values for lowland rice growth in anaerobic soils (Bouman et al. 2001), may be atypical of upland conditions; where (i) surface soil can be dryer than -600 kPa (Jensen et al. 1998) and (ii) roots can exploit soil layers deeper than 30 cm (Lilley and Fukai 1994).

Drought effects on rice growth depends on the timing thereof. Stress between germination and flowering was reported to delay development in lowland and in upland rice (Wopereis et al. 1996; Boojung and Fukai 1996), but the delay in development was much more pronounced in direct-seeded upland rice compared to transplanted lowland rice (Kijoji et al. 2014). Water stress during the ripening stage reportedly also hastens development (Dingkuhn and Le Gal 1996). The duration of these phases can also be altered by excess water (Dingkuhn and Asch 1999) and it remains to be investigated if upland rice is tolerant to some degree of soil saturation. Most studies, such as the one by Boojung and Fukai (1996), did not quantify thermal time, which makes it difficult to assess how sensitive the phenology of upland rice is to WS. Research that generates information on changes in growing degree day (GDD) requirements for different stages under water limited conditions will be useful for optimising crop production systems that entirely depend on rainfall, of which the distribution is usually uneven.

In addition to changes in the duration of different development stages, drought affects rice plants in various other ways. Stress between flowering and grain filling increases spikelet sterility (Matsuo et al. 2010), and during panicle initiation (PI) it inhibits panicle exertion (Okada et al. 2002), but Asch et al. (2005) reported that when stressed during vegetative growth, dry matter partitioning was not affected. Stress at one stage can also have cumulative effects on subsequent components, for instance tiller abortion with stress during early growth (Wopereis et al. 1996) may reduce panicle number (associated with tiller number) and the final spikelet number per unit area. No investigation considered the duration of development stages and demonstrated such effects with WS at all above stages in a single field study. Thus, relative yield loss due to stress during different phenological stages and ideal traits to cope with stress at each growth stage have not been studied well before. With respect to alterations in phenology, it has not been established if delay in flowering under vegetative stress may be a result of new tillers developing after relieve of severe stress (tiller abortion), tiller inhibition without death after mild stress, or due to alteration in dry matter partitioning between plant organs. It is noteworthy that rice tillering is spread over time. Delays in phenology has been related to size of source or canopy, and recovery, dry matter partitioning and growth stage in relation to leaf number (Boojung and Fukai 1996; Prasertsak and Fukai 1997; Bouman et al. 2001), with some contrasting reports. An aspect that has not been well reported is whether recovery of source capacity (e.g. canopy size) after stress will be to the same level as for a well-watered control, and whether it will affect the final grain yield. Clarification of source-sink relations is needed since WS during vegetative growth is known to slow development of rice. The crop therefore continues to grow (accumulates dry matter) but at a decreasing rate. It is noteworthy that crop development is different from growth. A crop that has recovered from stress can be of the same canopy size and similar height as a well-watered one, but at a different development stage. It is also important to identify desirable traits for yield improvement with stress during different development stages in view of variable and cumulative effects of WS on growth and changes after recovery. There is lack of information on effects of drought stress during different development stages on phenology (thermal time accumulation), sink-source relations when the stressed crop attains a similar development stage as a well-watered crop, and water use efficiency (WUE). This information is scarce because of a paucity of field studies on WS in rice, especially in unsaturated uplands (Kato et al. 2006), despite the significance of the crop.

The specific objectives were:

(i) To evaluate dry matter partitioning and leaf N content when a crop that recovered from WS, compared to a well-watered control.

(ii) To quantify water use and WUE when a rice crop was stressed at different development stages.

It is envisaged that this research will inform upland rice growers on best management practices to minimise yield loss under WS.

3.1 Materials and methods

3. 1.1 Planting material and soil analysis

Upland rice NERICA 4® (WAB450-I-B-P-91-HB) (Jones et al. 1997; Ndjiondjop et al. 1998) seed was acquired from the National Crop Resources Research Institute (NaCRRI) in Uganda. Variety NERICA® 4 is widely adopted in West and East Africa (Africa Rice Centre, 2007) and was chosen because of its high grain yield, estimated at 4.7 Mg ha^{-1} under rainfed conditions, and because it is still the top-ranked variety in Uganda (Lamo et al. 2010; Imanywoha et al. 2004). Furthermore, farmers prefer NERICA® 4 to other NERICA varieties for its heavy grains and medium growth duration.

Prior to the experiment, five soil samples were taken from the 0–0.2 m, 0.2–0.4 m and 0.4–0.6 m layers in a zig-zag pattern. The sub-samples from each layer were mixed to form a composite sample for analysis of soil physical and chemical properties using the following methods. Soil pH (1: 5 soil: water) was determined using a pH meter, soil organic matter (Walkley and Black 1934) and available P (Bray 1) using the Bray (1945) method as described in AgriLASA (2004). Soil texture was determined by the hydrometer method (Bouyoucos 1954). Inorganic N in the soil was extracted by shaking samples in 1 mol dm^{-3} potassium chloride solution [1:5 (mass basis) soil : KCl solution] for one hour (Bremner and Keeney 1966), and then filtered (Whatman® No. 2 filter paper, Sigma-Aldrich Co. LLC, California, USA). In 2014/2015, inorganic N [nitrate (NO_3^-) and ammonium (NH_4^+)] were determined using steam distillation (Büchi 321 Kjeldahl unit, LABEQUIP, Ontario, Canada) and Magnesium oxide (MgO), Devarda's alloy and boric acid-indicator solution (Keeney and Nelson 1982). Ammonium-N was determined by titrating with 0.005 M sulphuric acid (H_2SO_4).

3.1.2 Study site and rain-out shelter experimental set-up

The trial was conducted in a rain-out shelter on the Hatfield Experimental Farm of the University of Pretoria, South Africa (located at 25° 45′ S, 28° 16′ E and 1370 m a.s.l.), from

December 2013 to June 2014 (season 1) and from October 2014 to April 2015 (season 2). Daily solar radiation, minimum and maximum air temperatures and relative humidity and wind speed were recorded, and short grass reference evapotranspiration (ETo) was calculated by an automatic weather station located approximately 100 m from the rain-out shelter. Vapour pressure was calculated from relative humidity and temperature. Daily weather parameters during stress periods in the two years are presented in Table 3.1.

The soil at the site is a deep Hutton (MacVicar et al. 1977), loamy, kaolinitic, mesic, Typic Eutrustox (Soil Classification Working Group 1991), with an effective depth of 1 m. Soil characteristics over the top 0.6 m depth were: pH (water) 5.8 ± 0.14, 0.5 ± 0.06% C, 4.3 ± 2.4 mg kg^{-1} mineral N, 15.9 ± 11.01 mg kg^{-1} available P (Bray I), 95.6 ± 39.7 mg kg^{-1} K, 1377 ± 48 mg kg^{-1} Ca, 159.8 ± 29.4 mg kg^{-1} Mg, 10.2 ± 1.6 mg kg^{-1} Na, 1400 ± 40 kg m^{-3} dry bulk density, 0.3 ± 0.02 m^3 m^{-3} field capacity, 0.2 ± 0.02 m^3 m^{-3} permanent wilting point, 59.7 ± 1.2% sand and 33.3 ± 2.9% clay and 7.0 ± 2.8% silt. Soil characteristics of the 0–0.6 m depth were relatively similar, except for the 0.4–0.6 m layer, where available P (3.74 mg kg^{-1}) was substantially lower and pH water (5.9) was slightly higher than in the top 0–0.4 m layer. Soil mineral N (NH_4-N + NO_3-N) also varied greatly with depth, 6.8 mg N kg^{-1} at 0–0.2 m, 4.1 mg N kg^{-1} at 0.2–0.4 m and 2.0 mg N kg^{-1} in the 0.4–0.6 m layer. In the second season, the experiment was laid out on the opposite side of the rain-out shelter, which was rested in the first season.

3.1.3 Agronomic practices

Seeds of Nerica 4® were manually sown directly at about 0.03 m depth in dry soil. Sowing was done on 5 December 2013 (mid-summer) and 7 October 2014 (early summer) in the respective seasons. An inter-row spacing of 0.25 m was used in plots measuring 3.75 m × 2.75 m and separated by 0.75 m walkways. Before sowing, N:P:K [4-3-4(30)+Zn] fertilizer was applied at a rate of 54 kg N, 40.5 kg P and 54 kg K per hectare and incorporated into the soil. Limestone Ammonium Nitrate (28% N) was top dressed on 43 and 46 days after emergence (DAE) in seasons 1 and 2 at a rate of 66 kg N ha^{-1} so that total N applied was equivalent to 120 kg N ha^{-}

[1]. Fertiliser rates were based on guidelines for NERICA provided by the Africa Rice Centre (ARC) and timing of top dressing was done to optimize N uptake (ARC 2007; Fageria 2007). Prior to implementation of drip irrigation, sprinklers were used to irrigate about 15 mm weekly from sowing to 10 DAE in season 1 and to 7 DAE in season 2. Typical quality of the irrigation water used was: EC (12–41 mS m^{-1}), pH (7.7–8.2) and TDS (20–160 mg L^{-1}). All other chemical properties were within allowable levels for safe use (AQUA Earth, University of Pretoria, 2017). Plants were thinned at 20 and 22 DAE in the respective seasons, leaving 25 plants per metre row length, to achieve a spacing of 0.25 m × 0.04 m, equivalent to a population of $1x10^6$ plants ha^{-1}. Soil water deficit in the 0–0.4 m soil layer was replenished to field capacity twice weekly (except for water stress treatments) until a month before harvest, using a high-density drip irrigation system. Profile soil water content (θ) was estimated at 0.2 m depth intervals from readings of a neutron probe water meter (Model 503DR CPN Hydroprobe; Campbell Pacific Nuclear, California, USA) that was calibrated for the site. Weeds were regularly removed by hand and rice plants across plots were uniform before imposing treatments. Malathion® (active ingredient *O*,*O*-dimethyl phosphorodithioate) was sprayed once for aphids and Tiforine® (active ingredient azoxystrobin) for rice blast, according to manufacturer instructions. Symptoms of the disease were mild and aphid damage was minimal because spraying was done at an early stage of incidence.

3.1.4 Identification of development stages

Visual observations were made to characterise crop phenology. The Zadoks decimal code for cereals was used to describe the development stages (Zadoks et al. 1974; Fageria et al. 2010) before and after introduction of stress treatments. Development stages of rice as described by IRRI (2002) were identified based on morphological features, for instance mean tiller number during the active tillering stage and grain colour and texture during physiological maturity. The panicle initiation stage was marked by the observation of a furry tip of panicle primordium above the growing points under a light microscope. Four main stems were weekly randomly sampled from day of second tiller appearance (about 21 DAE) until peak tillering. Stems were cut just above the crown, hydrated in glycerol for 24 hours and dehydrated in sequential concentrations of ethanol for subsequent days (James and Tas 1984). Longitudinal sections were prepared and examined under a microscope. The number of folded and open leaves counted under a microscope was used to confirm stages.

3.1.5 Experimental design and water stress treatments

The trial was laid out as a completely randomized block design (CRBD) with three replications. The five water treatments were randomly allocated to each replicate, giving a total of 15 plots. All plots were well irrigated until a growth stage (GS) of interest was reached, whereafter water was withheld completely to induce WS from the onset of the following development stages (DVS): tillering, panicle initiation, anthesis or 50% flowering and grain filling. The five treatments were as follows:
(i) CT (well-watered control): Irrigating twice weekly (2–4 day interval) to replenish the soil water content in the top 0–0.4 m soil layer to field capacity.
(ii) STi (stress during tillering or early vegetative stage) or DVS 0.4: from GS 2.3 (two tillers per plant on average) to GS 6.0.
(iii) SPI (stress during panicle initiation or early reproductive stage) or DVS 0.53: from GS 6.0 (panicle primordium visible under a microscope) to GS 10.3.
(iv) SAT (stress around anthesis) or DVS 0.90: from GS 10.3 (50% of the stems have flowered, flowers may just be emerging for some tillers) to GS 11.2.
(v) SGF (stress around grain filling stage II or soft dough stage) or DVS 1.0: from GS 10.2 (grains are turning from green to brown and are not milky anymore) to GS 11.3 or DVS 2.0 [physiological maturity (PM), flag leaf drying and 90% grains are brown].

Initiation of the stress treatments above was based on crop development under well-watered conditions. Irrigation in all plots was terminated on the same day during both seasons. The periods of stress (days after emergence) in season 1 were: STi (43–66), SPI (66–95), SAT (95–117) and SGF (117–144) and in season 2 were: STi (51–75), SPI (78–101), SAT (101–121) and SGF (121–138). Due to one incident in season 2 when the rain-out shelter failed to close during a rainfall event, stress was ended prematurely during tillering and slightly delayed in panicle initiation. Temporary portable rain-out structures were then constructed and placed over each of the plots that was stressed during PI whenever there was a threat of rain. The structures were used for five days only until the shelter was repaired.

3.1.6 Plant growth analysis, yield and leaf N uptake

Plant height and number of tillers was monitored weekly on 10 plants in the centre row of each plot. Plant height was measured from the ground surface to the tallest green leaf. Tillering was monitored at least weekly from the date of first tiller appearance (GS 2.0) at 19 and 17 DAE in the respective seasons, but more frequently in the earlier stages before anthesis. Tillers were also counted on sampled plants during biomass measurements. For destructive growth analysis sampling, 14 plants were sampled weekly (from 30 to 130 DAE) from an area of 0.5 m x 0.25 m per treatment by carefully cutting off the plants at ground level. In some occasions, biomass harvests were done after 10 days from the previous date of harvest. Leaf blades were separated from the stems and passed through an LI-3100 leaf area meter (LiCor, Lincoln, Nebraska, USA) to determine leaf area and to calculate leaf area index (LAI). Stems, leaves, panicles and grains were separated and DM yields were determined after oven drying the samples at 65 –70 ^{o}C for at least 48 hours or until constant mass.

At final harvest, aboveground dry matter (ADM) yield was determined by cutting off all the plants at ground level from a net plot area of 1.75 m x 1.50 m (excluding border rows). Total biomass was weighed fresh for moisture content determination and grains were separated from the stover after threshing. The mass of grains (less empty grains) and stover was weighed on a scale (0.1 kg precision). Sub-samples of the stover (90–120 g) and grain (~20 g) from each plot were oven dried at 65 ^{o}C for at least 48 hours. Total dry biomass yields were then calculated from the fresh yields and dry matter contents of the different components. Grain yield was adjusted to a 12% moisture content for comparison with commercial harvests.

To assess N uptake of stress-recovered and well-watered crops, flag leaves from the main stems of 25 plants in each plot were sampled 25–30 days after heading (DAH) and before grain filling. This stage marks peak N accumulation in rice flag leaves, which is critical during grain filling (Shiratsuchi et al. 2006). Leaves were dried and analysed for total N content using the Dumas method in N Pro-Rapid Nitrogen / Protein Analyzer equipment (Dumatherm®, C. Gerhardt GmbH & Co., Königswinter, Germany). Yield components were assessed by considering plants sampled from a 0.75 m x 0.5 m subplot. Stems were counted and recorded as either non-productive tillers (without panicles) or tillers with panicles. Ten panicles were randomly selected from each plot and their lengths measured. The spikelets in each panicle were detached and counted to determine the number of spikelets and panicle size. The mean number of spikelets from 10 panicles was then expressed per unit area. Spikelets were floated in water to separate empty and full grains, oven dried and weighed. Full grain ratio and sterility were computed as the ratio of full or empty grain mass to the total spikelet mass. Full grains were counted using a seed counter (Numigral®, Triplette and Renaud, Paris, France) and the mass of 1000 grains was weighed. The mass was standardized to 12% moisture content to determine the 1000 grain mass.

3.1.7 Measurement of radiation interception, water stress and soil water content

Interception of Photosynthetically Active Radiation (PAR, 0.4–0.7µm) by the canopy was determined at least three times every month by measuring photosynthetic PAR above and below the canopy at ground level with a 1 m long Decagon Sunfleck Ceptometer (Decagon Devices, Pullman, Washington, USA). Four points were measured diagonally across rows in each plot and the average value was computed. Profile soil water content (θ) at 0.2 m depth intervals was estimated from the readings of a neutron probe (Model 503DR CPN Hydroprobe, Campbell Pacific Nuclear, California, USA) that was calibrated for the site. At the start of the experiment and before planting, soil samples were taken at 0.2 m depth increments using an auger. Composite samples from each depth were analysed for soil chemical and physical properties. A soil water retention curve (SWRC) for the top 1 m soil layer was also determined using a WP4-T Dewpoint Hygrometer (WP4-T PotentiaMeter®, Decagon Devices, Inc., Pullman, Washington, USA) with an accuracy of ± 0.1 MPa after calibration with the gravimetric method (van Genuchten et al. 1991). The SWRC was also plotted in a log-scale (log-pressure head, cm) using a software for describing hydraulic properties of unsaturated soils (RETC®, Scientific Software Group, Salt Lake City, Utah, USA). The curves for different depths were used to calculate the actual values of Ψ_{soil} during dry periods. Soil water pressure head (h) was estimated from values of θ (mm), using a graph of θ vs. h, and h was then converted into soil Ψ_{soil} using the equation below.

$\Psi_{soil} = \rho_w \times g \times h$……………………………………(3.1)

where; ρ_w = the density of water (1000 kg m^{-3}), g = acceleration due to gravity (9.8 m s^{-2}) and h (m). Pressure head is a negative value. Field capacity (FC) and permanent wilting point (PWP) were then estimated from the SWRC. Evapotranspiration (ET) was calculated using the soil water balance equation (Allen et al. 1998),

$I + P = ET + \Delta S + D + R$ ………………………(3.2)

where; *I = Irrigation, P = Precipitation, D = Drainage and R= Runoff.* P, D and R were considered negligible. During stress periods water inputs were zero (except for one event when the shelter failed to close in 2014/15). The change in storage (*ΔS*) was calculated as the difference in soil water content between consecutive neutron probe readings. During stress periods, the first neutron probe readings were taken about three days after the last irrigation. This was considered as the start of stress when calculating the initial θ. Soil water content calculated at the end of the water stress period was taken as terminal θ. Stomatal conductance (g_s) on the upper (adaxial) and lower (abaxial) surfaces of the uppermost fully expanded leaf was occasionally measured using a Decagon SC-1 Leaf Porometer (Decagon Devices, Inc., Pullman, Washington, USA). Four replicate stomatal conductance measurements per plot were taken at around 11:45–15:20 (range of time for all readings made in both seasons) on the same plants from the start to the end of stress periods. A measurement in a plot under stress was followed by a measurement in a well-watered plot to avoid any bias that could arise by delayed timing of measurements. Stomatal response to water stress was later expressed as the mean relative value, that is, the ratio of mean g_s under stress to mean g_s for the CT to normalise variations in atmospheric demand between stages during stress. It was not possible to take frequent measurements of g_s due to unavailability of the porometer and therefore the number of measurements during stress was not equal between growth stages.

3.1.8 Computation of crop growth parameters

Crop growth parameters were calculated in Excel spread sheets using equations described by Watson (1956); Lopes et al. (2010) and Fageria et al. (2010). Crop dry matter accumulation rate (g m^{-2} d^{-1}) was calculated as the increase in ADM from the harvested land area per unit time. The total one-sided leaf area (m^2) was divided by the sampling area (m^2) to obtain the leaf area index (LAI) on days of growth analysis sampling. Leaf area duration (LAD) between harvests was calculated as the area under the LAI curve over time, which mathematically is an integral of LAI over time. Thermal time to reach different growth stages was calculated by accumulating daily growing degree days (^{o}Cd) from sowing, using a base temperature of 8.2 ^{o}C for African rice and crosses thereof (Shrestha et al. 2011). Dry masses of individual plant parts were summed to obtain ADM.

The apparent contribution of photosynthesis or reserve assimilates from pre-reproductive stages to grain filling (DM_c) was calculated using the equation 3.3 by Yoshida et al. (1972):

$DM_c = ADM_m - ADM_{xi}$……………………………….(3.3)

where ADM_m is the above ground dry matter yield at maturity and ADM_{xi} is the above ground dry matter yield at either pre-flowering or pre-anthesis in the case of this study. The apparent contribution was then expressed as a percentage of (ii) ADM_m and (ii) the final grain yield. Grain harvest index (HI) was computed as the ratio of grain mass (fully developed grains) to total ADM on a dry mass basis. Sink size was calculated as the product of the mass of 1000 grains and number of grains per square metre (Kato et al. 2006). Dry matter efficiency (DME) was calculated as the harvest index divided by the number of days to crop maturity (Watson 1952). Dry matter efficiency was calculated because of delay in physiological maturity for one treatment. The relative decline in growth and yield was calculated as the difference in the parameter between a water stress treatment and the CT divided by the yield for the CT (stress index). Water use efficiency was calculated during stress periods and for the entire season. During stress, WUE was calculated as the difference in ADM (kg m^{-2}) between the start and end of stress divided by ET (mm) and for the entire season as grain yield (in kg ha^{-1} on dry mass basis) divided by total ET (mm).

3.1.9 Statistical analysis

The General Linear Model (GLM) Procedure in SAS® 9.3 version 6.1.7061 for Windows (Cary, NC, SAS Institute Inc., 2012) was used to perform statistical analyses. Correlation analysis were performed on selected growth parameters and derived parameters during stress, for crop growth rate and final yield components under stress and well-watered conditions to determine the degree of relationship and their contribution to variation in yields. Pearson's correlation coefficient (r) was used to indicate the most consistently related yield component to grain yield. Analysis of variance (ANOVA) was performed with treatments and seasons as factors, growth, yield and water status indicators as variables. Means for main and interaction effects were separated using Tukey's Studentized Range test at 0.05, 0.01, and 0.001 levels of significance. In order to test for statistical differences in weather parameters that determine crop water use between seasons, the F- test (two –sample for variances) was applied for every pair of daily temperatures, ETo and VPD.

3.2 Results

3.2.1. Weather conditions, crop phenology and development

The measured mean maximum and minimum air temperatures of 27.4 °C and 14.9 °C (season 1) and 29.2 °C and 15.6 °C (season 2) were optimal for rice growth, especially during critical stages of booting to flowering. Evaporative demand during the experimental period was fairly similar between the years (Table 3.1). Average reference evapotranspiration from sowing to physiological maturity (PM) (period of approximately 149 days) was 3.93 and 4.59 mm day^{-1} in season 1 and 2, respectively. The average VPD was also similar during periods of water stress, meaning similar intensities of stress. Table 3.1 further shows that the seasonal means were similar, although variances for seasonal averages were significant (except for VPD). Unequal variances in the weather parameters is expected since sowing was on different Julian calendar days of the year (DOY). The similar VPD between seasons and during periods of water stress, suggests similar intensities of stress. The duration of stress periods per growth stage was approximately equal for each season, except for the SGF treatment in season 2, which was 10 days shorter, as grain filling coincided with hotter weather conditions.

Table 3.1 Mean maximum, and minimum temperatures, mean vapour pressure deficit and mean reference evapotranspiration between stress periods during growing seasons at Hatfield experimental farm, Pretoria.

Year	DAE†	Parameter			
		T_{max} (°C)	T_{min} (°C)	Average VPD (kPa)	Average ETo (mm day^{-1})
2013/2014	1–42	28.7	16.3	1.47	4.65
	43–66	29.8	17.2	1.52	4.78
	66–95	26.2	16.5	0.98	3.27
	95–117	26.1	13.4	1.16	3.46
	117–144	24.6	9.1	1.16	2.86
Average		27.3	14.8	1.28	3. 93
2014/2015	1–51	28.5	14.1	1.66	4.56
	51–75	28.0	16.6	1.22	4.79
	78–100	30.1	16.8	1.57	4.95
	100–120	31.1	16.9	1.75	4.84
	120–138	30.0	15.8	1.71	4.56
Average		27.4	15.0	1.29	4.59
F-test		*	*	ns	*

†days after emergence on 15th December 2013 and 17th October 2014.
The periods before first stress treatment are 0–42 and 0–60.
*significant at $p < 0.05$ for paired data of parameters between years.
ns, not significant.
Mean values calculated for the period from first day of withholding water to the last day of stress.
Mean values calculated for the period from first day of withholding water to the last day of stress.

Development stages of upland rice with stress before flowering and in the CT are presented in Figure 3.1. Before imposing stress, onset of the stages was the same across plots since crop management was similar. Stages with stress during anthesis and grain filling were quite similar with those in the CT and are therefore not presented.

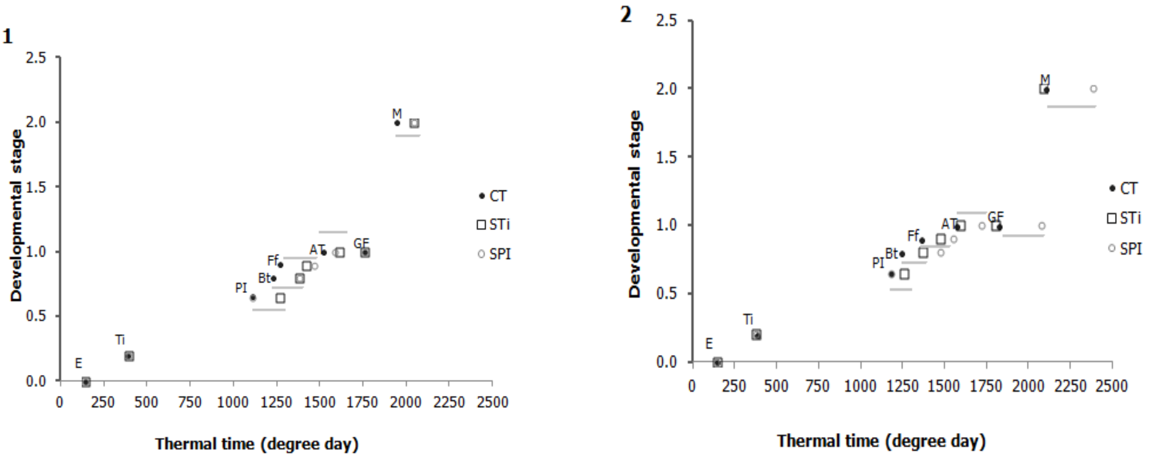


Figure 3.1 Thermal time requirement of upland rice cv. NERICA®4 in a well-watered control (CT) and with stress during tillering (STi), and panicle initiation (SPI) in season 1 and 2.

Horizontal grey lines represent the shift (increase in °Cday) for the same stage under stress. Development stages are indicated by E (emergence), Ti (first tiller), PI (panicle initiation), Bt (mid booting), Ff (first flower), AT (anthesis), GF (grain filling or soft dough stage) and M (physiological maturity) according to IRRI (2013) phenology definition.

Thermal time requirements to reach the different growth stages were similar between seasons for the well-watered control. Growing degree days to emergence was 140 ± 0.8 °Cd, 389 ± 1.0 °Cd to first tiller appearance and 1780 ± 24 °Cd to grain filling, averaged across years. At the time of imposing WS, plants were already past the first two stages while for grain filling, GDD was similar across treatments. Growing degree days to reach peak tillering (DVS = 0.2) differed between seasons under well-watered conditions (Table 3.2). Peak tillering stage in both years was characterised by the same mean number of tillers. Approximately the same GDDs were required in both seasons to reach first flower appearance (1219 ± 68 °Cd) and anthesis (1544 ± 36 °Cd). For tillering stage, maximum tiller number was attained around flowering (71 DAE) in season 1 and slightly earlier, at around booting (53 DAE) in season 2. This was equivalent to 368 ^{o}Cd more in the 2013/2014 season than in 2014/2015.

Stress imposed before first flower appearance delayed booting, flowering and anthesis highly significantly ($p < 0.0001$). In particular, stress during early reproductive growth increased GDDs to booting, first flower and anthesis stages more than stress during tillering (Table 3.2). The increase in thermal time to first flower (197 ± 2 ^{o}Cd) and to anthesis (120 ± 45 ^{o}Cd), averaged over the two seasons, was therefore considerable due to stress during PI. In contrast, the GDD to anthesis with stress during tillering was almost the same (+45 ^{o}Cd) as for well-watered plants to reach the same stage, in spite of considerable delay in appearance of the first flowers for STi, compared to the well-watered control. Stress during anthesis and grain filling did not affect development (except accelerated maturity for SGF) as much as other treatments, when compared to CT. The interaction effect of stress and season on onset of development stages, thus GDD, was highly significant ($p < 0.0001$), with slightly longer durations under stress in season 2 than season 1. Again, there was little variation in GDD for CT between years. Stress generally did not alter the time to maturity and GDDs were similar to that under well-watered conditions, except in season 2 when maturity for SPI was about 23 days (~285 ^{o}Cd) longer than for CT. Leaf area index and FI of solar radiation during 120–139 DAE were significantly higher for treatments that were stressed during Ti and PI than for the CT

Table 3.2 Growing degrees days of Nerica 4 to reach selected development stages for a well-watered control and for stress treatments during tillering and early reproductive stage.

Year, stages observed	Thermal time (°Cday) under treatments		
	CT	STi	SPI
2013/2014			
Peak tiller†	1201[a]	1505.61[b]	1201[a]
Panicle initiation	1111[a]	1267[b]	1111[a]
Mid-booting	1229[a]	1378[b]	1404[b]
First flower	1267[a]	1415[b]	1463[c]
Anthesis	1518[a]	1606[b]	1581[b]
Maturity	1947[a]	1947[a]	2041[a]
2014/2015			
Peak tiller†	833[a]	861[a]	833[a]
Panicle initiation	1192[a]	1206[b]	1192[a]
Mid-booting	1241[a]	1385[b]	1489[c]
First flower	1358[a]	1489[b]	1569[c]
Anthesis	1581[a]	1609[b]	1732[c]
Maturity	2099[a]	2086[a]	2384[b]

Note: Means followed by same letter within a row are not significantly different at $p = 0.0001$.

† DVS = 0.2 was the only stage with different GDD values between seasons. Within seasons, variation in GDD to peak tiller between plots that were subjected to water stress was negligible and in 2014/2015, it was very small.

3.2.2 Crop growth and recovery- flowering duration, tillering and plant height

Although plants exposed to the SPI treatment took long to flower, in season 2 some flowering was observed during the stress in all replicate plots. This was not anticipated but it might have been that thermal time to flowering accrued while still under stress and plants absorbed soil water from deep layers. Figure 3.2 indicates that flowering duration, measured as a percentage of stems with flowers on each date of measurements, was significantly ($p < 0.001$) longer for stress during PI than for stress during Ti. Stress during flowering (SAT) did not affect flowering rates. Likewise, flowering in plants stressed during grain filling (SGF) was also similar to that for CT. Plot-to -plot variation in ontogeny of plants and in flowering rates was negligible between replicates.

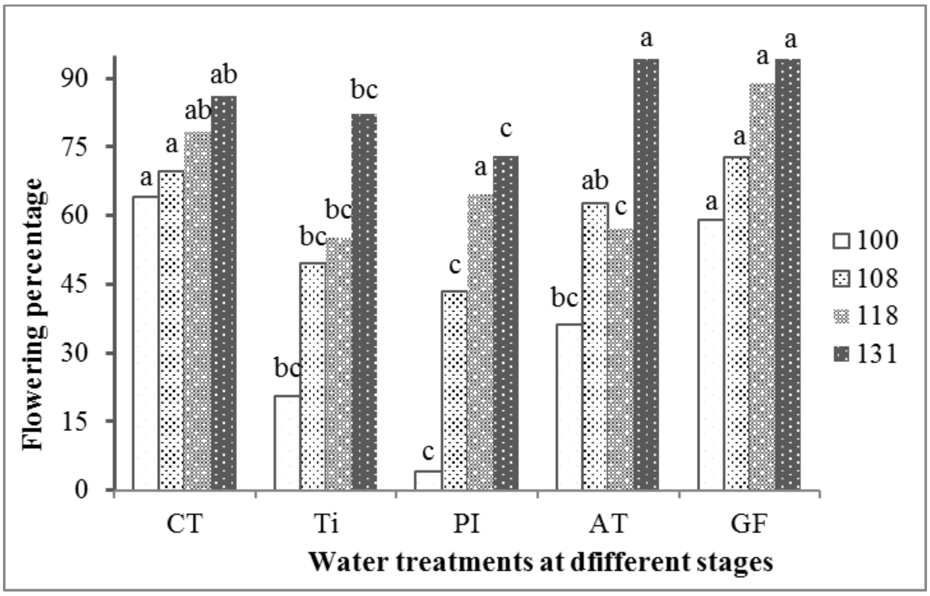


Figure 3.2 Flowering proportion under stress treatments compared to a well-watered control (CT), from 100 to 131 DAE. Bars fllowed by the same at each DAE are not significantly ($p > 0.05$) different by Tukey's Studentized *post hoc* test.

Most plant growth parameters were affected by stress and the interaction of treatment and season on growth during stress was also significant ($p < 0.05$), except for plant height. Results of both seasons are shown in Figure 3.3. Tillering was suppressed by stress in season 1 only, but mean number of tillers for SPI was similar to CT (Figure 3.3a). It is apparent in Figure 3.3a and Table 3.2 (season 1) that first peak of tiller growth for SPI was at 71 DAE and after the relieve of stress, it peaked again at around 108 DAE. However, in season 2 tillering ability was not significantly ($p > 0.05$) suppressed by stress, relative to CT and tillers were not aborted. As a result, the number of tillers per plant and tillers m^{-2} with early reproductive stress was similar to that of CT in season 2 (data on latter not presented). This can probably be explained as follows: by the time water was withheld for SPI plots in season 2, plants had already attained maximum tiller number and consequently there was virtually no tiller abortion due to stress, as can be seen in the growth analysis results presented in Figure 3.3b.

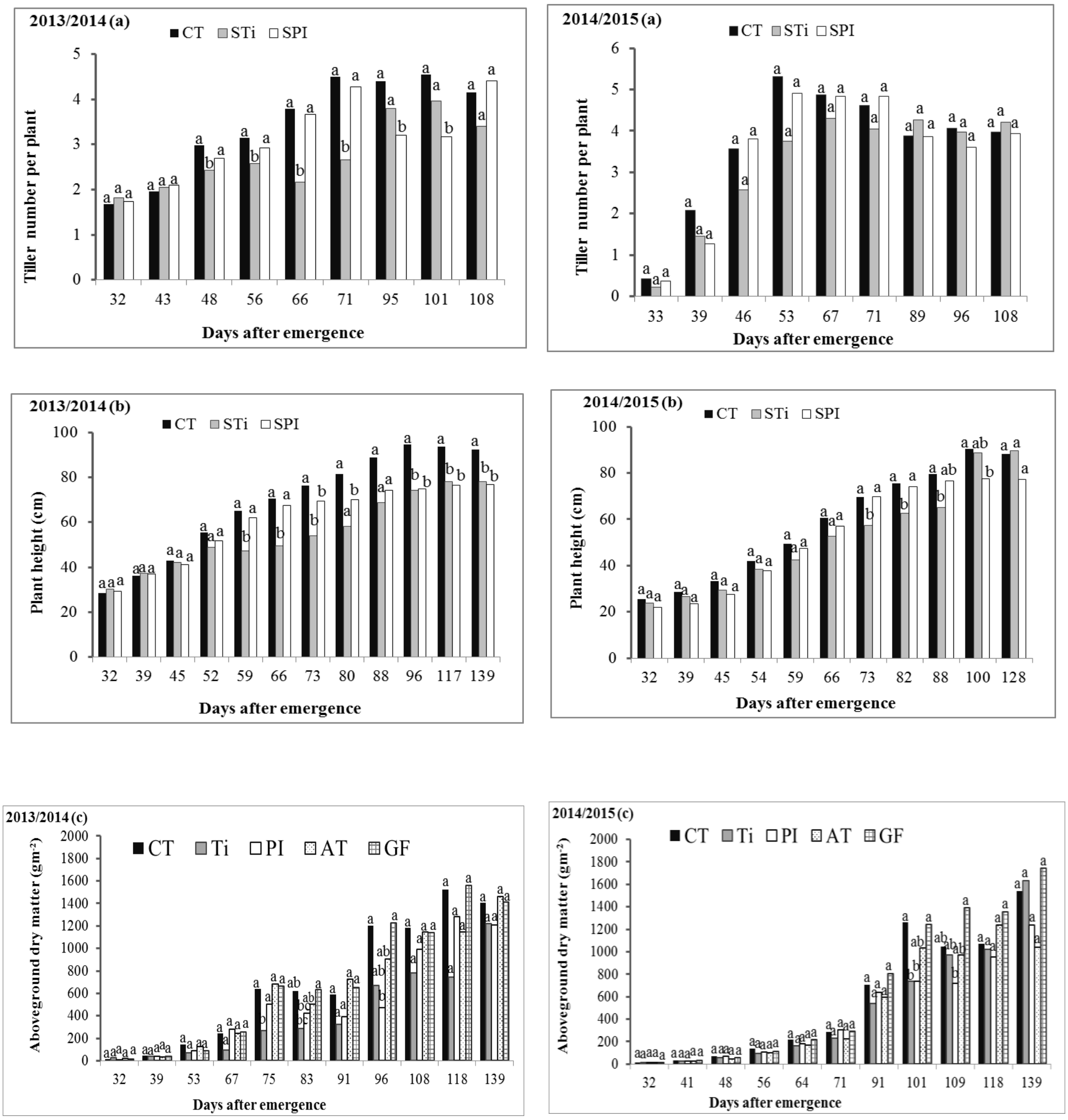


Figure 3.3 Changes in (a) tiller number and (b) plant height with stress during tillering (STi) and early reproductive (SPI) stages and (c) aboveground dry matter yield for all treatments, in comparison to a well-watered control in the seasons 1 and 2. Means followed by the same letters on the same day after emergence are not significantly ($p < 0.05$) different by Tukey's Student's test.

During plant growth analysis, significant differences in tillers m^{-2} between SPI and CT were detected only at the termination of stress (95 DAE), and the first flowers had already appeared in plants under stress. The average tiller number (grand mean = 4.13±0.42 per plant) in stressed and well-watered treatments was similar at 118 DAE, but the number of panicles m^{-2} at harvest was significantly ($p = 0.028$) lower for STI and SPI (in season 2 only). Therefore, more tillers did not produce under stress compared to well-watered conditions, because of more mutual shading by the canopy of a recovering crop, i.e. larger green LAI and FI values than CT post anthesis.

Plant height increased, albeit at a decreasing rate, for the rest of the stress periods of STi. Table 3.3 shows the change in growth, gs and Θ during stress period. Plant height was reduced by 30% in season 1 and by 17.8% in season 2 for the STi treatment, compared to only 20.8% and 14.3% for the SPI treatment relative to the CT, respectively. Reduction in green LAI was substantial compared to reduction in leaf dry matter yield during stress for the SAT and SGF treatments, unlike for the STi and SPI treatments (Table 3.3). Thus, these changes mean that specific leaf area (SLA, m^2 kg^{-1}) greatly reduced for especially SAT treatments.

Crop recovery from stress was more visible for tiller number than plant height, as at harvest tiller densities were similar, but plants significantly shorter for stress treatments than the CT. Aboveground biomass yield was not affected during stress periods, but several days after resumption of irrigation, differences relative to the control were significant. Pearson correlation analysis revealed that biomass production was well explained ($p < 0.05$; $r = 0.48$) by LAD during stress periods. The overall relationship of biomass and LAD for an entire season was strong in season 1 ($p < 0.05$; $R^2 = 0.78$), but this relationship was weak in season 2 ($R^2 = 0.30$).

Table 3.3 Decline in soil water content, mean ratio of stomatal conductance in stressed to unstressed control, and relative reduction (%) in growth parameters at the start and end of stress periods.

Parameter	2013/2014				2014/2015			
	STi	SPI	SAT	SGF	STi	SPI	SAT	SGF
Soil water content† (mm)	19.4	13.7	33.7	17.2	38.8	43.9	16.03	25.0
Adaxial g_s ratio†	0.99	0.74	0.77	0.94	0.82	0.49	1.26	< 0.2
<u>Relative reduction (%)</u>								
Aboveground dry matter	61.5^{ns}	61.0***	24.6**	(0.5‡)^{ns}	18.9*	41.5*	1.5*	1.3*
Leaf dry matter	61.1*	45.7*	5.1^{ns}	3.1^{ns}	18.5**	20.5**	(15.2‡)	(18.6‡)
Leaf area index	87.2**	47.8**	86.7**	81.3**	48.4**	75.7**	80.8**	82.2**
Plant height	30.8***	20.8***	0.1^{ns}	0.003^{ns}	17.0*	14.0^{ns}	0.6^{ns}	0.006
Tillers m^{-2}	35.8**	30.4^{ns}	17.8^{ns}	0^{ns}	6.8^{ns}	2.6^{ns}	0.6^{ns}	0^{ns}

Relative reduction (%) is the difference between a stress treatment and the control as a fraction of the control.

^{ns} not significantly different from the control at p = 0.05 level of probability.

* Significant at $p < 0.05$, ** Significant at $p < 0.01$, *** Significant at $p < 0.001$.

(‡) Represent an increase rather than a decrease as values of abaxial g_s during stress and leaf DM at the end of stress for SAT and SGF treatments were slightly greater than the CT.

† Soil field capacity in the top 0.6 m layer = 168 mm.

3.2.3 Soil water content, leaf morphology and stomatal conductance

The initial θ before onset of stress was similar across all treatments, with small differences ranging 2–5 mm (2013/2014) and 2–7 mm (2014/2015) per soil layer (Figure 4.2). Soils for all treatments then dried to the following ranges (percent plant available water remaining per layer): 34–45% at 0–0.2 m, 49–51% at 0.2–0.4 m and 55–69% at 0.4–0.6 m on average across seasons. The amount of soil water depleted was generally similar between treatments, but in 2014/2015 depletion from the 0.4–0.6 m soil layer for STi and SGF was approximately 7 mm less than other treatments (results not shown). The estimated Ψ_{soil} at termination of stress in each season using the SWRC ranged as follows: 0.18–0.22 MPa in season 1 and 0.30–0.58 MPa in season 2 at 0–0.2 m, 0.11–0.13 MPa in season 1 and 0.11–0.19 MPa in season 2 at 0.2– 0.4 m and 0.17–0.22 MPa in season 1 and 0.11–0.09 MPa in season 2 at 0.4–0.6 m depth.

Soil water consumption during stress for some treatments and under well-watered control for the same period is shown in Figure 3.4. Changes in θ were limited to the 0–0.4 m soil layer throughout the growth period, except during early reproductive stress when a decline in θ was measured in deeper layers. Stress during this stage had a unique trend (Figure 3.4) characterised by (i) a fairly stable level in θ at 0–0.2 m layer and (ii) a considerable decline in θ in the 0.4–0.6 m layer. The trends in θ for SPI suggest little water was extracted at shallower depths on the basis of roughly equal available θ (40 mm) during the first days of stress, relative to the CT. Later, as the soil became dryer, roots grew deeper into sub-soil layers. During stress at anthesis, θ for the surface layer was virtually constant in season 2, while in season 1, there was a sharp decline for the first 12 days after anthesis, where after θ remained virtually constant for the rest of the flowering period. The sharp decline in θ shortly after anthesis observed under CT in season 1 as well represents a critical period of water extraction. This initial decline indicates increased root activity, while the fairly constant trend later could mean that water uptake was limited due to root death. Otherwise, if it is not root death, the θ pattern for CT during anthesis should at least be on a downward trend at all depths. There were moderate to strong linear relationships (R^2 = 0.44–0.97) between the soil water depleted (mm) during stress periods and some yield components at harvest during both years. Mean grain yield decreased (R^2 = 0.86 and 0.71) and spikelet sterility increased (R^2 = 0.44 and 0.97) linearly with increase in amount of soil water depleted from each treatment during years. Correlation between the number of panicles m^{-2} at harvest, and $\Delta\theta$ during stress was negative ($p < 0.0019$, $R^2 = 0.43$) only in 2013/2014, and $\Delta\theta$ for 0–0.6 m layer was positive ($p < 0.017$, $R^2 = 0.63$) in both years. These two relationships showed that panicle number (which differed significantly between treatments) at least partly depended on the amount of water extracted during stress.

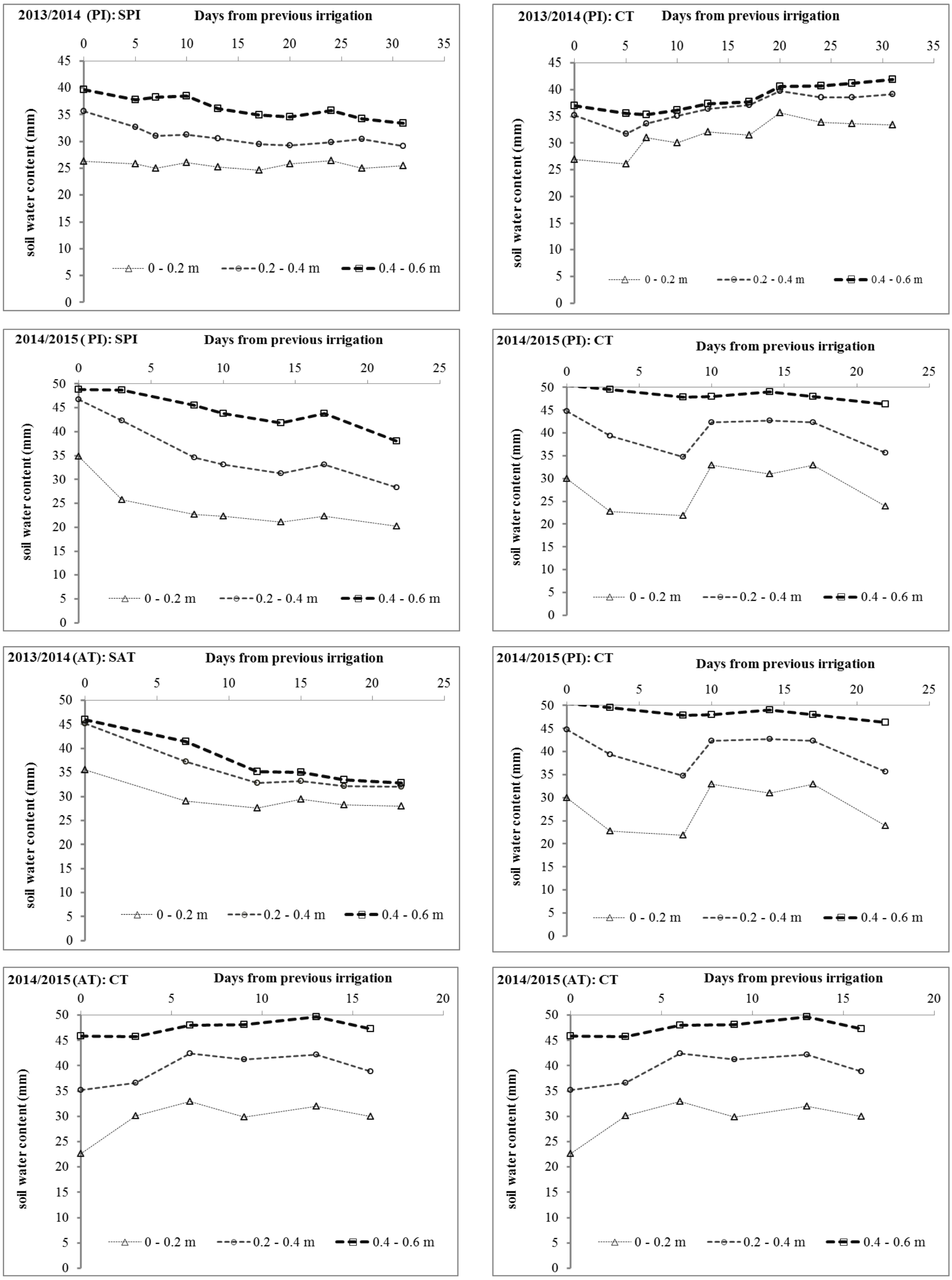


Figure 3.4 Trends in soil water content in different soil layers (at 0.2 m increments down to 0.6 m depth) during panicle initiation (PI) and anthesis (AT) stages, during stress (S) and in a well-watered control (CT) during the same period in two growing seasons. Treatments codes SPI and SAT are indicated. Patterns for other treatments were not unique from the CT and thus not presented.

Initial stress symptoms were mild, e.g. wilting after termination of irrigation water, but later (about seven days of stress) more severe symptoms were observed, e.g. leaf size was reduced. Symptoms of stress were distinct in each stage: leaf senescence in tillering stage, leaf rolling into bristle-like shapes in early reproductive stage, leaf wilting and gradual drying of flag leaves in anthesis and accelerated leaf drying in grain filling stage.

Stress during most development stages reduced g_s on abaxial (lower) leaf surfaces and consequently the relative ratios of mean g_s under stress: mean gs for CT. It was unexpected to measure slightly higher g_s values on abaxial leaf surfaces from four replicate plants with stress during anthesis than corresponding measurements for the CT (thus g_s ratios were greater than 1.0). This was common during most occasions when stomatal conductance was measured. Under well-watered conditions, the gs values on adaxial (206–443 mmol m^{-2} s^{-1}) and abaxial (143–384 mmol m^{-2} s^{-1}) surfaces of the flag leaf were roughly similar, suggesting equal distribution of stomata on both surfaces - gs values were either higher on abaxial or on adaxial surfaces. Stomatal conductance values for adaxial (upper) surfaces were generally higher under stress than under well-watered conditions, probably because of inward leaf rolling (results not shown). The upper leaf surface was thus less exposed to the atmosphere due to modification of the microclimate around the leaf. The frequency of g_s measurements was irregular between stages (due to unavailability of equipment and unfavourable weather), thus only initial and terminal measurements were used to calculate gs ratios to indicate severity of stress. The g_s ratios for abaxial flag leaf surfaces ranged between 0.8 and 0.9 after the initial withholding of irrigation, to between 0.41 and 0.35 at termination of stress, in all treatments. However, during stress at Ti, g_s did not decrease as much as during other stages (g_s ratio of 0.79 towards termination of stress), relative to the CT.

3.2.4. Growth, dry matter yield and leaf N content per development stage

Comparing growth attained under stress and well-watered conditions at the same development stage, LAI was only different at first flowering but shortly after anthesis, values of LAI were surprisingly similar. In fact, after the alleviation of stress during early reproductive growth (SPI), LAI exceeded that of CT in the subsequent development stages (Table 3.4). This phenomenon was also apparent in season 2, even when tiller abortion did not occur. Increase in canopy size was thus not as a result of new tillers emerging after stress relieve, as was likely in season 1. Further, when plants were at the same development stage of grain filling, LAI for SPI was again higher than that of CT. Plants in the SPI treatment were also able to maintain higher fractions of intercepted radiation than the well-watered control. This overgrowth (increase in LAI and FI) after the relieve of stress suggests that highly elastic growth occurs with stress during the early reproductive stage. This kind of 'elastic' growth was not apparent with stress during tillering, because the great reduction in LAI (Table 3.3) for SPI was due to wilting as opposed to senescence.

At first flower appearance, plants which had been stressed attained lower ADM than the well-watered CT. Aboveground dry matter yield for STi and for SPI were half and two thirds of that achieved by the well-watered CT, respectively. Thus, when the crop was stressed during early growth (STi), the source at first flower appearance was comparatively smaller than when stressed later at early reproductive stage (SPI) in both years. However, later on the ADM yield at anthesis was similar between the two treatments (Table 3.4). The differences in ADM then diminished towards maturity, such that the SPI treatment achieved almost 100% of the ADM value recorded by CT. During both years, ADM at final harvest was statistically similar ($p > 0.05$) between the well-watered CT and stress treatments, although on average over years, ADM for CT (13.11 Mg ha^{-1}) was higher than for SPI (9.54 Mg ha^{-1}), STi (10.09 Mg ha^{-1}), SAT (11.27 Mg ha^{-1}) and SGF (11.53 Mg ha^{-1}). It is noteworthy that maximum tillering for STi was delayed by approximately 24 and 14 days in the two seasons (meaning a longer tillering duration), relative to the control. It can be argued that plants under STi and SPI compensated for ADM loss through increase in leaf number per plant following longer vegetative growth duration than CT. Number of tillers was not a distinguishing contributor to biomass between stress treatments and well-watered conditions.

As was reported in previous sections, development was slowed down by WS, so it was important to clarify the indicators of source size when the crop attained the same development stages under different treatments. The contribution of reserve assimilates pre-flowering (16.1

± 1.9%) and pre-anthesis (54.3 ± 0.07%) to final ADM under well-watered conditions (and when not under stress) was identical between years. Pre-flowering and pre-anthesis reserves contributed more to final ADM under stress, than for CT, although results were variable between seasons. For example, 45.5 ± 9.5% of the final crop yield for STi and 51.6 ± 9.5% for SPI was contributed from pre-anthesis assimilates, while the contribution was only 42.5 ± 3.2% (averaged across seasons) under well-watered conditions. This contribution to grain yield for STi and SPI was exceptionally high. It is clear that the grain dry mass yield for these two treatments at harvest was on average 2–4 times the ADM at anthesis and approximately 4.6 times for CT (Tables 3.4 and 3.5). Considering that the proportion of ADM at anthesis to the final grain yield is similar for STi and CT, results suggest that partitioning of dry matter rather than the source size at the same development stage affected final yield (Table 3.6).

When plants were unstressed (except for plants of SAT, which were under stress at sampling time) and at the same development stage, leaf nitrogen uptake (g 100 g^{-1} d.w. basis) was higher in plants that were previously stressed than in plants of the control. Mean flag leaf N content for SPI (3.74%) and for STi (3.07%) were significantly ($p < 0.0001$) higher than for CT (2.80%) and SAT (2.70%). The significant increase in flag leaf N concentration after stress over well-watered conditions at 101–106 DAE (plants for STi and SPI had fully recovered) was consistent in both seasons. As leaf sampling was done during the stress period of SAT treatment, a lower leaf N content was thus expected. Total leaf N was not measured but based on leaf dry matter per unit area at sampling date, which was similar across treatments. We can thus assume that leaf N content was higher after relieving stress than without stress.

.

Table 3.4 Mean aboveground dry matter and leaf area index in different development stages under different treatments.

Year	Stage‡	Aboveground dry matter (g m^{-2})					Leaf area index (m^{-2} m^{-2})				
		CT	STi	SPI	SAT	SGF	CT	STi	SPI	SAT	SGF
2013/2014	PI	242.2^{a}	266.3^{ab}	282.1^{b}	243.5^{a}	256.1^{a}	0.46^{a}	0.46^{a}	0.53^{a}	0.53^{a}	0.45^{a}
	Ff	640.3^{a}	324.2^{b}	395.2^{c}	682.5^{a}	662.7^{a}	2.05^{a}	1.94^{b}	1.66^{b}	1.46^{a}	1.76^{a}
	AT	1205.1^{a}	779.3^{b}	993.3^{b}	1146.5^{a}	1227.8^{a}	3.61^{a}	1.59^{c}	2.31^{d}	2.89^{ab}	3.87^{a}
	GF	1523.9^{a}	743.1^{b}	1282.7^{c}	1149.0^{c}	1559.0^{a}	2.22^{a}	1.25^{b}	2.58^{c}	0.48^{d}	2.33^{a}
	M	1404.0^{a}	1218.4^{b}	1211.0^{b}	1458.7^{a}	1411.7^{a}	2.12^{a}	1.24^{b}	2.11^{a}	2.00^{a}	0.39^{b}
2014/2015	PI	283.7^{a}	230.2^{b}	302.8^{a}	223.2^{b}	291.3^{b}	0.82^{a}	0.54^{b}	1.43^{c}	0.69^{ab}	1.19^{d}
	Ff	703.9^{a}	539.9^{b}	718.2^{a}	593.7^{a}	804.8^{a}	2.16^{a}	1.71^{b}	0.25^{c}	1.88^{d}	2.07^{ad}
	AT	1260.5^{a}	736.4^{b}	736.8^{b}	1032.5^{a}	1243.1^{a}	1.97^{a†}	1.82^{a}	1.73^{a}	1.74^{a}	1.82^{a}
	GF	1073.2^{a}	1019.0^{a}	1036.3^{a}	1234.4^{c}	1080.9^{a}	0.98^{a}	1.41^{b}	1.61^{b}	0.18^{c}	1.10^{a}
	M	1719.6^{a}	1635.5^{b}	1240.2^{c}	1389.4^{d}	1741.3^{ab}	0.38^{a}	0.80^{b}	0.75^{b}	0.51^{c}	0.007^{d}

Means followed by the same letter within a row are not significantly different at $p = 0.01$ level of probability.

‡ Development stages; PI, panicle initiation; Ff, first flower; AT, anthesis; GF, grain filling; M, physiological maturity (M) was observed on each replicate per treatment. A development stage was delayed or advanced, depending on when stress was imposed.

† LAI under CT in season 2014/2015 was maximum on 03 February 2015, 8 d after anthesis. LAI value on 26 January 2015 (start of anthesis) was 1.41 m^{-2} m^{-2}.

3.2.5 Relationship between grain yield, yield components and growth parameters

The most highly correlated yield components with grain yield were spikelets per unit area and spikelet sterility (Table 3.5). Pearson correlation analysis, therefore, showed that variation in grain yield was explained best by the number of spikelets per panicle, as the number of panicles m^{-2} were quite similar. Several growth parameters like ADM plant height and LAI or LAD were related to grain yield (results not shown). There were no good relationships between LAD, grain yield and sink indicators or yield components. The mass of 1000 grains was positively related ($p = 0.018$, $r = 0.44$) to LAD, while dry matter accumulation rate was weakly related to panicle length ($p = 0.019$, $r = 0.43$) and to 1000-grain mass ($p = 0.009$, $r = 0.47$).

Table 3.5 Relationships between selected yield components and grain yield at harvest.

Parameter	Range	Pearson value	p-value
Panicle length (cm)	17.9 – 25.3	0.53	0.0033
Spikelet sterility (%)	1.99 – 49.10	-0.74	<0.001
Spikelets m^{-2} (x 10^3)	13.9 – 64.4	0.76	<.0001
Panicles m^{-2}	160 – 496	0.53	0.0035
Harvest index (%)	8.0 – 54.0	0.89	<.0001
Dry matter efficiency ($g\ g^{-1}\ d^{-1}$)	0.06 – 0.39	0.62	0.0004

Some of the yield components above, except 1000 grain mass, sink size and tillers m^{-2}, which are not presented, were significantly ($p < 0.05$) affected by WS. The treatment × season interaction effect on yield components was highly significant ($p < 0.001$) (Table 3.6). However, in season 1 grain yield was reduced by bird damage. Growth analysis before ripening of grains (some grains had not filled) showed higher yield overall than yield measured at final harvest. Mean grain yields (on dry mass basis) at last growth analysis were: STi: 2.18, SPI: 2.38, SAT:

3.65, SGF: 3.59 and CT: 5.46 Mg ha^{-1}. It is therefore likely that grain yield was underestimated in season 1, considering that stover yield was similar for both seasons. Grain yield components were not considerably affected by WS during the anthesis and grain filling stages. When stress was imposed during tillering stage, the number of spikelets per panicle and estimated spikelets per unit area, panicle length significantly ($p < 0.05$) reduced and spikelet sterility increased (Table 3.6). Stress during PI had a severely negative effect on panicle length and HI, but to a lesser extent on spikelet sterility, and this trend was consistent in both seasons. Thinner panicles were also observed at harvest, notably for plants that were stressed during PI. Sterility of spikelets was common across all water stress treatments, but based on mean full grain ratio values for the two seasons, spikelet sterility was more pronounced for SPI than for SAT. The high percentage of unfilled grains in season 1 was common to all water treatments, inclusive of the control, but sterility could not be associated with ambient weather conditions, as temperatures were favourable during booting (Table 3.1).

It was noted that if yield component analysis (panicle number m^{-2} x spikelets $panicle^{-1}$ x grain fill ratio x 1000 grain mass) was used to assess the final grain yield, as sometimes in agronomic studies, yields would be higher. For example, for CT mean grain yield would be 8.2 t ha^{-1}. This is to highlight that field studies should report rice yield measurements from a large surface area and not on the basis of a few hills.

Table 3.6 Yield components at final harvest as affected by water stress treatments.

Treatment	Grain yield[†] (Mg ha^{-1})	Harvest index (fraction)	1000 grain mass (g)	Panicle length (cm)	Spikelet sterility (%)	Spikelets m^{-2} ($x10^3$)	shoots m^{-2}
Season 1							
STi	1.04	0.11[a]	22.47	19.91[b]	43.90[a]	28.71	304
SPI	1.94	0.15 [a]	22.36	20.13[b]	28.53[ab]	26.84	345
SAT	4.08	0.30 [a]	23.15	24.24[a]	21.94[ab]	40.09	312
SGF	3.56	0.27 [a]	23.65	23.23[ab]	26.63[ab]	44.61	374
CT	4.40	0.32 [a]	23.68	23.75[a]	21.28[b]	40.73	357
p value	ns	*	ns	**	*	ns	ns
Season 2							
STi	6.49[ab]	0.41[ab]	24.87	21.65[a]	3.98[ab]	49.21[ab]	444
SPI	1.58[d]	0.18[b]	20.18	17.71[b]	12.11[ab]	35.32[b]	456
SAT	3.56[c]	0.36[ab]	21.10	21.19[a]	15.84[a]	47.95[ab]	412
SGF	5.23[bc]	0.40[ab]	23.82	21.33[a]	7.71[ab]	38.77[ab]	348
CT	7.16[a]	0.48[a]	22.85	21.57 [a]	3.80[b]	57.43[a]	466
p value	***	*	ns	***	*	**	*

* Significant at $p < 0.05$.

** Significant at $p < 0.01$.

*** Significant at $p < 0.001$.

3.2.6 Water use and water use efficiency of treatments

Since treatment means did not differ significantly between seasons, water use related parameters were averaged across the two seasons (Table 3.7). Water applied as irrigation was considerably lower under stress, compared to well-watered conditions, with minimal yield penalty, especially if water was withheld during GF. The amount of water irrigated to stress treatments was on average 130 mm per season less than for the well-watered control. Water used as ET was higher under stress, notably for STi (+72 mm) and SPI (+ 53 mm), than under well-watered conditions. The higher ET under stress could be mostly from soil evaporation (E) and less transpiration, because of smaller canopies during stress periods (due to leaf rolling and senescence), which exposed the soil surface to ambient conditions. Water use efficiency for grain yield (kg mm^{-1} ha^{-1} or kg m^{-3}, yield per ET) did therefore not increase under stress (Table 3.7), compared to well-watered conditions. Water use efficiency was higher in season 2 than in season 1 due to a higher grain yield response, especially for two treatments. For the respective seasons, WUE values for CT were 0.88 and 0.66 kg m^{-3} and 0.46 and 0.30 kg m^{-3} for SAT. Stress during grain filling did not affect WUE as much as during Ti and PI. Mean values averaged across seasons for SGF (0.64 kg m^{-3}) and for CT (0.75 kg m^{-3}) were similar, while for STi and SPI WUE values were very different from the CT (Table 3.7). These overall results indicated that the crop was less efficient in utilising water as water inputs were reduced. Results on WUE and water input indicate a possibility of reducing irrigation water with minimal yield loss if water is withheld during late development stages.

Table 3.7 Mean values (± SE) of water use related parameters during stress periods and at final harvest.

Treatment	WUE_g ($kg\ m^{-3}$)	ET (mm)	Irrigation amount (mm)	‡WUE_b ($kg\ m^{-3}$)	†WUE_b at end of stress ($kg\ m^{-3}$)	Dry matter Efficiency ($kg\ kg^{-1}\ d^{-1}$)
CT	0.88	627	818	na	na	na
STi	0.59	555	573	6.81±1.85	$11.65{\pm}8.46^{b}$	$0.22{\pm}0.02^{ab}$
SPI	0.27	574	602	10.82±1.85	$23.46{\pm}8.46^{b}$	$0.12{\pm}0.02^{b}$
SAT	0.56	609	704	12.39±2.06	$43.16{\pm}9.46^{ab}$	$0.24{\pm}0.02^{a}$
SGF	0.67	590	642	11.34±2.06	$65.06{\pm}9.46^{a}$	$0.27{\pm}0.03^{a}$
p value	**	ns		ns	**	**

Means for values in a column followed by the same letter are not significantly different.

* Significant at $p < 0.05$, ** Significant at $p < 0.01$ and *** Significant at $p < 0.001$.

ns, not significant.

na, not applicable.

DME, dry matter efficiency.

SE, standard error (n = 3).

[1] ET was computed from sowing to final harvest (~150 d) and not to maturity.

WUE_g for grain yield.

WUE_b, water use efficiency for biomass yield during stress calculated as, ‡WUE_b is change in biomass per unit of ET during stress and †WUE_b is biomass at termination of water stress divided by water used as ET from sowing to end of stress.

3.3 Discussion

3.3.1 Water stress effects on crop performance

Growth was clearly affected by WS during each stage. However, the lack of significant reduction in ADM indicates that not only WS, but also factors such as tiller number, leaf expansion and rooting affect biomass production (Asch et al. 2005; Kato et al. 2006). Below-ground biomass was not measured in the present study. The initial decrease in ADM (about eight days after withholding water) during tillering was because plants were source limited at this stage, due to fewer leaves, which limited DM production (Dingkuhn et al. 1989).

Constant soil water regimes or staggering of planting dates have previously been used to achieve WS in screening trials. When the staggering sowing dates was used and a delay in reproduction was considerable in a study by Boojung and Fukai (1996), unfavourable temperatures was blamed for confounding WS effects on rice growth. This unwanted effect did not occur in our study, despite delay to reproduction for SPI. Besides, the daily temperatures during sensitive growth stages of rice were within the optimum range for all treatments (Shrestha et al. 2011). This study used progressive drying of the soil to achieve intermittent WS, which is typical of natural field conditions (Vadez et al. 2014) and resulted in fairly equal initial θ. Using a similar water regime in potted rice, Okada et al. (2002) also found that roots were able to exploit water reserves from sub-soil layers. When rice plants maximise soil water uptake during stress, enhancement of biomass production occurs during stress (Blum 2009). These two mechanisms (increased rooting and optimal water use) explain the lack of significant response in ADM for most of the stress periods during tillering and early reproductive stages.

In terms of desirable traits to cope with stage-specific stress, tillering ability was not critical in determining biomass and grain yield under stress. Comparing tillering and biomass responses in each season (Figure 3.3), ADM was not significantly affected, whether tillers were aborted or not. Again, comparing the responses between treatments at a specific time point, for instance at 95 DAE, mean tiller number was lower for SPI than for STi, although total biomass was similar. Furthermore, despite similar tiller number m^{-2} at harvest, stressed treatments had less productive panicles than the control.

This study established that when WS occurs before flowering, there is no strong linkage between tillering ability and delay in reproduction stage. Although tillering was slightly suppressed by stress in the early reproductive stage relative to the control (Figure 3.3) and no tillers were aborted on individual plants in season 2, the delay in flowering was still considerable. Conversely, tiller abortion was apparent with stress during tillering stage, although not significant in season 2 (Figure 3.3). Otherwise, if an association between tiller abortion and delay to flowering and anthesis exists, then increase in GDD to first flowering and anthesis under SPI should have been negligible, at least in 2014/2015 when peak tillering stage occurred days before stress. Further, flowering occurred during the stress period for SPI in 2014/2015 without additional tillers thereafter. These two evidences thus also rule out the possibility of new tillers increasing GDD to reproduction under stress. We suggest this to be a result of preferential partitioning of assimilates to the roots, even though below ground biomass was not sampled. The proposition is, however, based on the increase in water uptake from sub-soil layers under SPI and findings by Price et al. (2002), who associated deep rooting in rice with more investment of C into the roots.

Explanations in literature for the changes in the time to peak tillering in rice under non-limiting conditions are rare. Clerget and Bueno (2013) reported that average number of tillers of potted-grown lowland rice varieties changed with sowing dates and it was related to duration of the vegetative phase. In our study, stress resulted in an extension of the time to reach peak tillering and therefore an extension of the vegetative phase, but the maximum number of tillers was still similar between treatments. Asch et al. (2005) reported that peak tillering in upland rice varieties CG14 and WAB 56-104 (which are parents of cv. NERICA) grown in chambers occurred around flowering. Our findings show that the time to peak tillering under well-watered (and non-limiting) conditions can also considerably change with season. It was difficult to explain why plants attained peak tillering (development stage 0.2) (Zadoks et al. 1976) earlier in season 2, as daily temperatures between sowing and about 60 DAE were similar in both seasons. More investigation for possible causes of changes in thermal time to peak tillering is needed.

We expected that biomass production will be lower when stressed in the early reproductive stage (SPI), rather than tillering (STi) stage because of a greater reduction in LAD and also because stress during PI enhances rooting depth (Okada et al. 2002). The positive correlation between ADM and LAD and the lowest mean values of ADM and LAD for SPI confirmed this expectation. Furthermore, we anticipated that the longer the delay to reproduction stage under stress, the higher the biomass would be at reproductive stage. Findings do not support this latter speculation because the delay of the reproductive stage was considerable, while the differences in biomass between STi and SPI were small.

Delay in flowering due to WS has been reported in previous studies in relation to soil water content, number of leaves produced and canopy size. For instance, Boojung and Fukai (1996) reported a delay in flowering for rice plants stressed at full canopy ('late vegetative growth'). Bouman et al. (2001) also stated that a delay in flowering occurs when the soil is too dry for plants to produce leaves. Their explanation can be interpreted as stress during late vegetative growth (full canopy) delays flowering because few leaves are produced thereafter. In contrast to our study, plants were still producing new leaves at the time of imposing stress. The SPI treatment started with a canopy intercepting 45% of solar radiation (about half the maximum FI) and LAI of 0.38 m^2 m^{-2} (about 17% of the maximum value). These results confirmed that the delay in flowering occurred irrespective of the number of leaves attained or canopy size at that stage.

High grain yield in the present study was due to the high contribution (42%) of pre-anthesis assimilates to grain dry mass. Yoshida et al. (1972) reported that, depending on the rice variety, 20–40% of pre-anthesis assimilate contribution is needed to attain high grain yields. The introduction of stress during PI resulted in considerable yield loss due to lower panicle size (shorter panicles plus lower number of spikelets on the panicle). Similar results, including pronounced spikelet sterility, has been reported with stress during panicle initiation in lowland rice (Garrity and O'Toole 1994; Bouman et al. 2001; Kato et al. 2006; Kumar et al. 2006). The new finding in our study is that spikelet sterility in rice is also common with stress during tillering, as was observed in 2013/2014 when tiller abortion was severe. Tiller abortion could have resulted in low assimilate supply for STi because spikelet sterility of more than 20% indicates that assimilate supply from photosynthetic tissues (source) to the grains limited yield (Fageria 2007). In contrast, negligible effects of WS during late reproductive stages on grain yield, yield components and WUE implies an opportunity to save irrigation water. It is important to highlight the adaptation to stress during anthesis that may have led to better grain yield under SAT treatment than was expected. Results of Table 3.3 showed that stress during anthesis resulted in the greatest reduction in SLA, compared to other treatments. This increase in leaf thickness indicative of high SLA indicates preferred allocation of assimilates to the stems than to leaves (Asch et al. 2005). Consequently, plants for SAT treatment could have remobilised assimilates more than those for SPI.

There is a great potential for yield improvement of upland rice and to save water under irrigated systems. Results from this study showed that yield components and HI were not affected by water stress, while irrigation water could be saved by withholding water during anthesis and grain filling (Table 3.7). Water use efficiency did not decline significantly for treatments that were water stressed during anthesis and grain filling, because although total ET increased considerably for these two treatments, grain yield was not much affected. Fertility of rice grains in our study was less affected by WS, compared to values reported in literature under well-watered conditions. Kato et al. (2009) documented grain fertility values of 68–73% (27–32% sterility) in lowland *O. indica* and *O. japonica* varieties, while Arai-Sanoh et al. (2014) reported at least 80% fertility in *O. japonica* varieties. Grain sterility in upland rice is generally higher than in lowland rice, with a difference of 5–10% on average between the two rice systems under well-watered conditions (Kato et al. 2006; Fageria 2007). Since canopy shading likely contributed to pronounced sterility for the SPI and STi treatments, low plant densities may reduce sterility in situations vulnerable to stress during tillering and panicle initiation.

3.3.2 Implications of responses for coping with stress under water-limited conditions

Rice is very sensitive to mild soil water deficits, not only in lowlands, partly because its root system is largely confined to the top (about 0.2–0.3 m) surface soil layers (Lilley and Fukai 1994; Okada et al. 2002; Kato and Okami 2010). In anaerobic soils, stress in lowland rice can develop at Ψ_{soil} below -86 kPa at shallow depths, which is only slightly below the lower limit of the optimum range for lowland rice (Bouman et al. 2001). Soil matric potentials estimated in our study during stress were above these generic values, indicating that the crop can adapt to drier soil conditions. Growth and morphological responses to stress, namely changes in leaf morphology, tillering ability and regeneration, deep rooting and leaf N uptake before grain filling of upland rice during and after stress in different development stages were distinct. These are useful traits in the adaptation of upland rice to water-limited environments. It is noteworthy in most upland rice growing areas in SSA, where NERICA genotypes are popular, that WS is prevalent and can occur at any stage during crop growth (Jones et al. 1997; ARC 2007). This makes it important to consider stage-specific responses and adaptations to water stress. Leaf rolling to reduce leaf transpiring surface (Wopereis et al. 1996) was peculiar during early reproductive stress, while leaf senescence for the same reason, was marked when stress occurred during tillering. Great reductions in leaf area or green LAI were measured with stress during tillering stage than with stress during early reproductive stage (Table 3.4). These results demonstrate that coping with stress during tillering or which occurs around this stage will be better for varieties which retain some green leaves (‘stay green’ trait) than otherwise. This could be beneficial in minimising water loss as E, because our results showed that fractional interception of radiation was greatly reduced during stress periods and seasonal ET was thus higher (due to higher E) under stress than under well-watered conditions.

Crop recovery after stress had negative and positive impacts on the final yield with respect to stage. ‘Bounce back’ ability and highly elastic recovery of canopy growth, green LAI and FI was observed, irrespective of whether tillering abortion occurred under stress. Thus, the low number of productive panicles m^{-2} under early reproductive stress, despite similar tillers m^{-2} at harvest as CT, could be improved by lowering plant density. This result also suggests that a low tillering ability would be desirable for coping with stress during the early reproductive stage. As the crop recovered to larger green canopies than the CT post-flowering stage (following resumption of irrigation), mutual shading likely affected flowering of some existing tillers. The slower recovery of plants after stress during tillering than during early reproductive stage resulted in shorter plants and consequently also shorter panicles. Improving recovery in plant height if stress occurs around early growth stages seems to be important for yield enhancement and is more convenient for manual harvesting. Harvesting using sickles is common among smallholder farmers and is difficult in short plants.

Changes in soil water content over time at different depths has been used in several studies to indicate the impact of drought on the extent of root activity (Kondo et al. 2000; Lopes et. al. 2010; Yoyoongwech et al. 2013). The observed deeper extraction of water during early reproductive stage, when root depth is likely at its peak for well-watered rice (Kato and Okami, 2010), could have helped to avoid leaf senescence (maintenance of leaves despite rolling) in contrast to stress during tillering. Increase in rooting depth in well-watered conditions has been shown to increase leaf N concentrations 20 days after heading (approximately 98 DAE), with higher N levels in deep than shallow rooting lowland rice varieties (Arai-Sanoh et al. 2014). Arai-Sanoh et al. (2014) attributed this difference to absorption of nutrients from lower soil layers by deep rooting varieties. In our study soil mineral N at sowing, particularly NO_3-N in the 0.4–0.6 m layer, where deep rooting was observed for SPI, was very low and plants did probably not benefit from that. These findings have implications on agronomic practices, breeding objectives and variety selection by farmers for improving rice yield under water stress. Further investigations are needed on allowable depletion levels for minimal yield loss in irrigated upland rice and on plant density optimisation to control unproductive tillers during early reproductive stress.

3.4 Conclusions

Thermal time to the onset of specific stages of development (except for the time to peak tillering) in upland rice was generally stable over seasons under stress-free conditions. However, upland rice phenology was very sensitive to water stress during early reproductive growth. Stress during this stage increased growing degree days greatly, not only to reach subsequent development stages, but also to reach maturity and thus it altered crop duration. Delay in flowering was not related to the effect of water stress during vegetative and reproductive stages on tiller development. Even without suppression of tillers or death of apical buds under stress, GDDs to flowering and anthesis still increased. Water stress before flowering resulted in a greater recovery of source size (canopy size) than for a well-watered crop at the same development stage. This 'bounce back' ability is specific to stress during early reproduction and is not related to tiller number during and after the relieve of stress. Grain yield loss under stress was largely as a result of fewer grains per panicle and spikelet sterility. Results suggest that improvements in spikelet number may be achieved through manipulating plant density. In rice growing areas that are prone to a high risk of stress during early reproductive stages, low plant densities may be recommended to minimise excessive unproductive tillers at harvest. Stress during anthesis and grain filling resulted in no substantial yield and water use efficiency penalty, while a considerable amount of irrigation water could be saved. The yields achieved in our study match typical grain yields reported for lowland rice systems, suggesting that there is considerable room for increased upland rice yields. The information gained in this study will help upland rice farmers to optimise water management practices, for example to irrigate only during a critical stage and save water during late reproductive stages. Dryland farmers can minimise risks of high water losses by opting for low plant densities and selecting planting dates that reduce chances of early reproductive stress.

CHAPTER 4

UPLAND RICE (*Oryza sativa* L. x *Oryza glaberrima* Steud) RESPONSE TO DIFFERENT NITROGEN FERTILISER RATES UNDER WATER NON-LIMITING CONDITIONS

I.N. Alou[ab], J.M.Steyn[a*], J.G. Annandale[a] and M. van der Laan[a]

[a] Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, 0028 South Africa

[b] National Agricultural Research Organisation (NARO), Bulindi ZARDI, P.O. Box 101 Hoima, Uganda

This Chapter was submitted on 01st October 2019 to Pedosphere as: Isaac Newton Alou, Joachim Martin Steyn, John George Annandale, Michael van der Laan. Unpubl. Nitrogen level affects resource use efficiency of upland rice (*Oryza sativa* L.). The manuscript is under review (Manuscript ID: pedos201910669).

Abstract

Growth, yield, crop water use efficiency (WUE) and nitrogen use efficiency (NUE) of upland rice (*Oryza sativa* L. x *Oryza glaberrima*) cv. Nerica 10 was investigated under non-water limiting conditions and varying nitrogen (N) rates in 2014/2015 (Y_1) and 2015/2016 (Y_2) at the University of Pretoria's Hatfield Experimental Farm, South Africa. Aboveground dry matter, grain yield and grain N content all increased with increasing N rates, linearly in Y_1 and following a quadratic trend in Y_2. Mean grain yield was highest (4.5 t ha^{-1}) for 120 kg N ha^{-1} and lowest for zero N (2.4 t ha^{-1}). Grain harvest index (HI) was slightly higher for zero N (0.45) than with N fertilisation, except for the 80 kg N ha^{-1} treatment (0.48). Higher number of unproductive tillers were observed in the fertilised treatments, which retained substantial N and increased spikelet sterility and reduced HI. Tiller number was high at harvest in Y_1 due to very wet soil conditions in early Y_1 in contrast to Y_2. Agronomic NUE was highest for 40 kg N ha^{-1} (32.7 kg kg^{-1} N) and lowest for 160 kg N ha^{-1} (11.7 kg kg^{-1} N), while WUE was highest for the120 kg N ha^{-1} (7.58±1.7 kg mm^{-1}) and lowest for the zero N (4.1±0.9 kg mm^{-1}) treatment. Nitrogen fertilisation increased water use by 17–36% in Y_1 and 3–7% in Y_2 relative to zero N. High soil water and N levels, especially during tillering, can reduce HI, WUE and to a lesser extent, grain N concentration.

Key words: Leaf area index; Nerica; nitrogen use efficiency; tillering; water use efficiency

4.0 Introduction

Rice (*Oryza sativa* L.) is an important food crop and source of income worldwide (IRRI 2009). In Africa, the rate of consumption of rice is increasing faster than most other staple food crops. For instance, between 2000 and 2010 the increase was estimated at 5.5% per year (USDA 2013). This increased demand for rice has been accompanied by a rapid expansion in cultivated rice area in upland areas of 0.4–7.7 % per year across sub-Saharan Africa (SSA) (ARC 2007). This increase in cultivated area in uplands is due to several reasons: Upland rice can be rotated with other crops, water and labour inputs (because it is not transplanted) are low compared to lowland rice, and above all, it often fetches higher returns on investment than most other crops (IRRI 2009; Bouman et al. 2007; Kaizzi et al. 2014). However, many rice-growing countries in Africa remain heavily reliant on imports to meet domestic rice demand (Saito et al. 2015) and will thus need to increase the area under cultivation and more importantly, the production per unit area, to become more self-sufficient. According to Saito et al. (2005), upland rice yield potential worldwide is unrealised because production is often limited to less fertile and drought-prone lands.

Nitrogen (N) management, in addition to water management, differs considerably across rice cropping systems (George et al. 2002; Saito et al. 2005; Oikeh et al. 2008). In Africa, low N application rates are predominant in upland rice production, rice monocrops are common, crop rotations involving legumes are rare, and recycling of residues is mostly not practiced (Kijima et al. 2008). These practices collectively contribute to N deficiencies being common in upland rice, as intensive cropping requires replenishment of nutrients for sustainable production (Motior et al. 2011). Upland rice is most commonly practiced under rainfed conditions in many parts of SSA, and uneven distribution or lack of rainfall during the growing season often causes water stress (WS), which negatively affects yields (ARC 2007; Kijoji et al. 2014). Related to this, N use efficiency (NUE) in rainfed upland rice is mostly low (15–20 kg grain kg^{-1} N applied) (George et al. 2002; Onaga et al. 2012). Based on these NUE levels, approximately 50–67 kg N is required for each 1 Mg of grain yield, which is costly for the average SSA rice farmer.

Compared to lowland rice, upland rice is an understudied crop. Studies on N fertilisation, including under favourable growing conditions, are lacking (Kato et al. 2006; Kijoji et al. 2014). In South Africa, some desktop feasibility studies reported upland rice production as viable under rainfed conditions, while others concluded it was not viable (Polity 2012; Prinsloo 2012). Earlier, rice had also been grown successfully on small scale in KwaZulu-Natal Province (van den Berg and Waele 1989, personal communication C. Mulder 2018). Further interest in rice as a new crop is emerging in South Africa and another feasibility study is currently underway (Department of Science and Technology 2018, 2019). Past studies on N fertilisation in upland rice (sometimes referred to as 'aerobic' rice) in Asia neglected to consider water use when fertiliser rates were varied (Belder et al. 2005; Kato et al. 2009). Kondo et al. (2000) observed that water uptake of potted rice under aerobic conditions increased with N fertilisation, suggesting a modification in crop water demand by N. Nitrogen can reduce soil evaporation and increase transpiration (T) through improved canopy development (Sadras and Rodriguez 2010). Belder et al. (2005) reported that fertilisation at 150 kg N ha^{-1} improved water use efficiency (WUE) of irrigated rice in the Philippines from 4.0 to 7.5 kg mm^{-1} (based on volume of water applied). So, previously reported N recommendations may be too low to achieve such WUE levels (George et al. 2002; Onaga et al. 2012). Investigating the influence of N fertiliser rate on crop water use is also important to achieve simultaneous maximum uptake of N and water.

The importance of irrigation has been recognised to maximise yield and improve water and nutrient use efficiencies (Wang et al. 2015; Lenka et al. 2013). Irrigating according to crop requirements or soil water depletion is a recommended practice to reduce deep drainage and improve rainfall use efficiency (Wang et al. 2017). Because rice has a shallow root system (<0.4 m depth) (Okada and Kato 2010) and N management can also be more challenging as a result, it is important to optimise N applications to avoid nitrate (NO_3^-) leaching and reduce production costs. Understanding the relationship between crop water use/ N uptake and growth is also needed to close yield gaps in such cropping systems (Blum 2002; Sadras et al. 2016). In addition, information on traits that enable high NUE in rice through agronomic investigations under non-limiting conditions is needed to improve variety breeding programmes (Dingkuhn et al. 2015). While a number of studies have explored rice N dynamics in lowland systems (Belder et al. 2005; Motior et al. 2011), few studies have investigated these dynamics in upland systems.

The aim of this study was to improve our understanding of the response of upland rice to N fertiliser rates under water non-limiting conditions and the relationships between WUE and NUE. This study further sought to address knowledge gaps regarding optimal N application rates and seasonal water requirements for upland rice.

4.1. Materials and methods

4.1.1 Variety selection

Upland rice cv. NERICA10 seed was sourced from the National Crop Resources Research Institute (NaCRRI) in Uganda. New Rice for Africa (NERICA) lines are progeny derived from interspecific crossings between Asian lowland rice, WAB 56-104 (*O. sativa* L. Japonica), and African indigenous upland rice, CG 14 (*O. glaberrima* Steud), and were released as NERICA varieties 1 to 18. NERICA varieties 1 to 7 are genetically similar, while NERICA 8 to 18 have a different genome from the first group (Jones et al. 1997; Ndjiondjop et al. 2008). The NERICA varieties were specifically developed for low input systems, but be able to achieve high yields under rainfed conditions in some seasons (Onaga et al. 2012). Nerica 10 is a short-duration variety and takes about 110 days to maturity in the tropics.

4.1.2 Description of study site

The field experiment was conducted on the University of Pretoria's Hatfield Experimental Farm, South Africa (25^{o} 45' S, 28^{o} 16' E, 1370 m a.s.l.). The sandy clay loam soil is classified as a Hutton (loamy, kaolinitic, mesic, Typic Eutrustox) (Soil Classification Working Group 1991). The profile is deep (> 1.15 m) and well-drained and the soil had no physical restrictions to root growth, based on observations during soil sampling. Soil properties and inorganic N levels at the start of the experiment are shown in Table 4.1. Soil tests before the study commenced indicated that there was 23.3 mg kg^{-1} Phosphorus (P) (Bray 1), 258 mg kg^{-1} Calcium (Ca), 83 mg kg^{-1} Potassium (K), 92 mg kg^{-1} Magnesium (Mg) and 2 mg kg^{-1} Sodium (Na) in the top soil (0-0.2 m) layer. Hatfield has distinct winter (May–August), spring (September), summer (October–February) and autumn (March) seasons (De Jager 2016). The area receives about 670 mm of rainfall per annum, falling mainly between October and March (summer) (Annandale et al. 1999).

Table 4.1 Selected soil properties and inorganic nitrogen levels at the beginning of the trial.

	Soil layer (m)				
Soil property	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
Field capacity (m^3 m^{-3})	0.24	0.27	0.29	0.24	0.25
Sand (%)	71.8	64.6	57.7		
Clay (%)	24.7	30.7	36.3		
Soil pH (2.5 water: 1 soil)	5.8	5.5	5.6		
Bulk density (Mg m^{-3})	1.65	1.65	1.55	1.53	1.40
NH_4-N (kg ha^{-1})	14.8	17.0	17.2		
NO_3-N (kg ha^{-1})	2.7	5.8	5.7		

Soil samples for ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N), converted from soil analysis data, were taken 35 days before sowing.

Daily weather data from sowing to harvest for selected parameters are presented in Figure 4.1. The growing period in 2015/2016 was generally hotter than 2014/2015 but on average air temperature was favourable for rice growth, while rainfall was more biased towards the late season in 2015/2016 compared to the previous year. Average maximum and minimum temperatures ranged from 27.9°C to 31.0°C and from 13.8°C to 15.2°C, respectively.

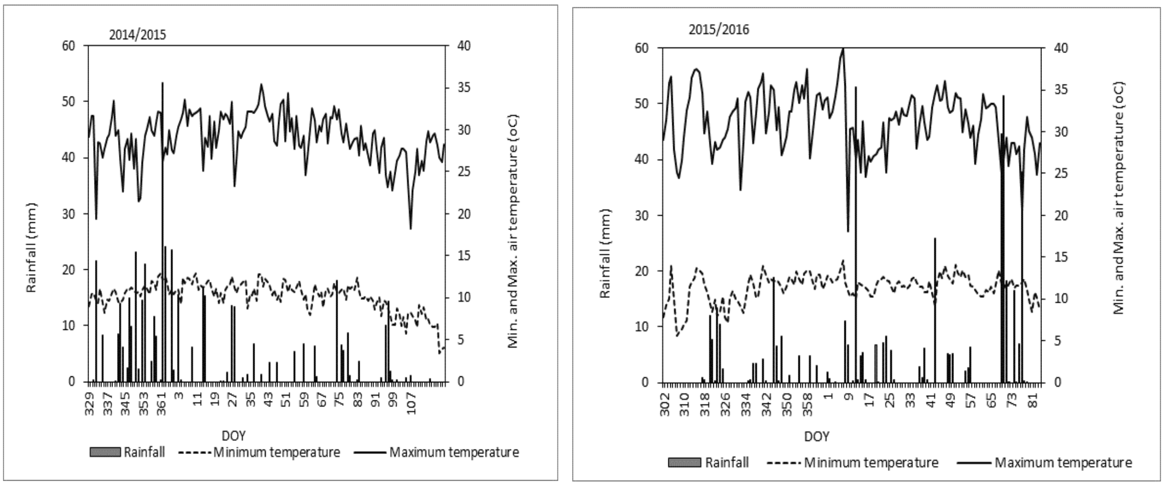


Figure 4.1 Daily temperature and rainfall from sowing to harvest of two summer-to-autumn growing seasons of a rice field experiment under irrigation at the Hatfield Experimental Farm, Pretoria, South Africa. Irrigation data are not presented.

4.1.3 Agronomic practices and experimental design

Winter wheat (*Triticum aestivum* L.) was grown under sprinkler irrigation without fertilisation before each rice crop to remove excess inorganic N from the soil profile. The wheat was sown on 21 May 2014 and 5 June 2015 and on average, 10 to 15 mm of water was applied weekly to ensure good establishment and growth. The wheat was harvested on 9 October in both 2014 and 2015, when all aboveground plant material was removed from the trial site before primary tillage. For the rice, a randomized complete block design (RCBD) was used with three replicates and five N application rates (0, 40, 80, 120 and 160 kg N ha^{-1}). Plot dimensions were 5 m × 4 m and paths of 1 m wide were used to separate plots. Muriate of potash (11% K) and single super phosphate (12% P) were applied at equivalent rates of 55 kg K ha^{-1} and 42 kg P ha^{-1} two days before sowing the rice. Fertilisers were then incorporated into the soil with a rotovator to achieve a fine tilth. Nerica 10 seed was sown in shallow furrows of ±0.03 m deep (drill planting method) on 29 November 2014 and 20 October 2015. The spacing between rows was 0.25 m.

Sprinkler irrigation was used to supplement rainfall on three occasions (10–15 mm per event) between 0 to 14 days after sowing (DAS) before a high-density drip irrigation system was installed. Soil water content in the 0–0.4 m layer was restored to field capacity at three to five day intervals to avoid WS and minimise N leaching. Soil water depletion rarely exceeded 30% of plant available water. Excess plants were thinned at 21 and 25 days after emergence (DAE) each season to approximately 25 plants m^{-1} row length. This gave an equivalent plant population density of 100 plants m^{-2} (1,000,000 plants ha^{-1}). A uniform plant stand was achieved prior to application of N fertiliser treatments. Limestone ammonium nitrate (LAN, 28 %N) was top dressed 27 DAE and 50–55 DAE in two equal splits, 50% at planting and 50% as top dressing, at the respective N application rates. The N fertiliser was applied along plant rows and incorporated into the soil to a depth of approximately 0.01 m using a hand hoe. Irrigation (± 20 mm) was applied if the topsoil was dry after top dressings. Weeds were regularly removed by hoe and handpicking. The crop was kept free of pests and diseases as needed. Malathion® (active ingredient *O*, *O*-dimethyl phosphorodithioate) was sprayed once for aphids during vegetative growth in the 2014/2015 season, according to manufacturer instructions. A net was placed over the crop at grain-filling stage to minimise damage by birds.

4.1.4. Measurements of soil water content and water supply

Aluminium access tubes for a neutron probe water meter (CPN Hydroprobe model 503DR, Campbell Pacific Nuclear, California, USA) were installed after seedling emergence within plant rows at the centre of each plot. Neutron probe readings were taken from about 7– 14 DAE onward in both seasons. Profile soil water at 0.2 m depth intervals was monitored to 1.0 m depth. Each N treatment was irrigated independently after determining the volumetric water content (θ) and calculating the deficit to field capacity (FC) for individual replicate plots. The profile deficit was determined as the difference between measured θ and FC in the top 0.4 m depth. However, on few occasions, when the neutron probe was unavailable, water was applied based on reference evapotranspiration (ETo) from nearby weather station and growth stage of the crop (Allen et al. 1998). Before sowing, the neutron probe water meter was calibrated for the soil under dry and wet conditions.

A flow meter (CL. C, qp 1.5 SA 1453, Elster Kent Metering Pty Ltd, South Africa) was used to measure the amount of irrigation applied to each treatment. In addition to a nearby automated weather station, three rain gauges were installed within the field for measurement of rainfall. The soil water balance equation, $I + P = ET + \Delta S + D + R$ (Allen et al. 1998) was used to estimate evapotranspiration (ET). Irrigation (I) and precipitation (P) were measured, and drainage (D) and runoff (R) were assumed to be zero. Drainage was assumed negligible over the growing seasons because rainfall events coinciding with irrigation were uncommon. The amount of soil water consumed or depleted (change in storage) was calculated as:

$$\Delta S = \theta_n - \theta_{n-1} \quad \text{......................................(4.1)}$$

where θ is the volumetric water content of a layer on a specific day ($_n$) and on the preceding day ($_{n-1}$). The effective ΔS was calculated between growth stages or up to specific DAE by summing values of ΔS to the date of interest.

4.1.5 Measurement of soil inorganic nitrogen

Soil samples for N analysis were taken from 0–0.2, 0.2–0.4 and 0.4–0.6 m layers just before sowing, during flowering (76/90 DAE for Y_1/Y_2) and at crop maturity (110/125 DAE for Y_1/Y_2). Although rice roots are rarely found beyond 0.4 m depth in artificial conditions (Asch et al. 2005; Okami and Okada 2010), this study sought to clarify the possibility of N uptake from deeper soil layers, so soil sampling was done to 0.6 m depth. Before sowing the rice, nine points in the field were randomly selected for sampling. Samples during crop growth were taken from the middle of each plot. In 2014/2015, two sub-samples per plot were taken, mixed to a homogenous sample and a composite for each N treatment was submitted to the laboratory, while in 2015/2016 two sub-samples were composited per plot and three samples per N treatment were taken and analysed. Inorganic N in the soil was extracted by shaking samples in 1 mol dm^{-3} potassium chloride solution [1:5 (mass basis) soil : KCl solution] for one hour (Bremner and Keeney 1966), and then filtered (Whatman® No. 2 filter paper, Sigma-Aldrich Co. LLC, California, USA). In 2014/2015, inorganic N [nitrate (NO_3^-) and ammonium (NH_4^+)] were determined using steam distillation (Büchi 321 Kjeldahl unit, LABEQUIP, Ontario, Canada) and Magnesium oxide (MgO), Devarda's alloy and boric acid-indicator solution (Keeney and Nelson 1982). Ammonium-N was determined by titrating with 0.005 M sulphuric acid (H_2SO_4). The colour change at end-point was from green to a permanent faint pink. The colorimetric method (Wright and Stuczynski 1996) was used in 2015/2016 for determination of NO_3^- and NH_4^+ concentrations in solution extracts because the distillation equipment was not functional. Absorbance was read at 520 nm (NO_3^-) and 660 nm (NH_4^+) wavelengths using a Beckman Coulter™ Spectrophotometer (DU® Series 530, Life Science UV/Vis, Lockport Place Lorton, Virginia, USA). The instrument was calibrated using standard solutions of ammonium sulphate [$(NH_4)_2SO_4$] and potassium nitrate [KNO_3] for sources of NH_4^+ and NO_3^-, respectively. The detailed procedures of each method are available in AgriLASA (2004).

A pair of ceramic suction cups were installed at depths of 0.2 m and 0.4 m between plant rows in the middle of a plot at planting during each season. The cups were installed in three plots for 40, 80 kg and 120 kg N ha^{-1}, all in the same replicate. Vacuum was applied before sampling and suctions of approximately 60–70 kPa were applied when extracting soil solution samples.

4.1.6 Plant growth and yield components

Plant height, number of tillers per unit area, leaf area index (LAI), and aboveground dry matter were measured at 7 to 10 day intervals from about 20 DAE to maturity. Height was measured from the ground to the tallest green leaf (the variety has erect leaves, so a leaf was only pulled upwards in the late stages) or to the panicle tip of ten plants in the middle of each plot. Fourteen plants in a 0.25 m x 0.50 m area were carefully cut at ground level. Number of shoots was counted, from which number of tillers was determined. During flowering, the number of flower-bearing tillers, main stems inclusive, were counted for estimation of 50% flowering (anthesis) and flowering duration. Leaf blades were detached from plants and passed through an LI-3100 leaf area meter (LiCor, Lincoln, Nebraska, USA) to determine surface area. Leaf area index was calculated as total area of the leaves divided by the corresponding ground surface area. The other plants organs, namely, stems and in later stages panicles and grains, were separated and biomass was weighed fresh for percentage moisture determination. Dry matter (DM) content of each plant organ was determined after oven drying at 65–70^{o}C to constant mass (approximately four days).

A sub-plot area of 1.25 m x 1.00 m was used for determination of aboveground dry mater and grain yield at final harvest. Sub-samples of the stover and the grains from each plot were oven dried for determination of moisture content. Grain yield (only full grains) was adjusted to 120 g kg^{-1} water content for comparison with commercial yields. Yield components, namely panicles m^{-2}, length of panicles, spikelets per panicle, 1000 grain mass, and sterility percentage were assessed from plants harvested from a 0.25 m x 0.5 m area. Sterility was calculated as the ratio of the mass of empty grains to the total mass of spikelets for ten panicles. Full grains were counted using a seed counter (Numigral®, Triplette and Renaud, Paris, France).

4.1.7 Measurement of leaf and grain N concentration

All leaf blades from a 0.50 m x 0.25 m area (14 main stems) were taken at booting, flowering and anthesis for determination of leaf dry matter and analysis of N concentration. Destructive sampling of all plants (main stems plus tillers) from a specific area (0.125 m^2) was preferred to selection of random plants across the plot to better capture the crop leaf N variability that is common under field conditions. Except at booting, leaves were profiled into the flag and lower leaves, as a gradient in leaf N along the canopy profile is known to exist (Shiratsuchi et al. 2006), and using a composite of older and younger leaf samples may obscure N treatment effects on leaf N content. Leaf blades were weighed fresh, part of the sample was taken for moisture content determination and the remainder was kept for chemical analysis. Leaves were oven-dried and ground, passed through a 1-mm sieve and kept in a sealed plastic bag in a cold room before analysis of total N was done. At the time of analysis, powdered subsamples were again oven dried at 65ºC to constant weight to determine the exact moisture content. This was needed for accurate measurement of total N since the procedure described below uses very small masses.

Approximately 100–130 mg of powdered samples of leaves and grains were weighed on a scale (precision = 0.1 mg) and enclosed in aluminum (Al) foil before combustion in a Dumatherm chamber. Nitrogen and protein analysis was done using the Dumas Method (Dumatherm® N Pro- Rapid Nitrogen / Protein Analyzer, C. Gerhardt GmbH & Co., *Königswinter, Germany*). A combustion temperature of 950ºC and reduction temperature of 650°C in the reactor was used, with helium (He) as a carrier gas. For the two stages when samples of the flag and lower leaves were analysed separately, leaf N concentration per plot was calculated as the mean concentration of the two leaf positions.

4.1.8 Water and nitrogen use water use efficiencies

To study N uptake, absorption and utilisation from indigenous soil supply (unfertilised treatment) and from fertiliser, selected metrics of NUE as defined by Cassman et al. (1996) and Fageria et al. (2010) were calculated. These components relate acquisition and utilisation of N to application rates and grain N content at physiological maturity, and therefore one parameter alone is not sufficient (Cassman et al. 1996). Harvest index (HI) (Eq. 4.2) is the ratio of grain yield to top dry matter yield. Agronomic N efficiency (AE) (Eq. 4.3) is the increase in grain yield per unit N applied (kg kg^{-1}). Apparent N recovery or recovery efficiency (AR) (Eq. 4.4) of fertiliser N is the ratio of increase in plant N accumulation at maturity per unit N applied (%). Water use efficiency (Eq. 4.5) was calculated as the ratio of Y to seasonal crop ET at the respective N rates (Allen et al. 1998). Agricultural use efficiency (UE; Eq. 4.6) as defined by

Perry (2007) was used as a metric for utilisation of applied N and water in grain production. The following equations were thus used:

$$\text{Harvest index} = \frac{\text{Y}}{\text{TDM}} \quad \text{...} (4.2)$$

$$\text{Agronomic efficiency} = \frac{\text{Y}_\text{F} - \text{Y}_\text{O}}{\text{NA}} \quad \text{....................................}(4.3)$$

$$\text{Apparent recovery} = \frac{(\text{NU}_\text{F}\text{-NU}_\text{O}) \times 100}{\text{NA}} \quad \text{...........................}(4.4)$$

$$\text{Water use efficiency} = \frac{\text{Y}}{\text{ET}} \quad \text{..}(4.5)$$

$$\text{Agricultural UE} = \frac{\text{Y}}{\text{ET} \times \text{NA}} \quad \text{...}(4.6)$$

where Y (kg ha^{-1}) is the grain yield (dry mass basis), Y_F in the N-fertilised plot and Y_O in the zero-N plot and NA (kg N ha^{-1}) is N application rate.

$$\text{Grain N uptake (kg N ha}^{-1}) = \frac{10 \times [\text{N concentration (g N 100 g}^{-1}) \times \text{Y (g m}^{-2})]}{100 \times 10} \text{...........}(4.7)$$

Grain N content (kg N ha^{-1}) to WUE (kg ha^{-1} mm^{-1}) ratios were calculated to better understand the relationship between N utilisation in grains and crop evapotranspiration (ET) (Sadras et al. 2016). A plot of Agricultural UE and WUE as a function of N rate was used to determine the point of intersection using the graphical method (Bianconi 2013).

Dry matter yield of each plant part was multiplied by the corresponding N concentration to obtain N uptake in the part as illustrated in equation 4.7 for grains. Stems were assumed to contain at most 0.25% N (dry weight basis) because typical values of N in upland rice straw (stems and leaves) is about 0.5% N and stem N concentration relative to leaf N is small (Kaizzi et al. 2014). Plant N content (kg ha^{-1}) was calculated as the sum of N content in the grains, leaves and stems at maturity.

4.1.9 Statistical analysis

Data were analysed in SAS® 9.3 version 6.1.7061 (SAS Institute Inc., Cary NC, USA) for Windows using General Linear Model (GLM) procedures. The differences between treatments and years were tested at α = 0.05 level of significance using the F-test. Means for main and interaction effects that were significant were separated using the Tukey's Studentized *post hoc* test. The means of WUE could not be separated using ANOVA because a single water meter was used to measure irrigation applied for three replicate plots, even though ΔS was measured per plot, so the calculated ET is thus per N treatment.

4.2 Results

4.2.1 Seasonal weather conditions

Although the growing period in 2015/2016 was generally warmer than 2014/2015, mean air temperature was favourable for rice growth in both seasons. Maximum and minimum temperatures averaged over the growing periods were 29.0 °C and 15.3 °C (Y_1) and 31.2 °C and 13.7 °C (Y_2), respectively. Rainfall received during the period 52–112 DAE was 105 mm in the 2014/2015 season and 175 mm in 2015/2016. Figure 4.1 shows rainfall was more biased towards the early season in 2014/2015 and to the late season in 2015/2016. During early March 2016 (DOY 69–77, late reproductive growth), heavy rainfall events coincided with the ripening stage. In contrast, during mid- to late December 2014 (DOY 346–362, early vegetative growth), rainfall was frequent. The amount received from sowing (DOY 324) to 20 DAE in 2014/2015 was 155 mm compared to 48 mm for the same growth stage in 2015/2016. Weather conditions may therefore have impaired N uptake during 2014/2015 and affected grain ripening during 2015/2016.

4.2.2 Leaf area index, tiller growth and crop development

Crop growth was very variable between the seasons even though statistically, the interaction effect of year and N rates on growth (except for plant height) was not significant ($p > 0.05$). Growth was generally better during Y_2 than Y_1. Maximum LAI was greater in Y_2 by 15–66%, compared to the same N treatment mean values in Y_1 (Figure 4.2a). There were no significant ($p > 0.05$) differences in LAI and TDM between treatments during most development stages. Leaf area index response to N rates was only significant ($p = 0.01$) during mid-tillering in 2014/2015, but mean values for N fertilised treatments were not significantly different. Thus, LAI did not change significantly with increase in N rate beyond 40 kg N ha^{-1}. Figure 4.2a also shows that LAI for the two highest N rates did not differ significantly post-anthesis, in contrast to the two zero N treatments for the separate seasons. Plants receiving 120 and 160 kg N ha^{-1} maintained greener canopies (stay green attribute) for longer than the other treatments (Appendix, Figure A4.2). In contrast, plants receiving 0 and 40 kg N ha^{-1} showed faster leaf senescence and had significantly ($p = 0.01$) lower LAI values at maturity in both seasons. Top dry matter yield at maturity was significantly ($p < 0.001$) different between N treatments, but season x treatment interaction was non-significant.

Tiller number, except at harvest, was lower during 2014/2015 than in 2015/2016 (Table 4.2). During Y_1, tiller number for only N-fertilised treatments increased after flowering in contrast to a decline post-flowering during Y_2. Mean tiller number per plant at harvest for 0 kg N ha^{-1} was much lower than the fertilised treatments in Y_1 compared to Y_2 (Table 4.2). Tiller number was therefore variable between treatments and seasons, especially for 0 kg N ha^{-1}, which had the highest variability. The mean number of tillers counted during vegetative growth (19–65 DAE) for instance in Y_1 at 65 DAE was lowest (1.3±0.1) for zero N treatment but not significantly ($p > 0.05$) different from other treatments. Contrast to Y_2, the mean number of tillers in Y_1 were more at harvest than during earlier stages of development, except for the zero N treatment. Tiller abortion therefore occurred only during Y_2, a normal phenomenon during rice development, and it was slightly more for 0 kg N ha^{-1} than for most N-fertilised treatments. During Y_2, a season of normal tiller development, maximum tiller number for 80–160 kg N ha^{-}

^{1} was early (80 DAE) compared to 92 DAE for the lower N rates (Table 4.2). It is noted that a medium planting density was used in both seasons and still a low tillering number resulted for this variety. Consequently, maximum canopy cover measured was too low (results not shown) to result in mutual shading and tiller abortion.

Table 4.2 Tiller number development from flowering to maturity as affected by N fertiliser rates.

Treatment	2014/2015			2015/2016			
	DAE			DAE			
	73	95	117	80	92	113	128
0	1.4^{a}	1.76^{a}	1.76^{a}	2.79^{a}	3.50	3.21^{a}	2.61^{a}
40	1.64^{ab}	2.07^{ab}	3.31^{ab}	3.88^{ab}	4.40	4.00^{ab}	2.64^{a}
80	1.64^{ab}	3.31^{ab}	3.52^{ab}	4.20^{ab}	3.80	3.60^{ab}	3.21^{ab}
120	1.74^{ab}	3.45^{b}	3.76^{ab}	4.55^{bc}	4.30	4.95^{b}	4.23^{b}
160	2.33^{b}	3.64^{b}	4.19^{b}	5.21^{bc}	4.90	4.36^{b}	3.65^{ab}
F-test	**	**	*	*	ns	*	**

DAE, days after emergence.
ns, not significantly different at $p < 0.05$.
* Significant at $p < 0.05$.
** Significant at $p < 0.01$.
*** Significant at $p < 0.001$.

Growth analysis showed that from anthesis to maturity, tiller number and LAI decreased considerably for 0 kg N ha^{-1}, 40 and 80 kg N ha^{-1} (in order of more to least decrease) while for 120 and 160 kg N ha^{-1}, the two variables virtually did not change. Growth response of other variables measured is shown in appendix (Figure A4.1).

Nitrogen fertiliser rates influenced on onset and duration of flowering. In Y_1, first flowers of plants at the 0 and 40 kg N ha^{-1} rates appeared six days after those of other treatments, and flowering duration was also shorter. Delay in flowering of plants for these two treatments was also very prominent in Y_2. However, although onset and duration of flowering was delayed in plants at low N rates, maturity was also reached much earlier for these treatments during both years.

4.2.3 Yield attributes and N use efficiency

Grain yield measured during maturity was consistently higher in 2015/2016 (3.27–5.46 t ha^{-1}) than in 2014/2015 (1.75–4.09 t ha^{-1}) for corresponding N application rates. However, the response to N rates was only significant ($p = 0.027$) in few cases in Y_1 as well as in Y_2. Increase in grain yield was non-significant with increasing N rate above 80 kg N ha^{-1}. Figure 4.2 shows that the grain yield and TDM responses to N rate were different for the two seasons. Grain yield (Y) followed a linear relationship, ($Y = 1.926 + 0.0126x, R^2 = 0.72$) with N rates (x) during Y_1, suggesting yield increase with additional N fertilisation. The function was quadratic ($Y = 3.04 + 0.04486x + 0.0003x^2, R^2 = 0.77$) during Y_2, with the maximum yield achieved at 120 kg ha^{-1}. These high inter-annual yield differences were partly attributed to differences in canopy growth and LAI linked to rainfall as noted previously and the associated yield response (Table 4.3).

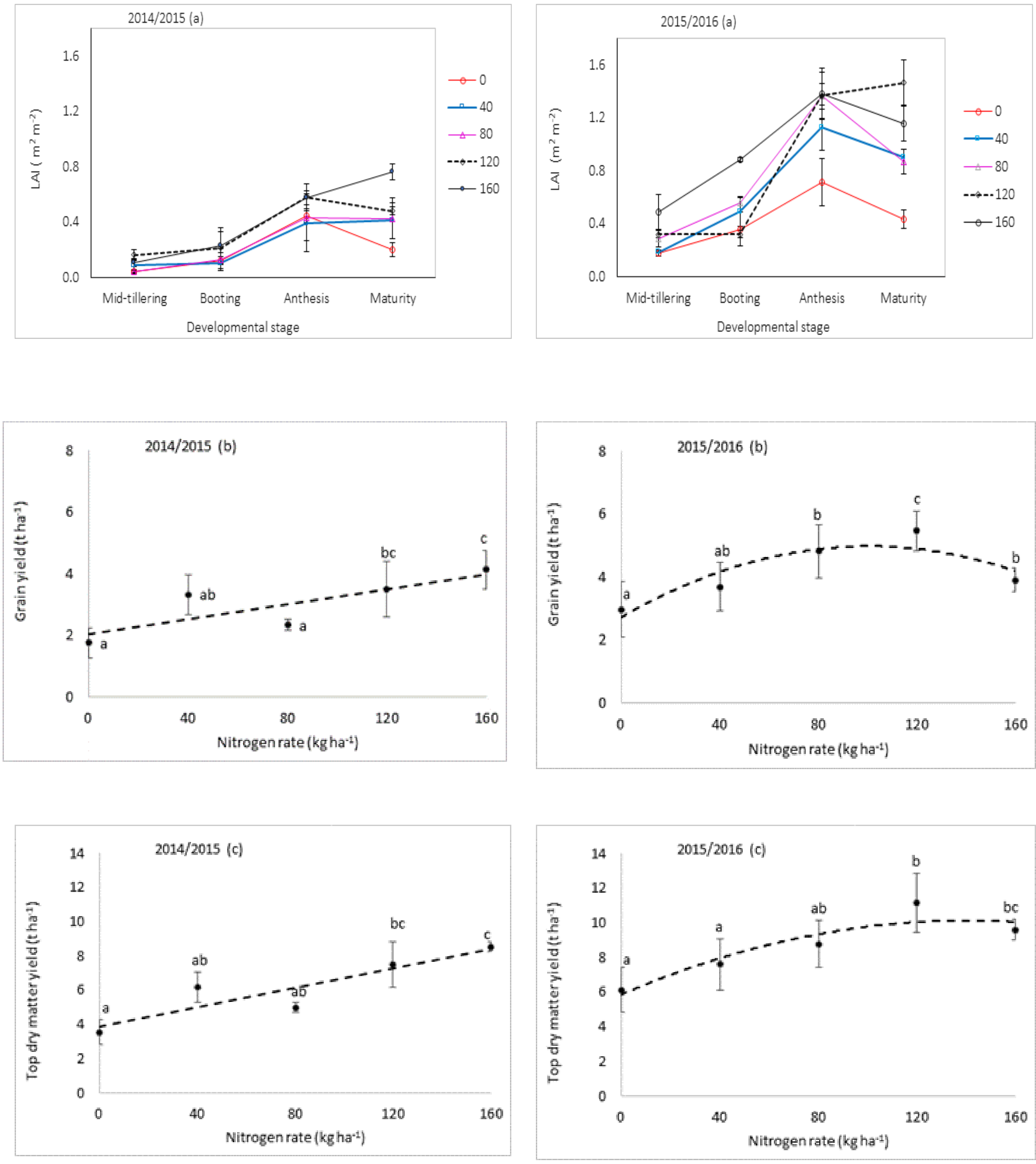


Figure 4.2 Changes in leaf area index (LAI) over the crop growing season (a), grain yield (b) and top dry matter yield at final harvest (c) in response to N fertiliser rates in two consecutive years. Standard deviation bars show within treatment variability in the data. Means followed by the same letters for each parameter do not differ significantly at $p < 0.05$ according to Tukey's Studentized test.

Correlation analysis revealed that grain yield variations due to N rates were closely linked to the number of spikelets ($R^2 = 0.91$, $p < 0.05$) and panicles ($R^2 = 0.56$, $p < 0.05$) per unit area. At harvest, these two yield components were the only parameters that were significantly ($p < 0.01$) affected by N rates, and only in Y_2 (Table 4.3). However, grand mean number of spikelets per panicle was significantly ($p < 0.001$) higher during Y_2 than Y_1. Although the number of tillers at harvest was significantly ($p = 0.041$) different between N rates for both Y_1 and Y_2 (Table 4.2), the number of productive panicles per unit area was similar between most N-fertilised treatments, except between 120 and 40 kg N ha^{-1} in Y_2 (Table 4.3). Excess tillers without panicles were produced at N rates above 40 kg N ha^{-1}, which limited potential gains in yield. Tiller growth in Y_2 thus contributed to higher TDM at harvest, but with no considerable effect on grain yield. Analysis of variance of TDM during different sampling dates showed that biomass accumulation during mid-tillering and before flowering stages was not significant ($p > 0.05$) except at anthesis ($p = 0.04$) between N treatments (results not shown). It means that N effects on yield response were largely determined post-flowering and was brought about by differences in DM partitioning.

Table 4.3 Means of selected yield components at different N rates in two seasons.

Year, N rate (kg N ha^{-1})	1000 grain mass (g)	Panicle length (cm)	Grain sterility (%)	Spikelets per panicle	Panicles (m^{-2})	Spikelets $x10^3$ (m^{-2})
2014/2015						
0	21.64	15.32	8.32	65.0	261.3	13.94
40	22.24	15.81	6.52	61.1	381.3	22.76
80	21.21	15.91	8.27	60.1	416.0	27.17
120	22.29	17.73	7.05	58.2	448.0	30.31
160	21.42	16.23	5.84	51.9	509.3	30.08
p value	ns	ns	ns	ns	ns	ns
2015/2016						
0	21.84	16.48	8.89	87.7	348^{a}	30.53^{a}
40	22.87	17.96	5.23	94.4	384^{a}	36.83^{ab}
80	20.85	18.23	5.73	83.0	480^{ab}	41.18^{b}
120	22.20	18.59	7.17	99.1	556^{b}	64.30^{c}
160	21.72	18.28	7.30	96.4	468^{ab}	45.26^{b}
p value	ns	ns	ns	ns	**	**
Year x N rate interaction	ns	ns	ns	ns	ns	ns

* Significant at P < 0.1; ** Significant at P < 0.05; *** Significant at P < 0.01, **** Significant at P < 0.001.

ns, not significant.

Mean values within columns followed by the same letters do not differ significantly at stated levels of probability by Tukey's Studentized *post hoc* test.

4.2.4 Water supply during growth stages and soil water content

Nitrogen fertilisation affected seasonal irrigation amount required to refill the soil water content deficit in the top 0.6 m depth, as well as the cumulative amount depleted at end of the season. Irrigation water at end of the season was more for N fertilised treatments than zero-N fertilised which could be attributed to higher soil water depleted, for example depleted θ was higher in plots receiving 120 and 160 kg N ha^{-1} than in plots receiving 0 and 40 kg N ha^{-1} (Table 4.4). Between seasons, irrigation water used to refill the depleted volume did not significantly ($p > 0.05$, paired *t*-test) but in each year means differed between N rates by the same test. Although not consistent, irrigation amount generally increased with increasing N rates, with the highest amount for the 120 kg N ha^{-1} treatment in Y_1 and 80 kg N ha^{-1} in Y_2. It is noted in Y_1, when considerably much rainfall was received during vegetative growth stage (Figure 4.1), the zero-N fertilised treatment used considerably less irrigation amount than the N-fertilised treatments (Table 4.4). The increase in seasonal irrigation with N fertilisation can be attributed to previously reported LAI response in part and to enhanced water use from soil layers below 0.4 m depth. For instance, in Y_1 when rainfall was biased towards the early season, total water extracted from the soil profile was highest at 120 kg N ha^{-1} plots (591 mm). Though depletion was only refilled for the top 0.4 m profile, an estimated 54–66% of water uptake across N-fertilised treatments occurred from 0.4–0.6 m layer (data not shown).

Table 4.4 Irrigation, rainfall at growth stages and soil water content and depletion at 0.6 m depth

Seasons	Treatment (kg N ha^{-1})	Rainfall (mm)		Irrigation (mm)		Depletion (θ , mm)	Final θ at depths (mm)
		Vegetative	Reproductive	Vegetative	Reproductive		
2014/2015	0	365	66	60	154	3.4	125.9
	40	365	66	119	150	3.5	125.7
	80	365	66	122	157	3.2	126.2
	120	365	66	135	156	8.9	120.9
	160	365	66	90	160	5.2	125.2
2015/2016	0	192	65	392	67	3.3	132.8
	40	192	65	399	90	8.9	129.1
	80	192	65	386	93	9.6	124.3
	120	192	65	367	69	9.3	125.0
	160	192	65	399	73	5.8	125.4

4.2.5 Water and nitrogen use efficiencies and relationships

Table 4.5 shows crop water use, WUE and NUE metrics as affected by N rates over the two growing seasons. Crop ET differences between N treatments were negligible, meaning that the calculated differences in WUE were a result of different grain yields.

Grain harvest index (HI) was slightly higher without fertiliser N (mean = 0.45) than with, for example, for 160 kg N ha^{-1} the average HI for both seasons was 0.39. Harvest index for the 160 kg N ha^{-1} decreased from 0.41 in Y_1 to 0.36 in Y_2 when the trial was repeated on the same plots. Grain N accumulated at harvest was only significantly different in Y_1 between 0 kg N ha^{-1} and all the other treatments, except 80 kg N ha^{-1}. However, grain yield per N content in grain (IE) was significantly ($p > 0.05$) affected by N rate, year and N rate x year interaction (Table 4.5). Mean values of AR indicate that recovery of N was not affected by season and the interaction effect of N x season. As expected, AE of applied N tended to decrease with increasing fertiliser rates. The values of AE in Y_1 and Y_2 were highest for 40 kg N ha^{-1} and lowest for 160 kg N ha^{-1}. Agronomic N efficiency decreased linearly with increasing N fertiliser rate. Per unit of N fertiliser applied, therefore the 40 kg N ha^{-1} treatment was the most efficient rate. This large increase in grain yield at 40 kg N ha^{-1} resulted from large N uptake as confirmed by the highest value of grain yield per N uptake in grains. Agronomic efficiency and AR had a highly significant ($p < 0.0001$, $R^2 = 0.98$) correlation over the two years (data not shown), which indicates the low yield response in Y_1 could be attributed to recovery of N.

Table 4.5 Water and nitrogen (N) use efficiencies of upland rice over two consecutive years.

Season, N rate (kg N ha^{-1}) 2014/2015	ET (mm)	Grain† yield (t ha^{-1})	Harvest index	WUE (kg ha^{-1}mm^{-1})	Agric UE (kg mm^{-1} kg^{-1} N applied)	Grain N (g 100 g^{-1})	Grain N uptake (kg ha^{-1})	Leaf N uptake (kg ha^{-1})	Stem DM (kg m^{-2})	Grain N uptake /WUE	AE (kg kg^{-1})	AR‡ (%)
0	573	1.76^{a}	0.43	3.06	-	1.58^{a}	23.85^{a}	15.60^{a}	0.14^{a}	7.8	-	-
40	585	3.41^{ab}	0.44	5.83	0.15	1.70^{a}	49 50^{a}	27.80^{b}	0.27^{bc}	8.5	33.97^{a}	77.49^{a}
80	587	2.26^{a}	0.38	3.85	0.05	1.69^{b}	38.71^{a}	28.10^{ab}	0.23^{ab}	9.5	7.13^{b}	37.01^{b}
120	591	3.49^{bc}	0.40	5.91	0.05	1.95^{b}	60.58^{b}	42.90^{c}	0.33^{bc}	10.3	19.72^{c}	57.24^{a}
160	587	4.15^{c}	0.41	7.07	0.04	2.07^{b}	74.69^{b}	41.40^{c}	0.36^{c}	10.6	14.98^{bc}	52.43^{b}
p value	na	*	ns	na	-	***	***	*	***	na	*	**
2015/2016												
0	588	2.96^{a}	0.46	5.04	-	1.65^{a}	46.01	9.140^{a}	0.22^{a}	9.1	-	-
40	594	3.82^{ab}	0.47	6.43	0.16	1.76^{a}	60.67	12.28^{a}	0.27^{ab}	8.8	31.36^{a}	47.85^{a}
80	591	4.81^{b}	0.48	8. 14	0.10	1.86^{ab}	79.04	10.83^{ab}	0.32^{ab}	9.7	20.68^{a}	46.41^{a}
120	590	5.46^{c}	0.42	9.26	0.08	1.88^{ab}	91.22	29.52^{c}	0.42^{bc}	9.9	20.84^{a}	58.78^{a}
160	593	3.90^{b}	0.36	6.58	0.04	2.05^{b}	69.65	17.82^{d}	0.41^{bc}	10.6	8.34^{b}	23.15^{b}
p value	na	*	ns	na	-	**	ns	*	*	na	*	**
N rate x season	na	*	ns	na	-	ns	ns	ns	ns	na	ns	ns

AE, Agronomic efficiency; AR, apparent recovery; IE, internal efficiency; Agric. UE, Agricultural use efficiency
* Significant at P < 0.05; ** significant at P < 0.01; *** significant at P < 0.001; ns, not significant at 5% level of probability.
na, not applicable. † Differences in WUE between treatments were based on ANOVA of grain yields as ET values are calculated per treatment.
Means within columns followed by the same letter do not differ significantly at p < 0.05 by Studentized *Post hoc* test.

Increasing N fertiliser rate from 40 to 160 kg N ha^{-1} increased grain N content per unit evapotranspiration from 10 to 12 kg N kg^{-1} mm^{-1} on average. Agricultural UE decreased with increasing N fertiliser rate (Figure 4.3). Mean values at 160 kg N ha^{-1} were the same in both years, despite a substantial reduction in grain yield for this rate in Y_2. Agricultural UE decreased at a strongly (R^2 = 0.80 and 0.97) negative exponential rate with increases in N rate in both years. Since grain quality did not change considerably with increasing N rate (except for 160 kg N ha^{-1}), the relationship indicates that to produce grain with about 1.7% grain N (the grand average), the most efficient utilisation of N fertiliser and water was achieved with a lower N rate than for maximum yield.

During both seasons, intersection between the WUE and Agricultural UE functions occurred at rate slightly lower than 80 kg N ha^{-1} (Figure 4.3), indicating that maximising use efficiency for N and water simultaneously was achieved at approximately this N rate. It is noted that this N rate did not result in the maximum grain yield in both years. The pattern of Agricultural UE is similar in both years and declined with increasing N rates. Water use was strongly influenced by N rates.

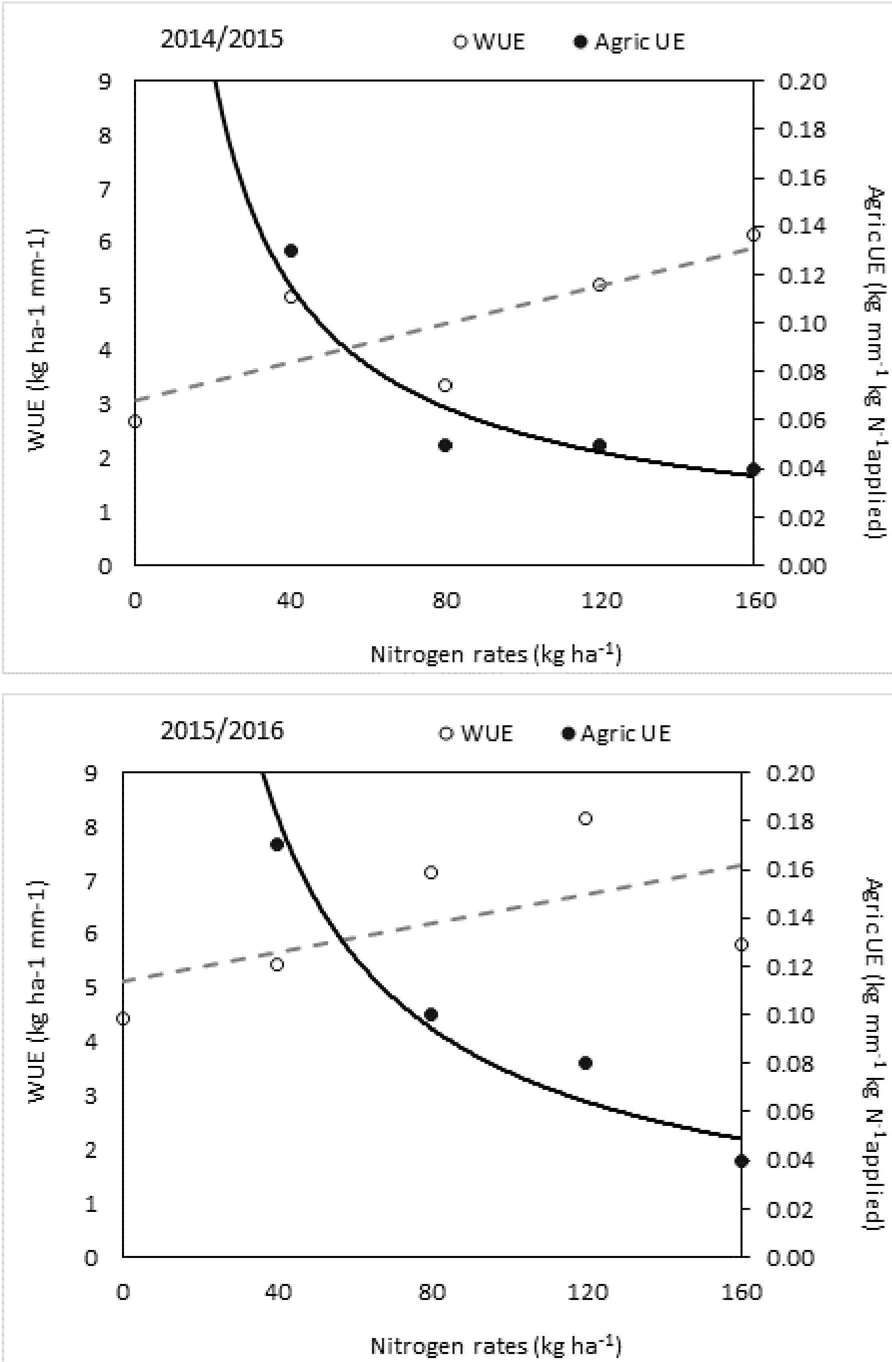


Figure 4.3 Agricultural use efficiency (Agric UE) and water use efficiency (WUE) of rice as influenced by nitrogen (N) rate in the two seasons at Hatfield, South Africa.

4.2.6 Crop N uptake and soil inorganic N dynamics during crop growth

Nitrogen concentration in leaf blades during booting, anthesis and physiological maturity was generally higher during Y_2 than Y_1 (Figure 4.4). Season had a significant ($p < 0.01$) effect on leaf N levels but the season x N rate interaction was not significant ($p > 0.05$). Leaf N concentrations during vegetative growth in each season was not significantly affected by N rates. It was expected that leaf N concentrations follow a normal pattern with time - initially high during early stages with a gradual decline as the crop approaches maturity. In Y_1, the highest N concentrations were measured during anthesis, while in Y_2 the highest was at booting. Nitrogen concentration was lowest at maturity stage in both years (Figure 4.4). The unusual/unexpected pattern of leaf N concentrations during 2014/2015 for only fertilised treatments may have been because of frequent rainfall events during early vegetative growth stage (Figure 4.1). The very wet soil conditions may have caused anaerobic conditions that were detrimental to root growth, denitrification and/ or the leaching fertiliser N, which could have resulted in reduced N uptake.

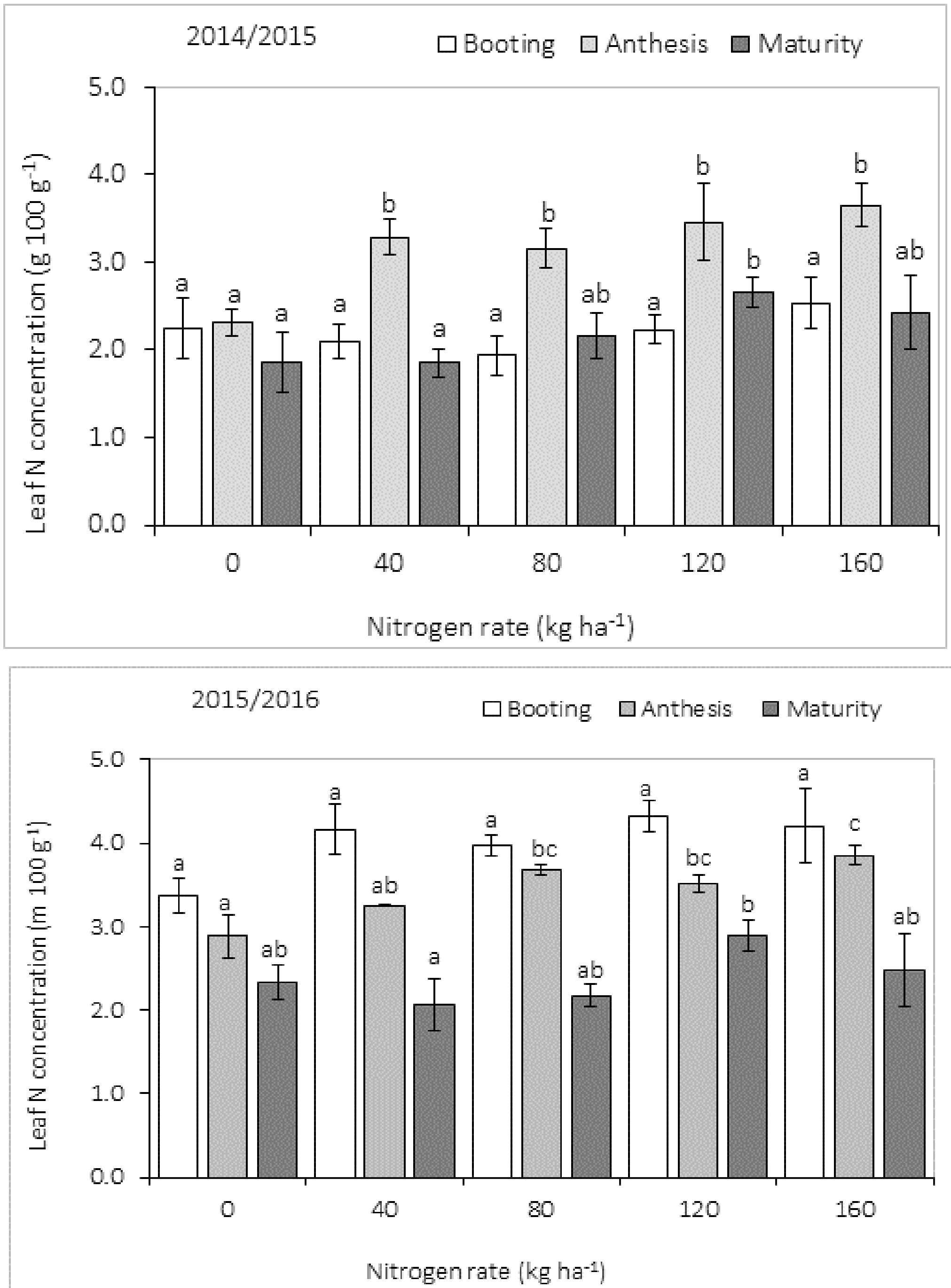


Figure 4.4 Composite sample leaf nitrogen (N) concentration during booting, anthesis and physiological maturity as influenced by N application rates. Means for a stage followed by the same letters do not differ significantly by the Tukey's Studentized test at $p < 0.05$. Standard deviation (s.d.) bars show variability in data.

Although N concentration in the stems was not analysed, the highly significant ($p < 0.0001$) stem DM yield measured at harvest (Table 4.5), indicates that retention of N in the parts is very high for N fertilised treatments. It is likely that stems of plants receiving 120 kg N ha^{-1} and 160 kg N ha^{-1} treatments contain more than twice the N content for the zero N treatment, based on a 1.8: 1–2.8:1 ratio of stem DM to the zero N treatment.

The 120 kg N ha^{-1} treatment led to the highest leaf N content and concentration, irrespective of leaf positions. Averaged across seasons, N concentration (g 100 g^{-1}) in lower leaves was higher for 120 kg N ha^{-1} (2.68 ± 0.16) than other treatments, including 160 kg N ha^{-1} (2.24 ± 0.08). Although not always significant, there was a clear trend of leaf N concentration increasing with N application rate, independent of stage. In Y_2 differences in leaf N concentration between treatments diminished, as the trials was repeated on the same soil, as is indicated by similar leaf N levels, even at anthesis, between 40 kg N ha^{-1} and 0 kg N ha^{-1}. These findings suggest that the more N is applied, the more the crop takes up beyond it needs for growth and grain production. Furthermore, N requirement may be low during vegetative growth stage as differences in leaf N were non-significant in both seasons.

Soil inorganic N values at harvest (range = 2–8 mg kg^{-1}) were generally lower than values measured at sowing across all treatments (Figure 4.5). Differences in soil inorganic N levels, although not consistent with N rates, were small in Y_2 compared to Y_1, most notably at 0.4–0.6 m soil layer. Late season rains in Y_2 could have diluted treatment effects on soil inorganic N, and in this layer, where most water was extracted. Although soil inorganic N over the entire 0.6 m depth was not significantly ($p > 0.05$) affected by N rates, levels within the 0.4–0.6 m layer showed a pattern linked to N rate (Figure 4.5). For the 0.4–0.6 m soil layer, plots without N fertiliser had higher mean soil inorganic N than for fertilised treatments at crop maturity, and this is most likely linked to limited uptake of soil water below 0.4 m depth by plants that received zero N fertiliser. The high residual soil inorganic N for 0 kg N ha^{-1}, approximately 16–47% more than the mean levels for the higher N rates in Y_1 and by 44–51% in Y_2, can be associated with poor root development and low root activity. Furthermore, the lowest residual soil inorganic N measured for 120 kg N ha^{-1} and the highest soil water was depleted for the same rate confirms that N fertiliser simultaneously increased water use and N recovery.

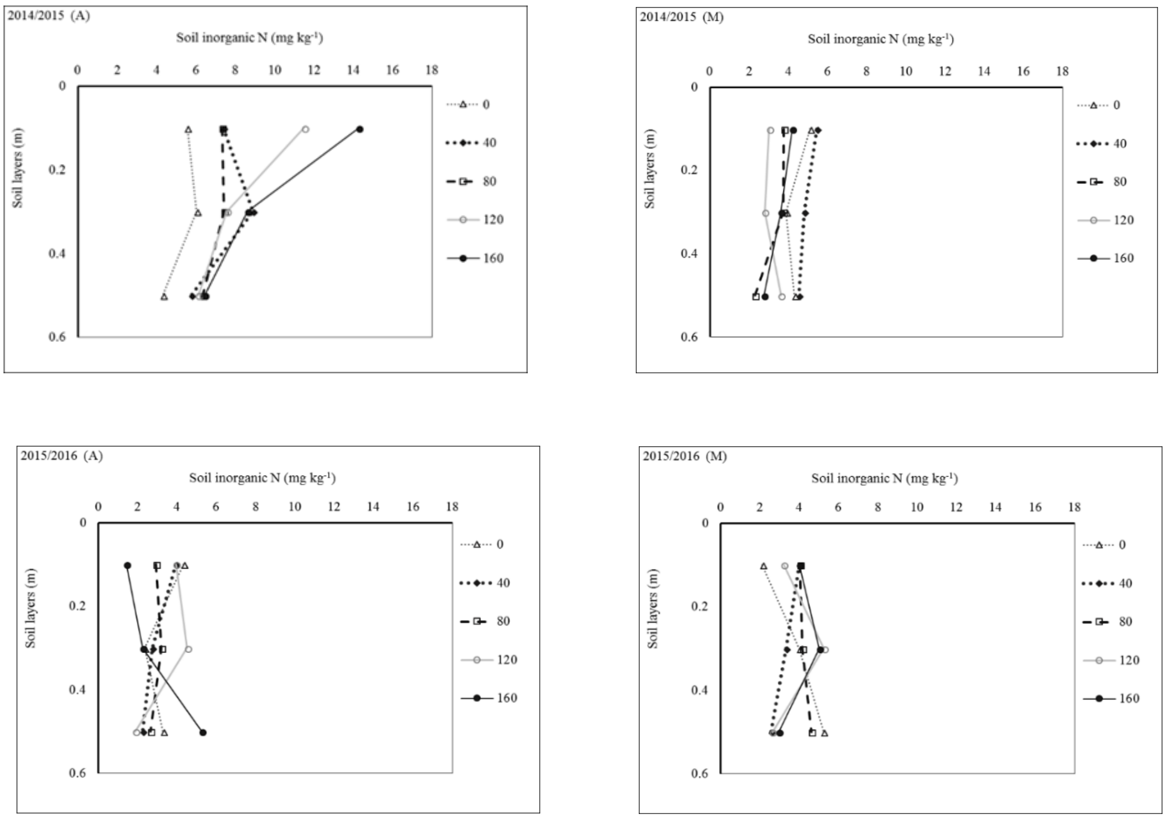


Figure 4.5 Distribution of soil inorganic nitrogen (N) around anthesis (A) and maturity (M) in the 0–0.6 m soil layer during two seasons. Standard deviation bars show within treatment variability in the data are not indicated for 2014/2015 because one composite soil sample per treatment was analysed.

4.3 Discussion

Crop yield varied between seasons for the same N rate because canopy growth was greater during 2015/2016 than in 2014/2015 due to different rainfall patterns. High rainfall during tillering in Y_1 indirectly affected N dynamics, which was mirrored by low leaf N levels at booting compared to Y_2. Great variation in rice yields between seasons has been previously reported (Yoshida et al. 1972; Onaga et al. 2012). Yoshida et al. (1972) alluded inter-seasonal yield variation to the available amount of solar radiation (R_s) during a season. There was no possibility of this effect in our study as total R_s differed by only 77.5 MJ m^{-2} between the seasons.

High grain yield in Y_2 compared to Y_1 was correlated to generally higher number of spikelets per panicle and productive panicles per square meter, due to high LAI. While the contribution of spikelets per unit area to grain yield was strongly significant in both years, influence of leaf N was only evident in Y_2. Murata et al. (1966) found that the number of spikelets strongly depends on LAI at heading and the latter is positively related to total N uptake up to flowering. Differences in leaf N, which were only significant between 0 kg N ha^{-1} and 80 kg N ha^{-1} in Y_2, support the findings of Murata et al. (1966). During Y_2, a reduction in grain yield at 160 kg N ha^{-1} was linked to a lower number of spikelets and lower leaf N concentration post-anthesis than for the 120 kg N ha^{-1} treatment. Furthermore, the reduction in grain yield was likely due to higher tiller production at 160 kg N ha^{-1} than for other rates. In addition, a delay in ripening of secondary tillers at rates above 80 kg N ha^{-1} compared to the unfertilised treatment resulted in small gains in grain yield and a reduction in HI. Findings suggest that reducing tillering could be critical to improve spikelet number and compensate for low HI under high N rates.

The relatively high grain yield for the unfertilised treatment, which also increased in Y_2 despite rotation with two winter wheat crops to which no fertiliser was applied is attributed to N made available through soil mineralisation. Similar observations have been reported by Dobermann et al. (1998) and Linquist and Sengxua (2001). In rice production, N is commonly applied at early vegetative stage to promote tillering and increase panicle number per unit area and top-dressing around panicle initiation to increase spikelet number per panicle (Peng et al. 2002). In the present study, it is important to pay more attention to promoting reproductive growth to achieve high yield because non-significant increase (between mostly fertilised treatments) in grain yield with increasing N rate was mainly attributed to small increase in spikelets per panicle and poor spikelet filling. It is also noted that lack of significant differences in grain yield in many cases was attributed to low N allocation to grains. Results suggest luxurious N uptake, which largely remains in the vegetative parts and in emerging tillers. A larger fraction of N is likely retained in the straw of fertilised plants based on a highly significant increase in stem DM yield and leaf content with increasing N rate. Taking rice straw DM (stems and leaves) of 0.5% N (Kaizzi et al. 2014), 0.25% N in stems, our estimates of 30–50 kg N ha^{-1} in straw across N fertilised treatments suggests that more was locked up in the vegetative parts. Therefore, even if over 160 kg N ha^{-1} was applied, no further yield gains would have been achieved. So integrated N management is needed to better N response for example planting density and modifying the proportion of N split at the growth stages. Farmers applying high N rates under non-water limiting conditions could reduce tillering ability, undesirable in the late stages, through high planting densities. Despite yields not significantly differing in many cases, the yield response curve in Y_2 is useful in deciding what N rates are excessive in a specific management system for a variety of known yield potential. Most previous studies on N nutrition in *Oryza sativa* L. under rainfed conditions reported that crop yield response was always linear over a wide range of N rates (George et al. 2002; Oikeh et al. 2008). Incidences of water shortages during a season were documented in those studies in contrast to the present study.

It is important to achieve balance between grain N concentration (grain quality) and yield when applying N fertilisers to achieve effective increase in both variables. It is also apparent from Figure 4.6 in 2014/2015 that upland rice can still accumulate substantial N levels in the leaves during the reproductive growth stages, even when N uptake is hampered during vegetative growth. The crop attained closely equal leaf N concentrations during anthesis to levels in 2015/2016. Such 'compensative uptake' of N after flowering was not previously documented in upland rice, but, has been observed in irrigated sugarcane (*Saccharum officinarum*). Wood et al. (1996) found late accumulation of leaf N, just before maximum biomass production, during a first sugarcane crop compared to an early accumulation during a ratoon crop.

Results in Table 4.2 showed that tiller number and development can be altered by seasons which affects use efficiency of applied N at high rates. The normal tiller growth pattern in well-watered rice is a peak number around flowering, where after the numbers usually drop (Asch et al. 2005). The higher tiller numbers after flowering for N fertilised treatments in Y_1, could be because the crop took up more N later in the season which was reflected by a small decline in leaf N from booting to maturity for fertilised treatments. In contrast to most crops, tillering in rice is widely spread over time, shoots in a hill are at different chronological ages and a substantial overlap between the vegetative and reproductive stages occurs (Alou et al. 2018). It means that uptake and utilisation for N at a point in time considerably differ between a primary stem and tertiary tillers. Like cotton (*Gossypium hirsutum* L.), spread of ball production over time results in different N demands within a single cotton bush (Milroy et al. 2001). Since the growth habit of rice is partly similar to that of cotton, competition for N between tillers at vegetative growth stage and storage organs can be expected, the degree of which depends on N availability. The decline in tiller number in Y_2 for lower N rates after flowering was quite consistent and expected, signifying a small maintenance burden at lower N rates.

Generally, the values of NUE were slightly higher compared to values reported by Fageria et al. (2010), Kaizzi et al. (2014) and Kondo et al. (2005). One likely reason for the differences in NUE trends between studies is that water supply was optimised in the present study and the rice varieties are different. The present study identified quick N recovery or compensative uptake of N, high grain N uptake, increased rooting depth and stay green attribute as physiological traits that are related to high NUE of the variety. However, it was noted that low panicle number due to few productive tillers in Y_1 occurred with late accumulation of N in leaves, which reduced grain yield and thus utilisation efficiency.

Nitrogen fertilisation has a considerable influence on irrigation water demand, effective soil water extraction depth and water use of irrigated rice. The lower irrigation requirement (60 mm) in the zero-N treatment compared to the 120 kg N ha^{-1} (135 mm) during vegetative growth in Y_1 indicated that N stress limited water consumption. This is a consequence of limited N available for metabolic processes such as photosynthesis leading to less DM to invest in canopy and root development (Cooper et al. 1987). This present study thus confirmed the influence of N fertiliser on rooting depth and soil water use as it was conducted under water non-limiting conditions. Similarly, Asch et al. (2005) and Kijoji et al. (2014) reported enhanced water extraction at lower layers than 0.4 m depth under drought, even though effective rooting depth of rice is around 0.4 m (Kato and Okami 2010).

4.4 Conclusions

Nitrogen fertiliser had a positive effect on crop water use, WUE and NUE of irrigated upland rice. Yield highly varied more without N fertiliser between seasons due to large differences in tiller number, canopy development and spikelet number per panicle. Agricultural use efficiency (kg mm^{-1} kg^{-1} N applied) decreased exponentially with increasing N rate. High N rates increased secondary tillers which tended to delay ripening and consequently reduced filled spikelets and HI. High soil water and N levels during tillering significantly increased the number of unproductive tillers, increased N demand and reduced both WUE and NUE. Seasonal water use of upland rice was lower without than with N fertilisation. Findings highlight the need to understand what limits yield improvements in irrigated upland rice and crop traits which are stable over seasons to optimise N fertiliser. Furthermore, findings have implications on seasonal water requirement of upland rice as N rate is increased and sustainability of yields in intensive systems.

CHAPTER 5

CROP MODEL PARAMETERS FOR UPLAND RICE (*Oryza sativa* L.) TO SIMULATE GROWTH, PHENOLOGICAL DEVELOPMENT AND WATER UPTAKE UNDER WELL-WATERED AND STRESS CONDITIONS AND NITROGEN LIMITING CONDITIONS

This Chapter is at the final stages of preparation for submission to Agricultural Water Management. The paper is presented as:

I.N. Alou[ab], J.M. Steyn[a]*, J.G. Annandale[a] and M. van der Laan[a]. Crop model parameters for upland rice (*Oryza sativa* L.) to simulate growth, phenological development and water uptake under well-watered and stress conditions.

[a] Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, 0028 South Africa

[b] National Agricultural Research Organisation (NARO), Bulindi ZARDI, P.O. Box 101 Hoima, Uganda.

Abstract

Crop water use and availability of irrigation is already under pressure from urban and industrial demands. The use of crop simulation models is very important, especially in rice (*Oryza sativa* L.) grown on uplands, because production risks associated with water stress (WS) are high. The objective of this study was to determine crop parameters of two widely adopted upland rice varieties (NERICA®) in sub-Saharan Africa. The generic crop Soil Water Balance (SWB-Sci) model was parameterised, calibrated and validated using growth analysis data from field experiments conducted from 2013 to 2016 on the University of Pretoria's Hillcrest Campus Experimental Farm, South Africa. Crop parameters of the medium-duration variety (Nerica 4) and the short-duration (Nerica 10) were determined under well-watered, adequately fertilised treatments. The model was validated using independent data collected during 2013/2014 and 2015/2016 growing seasons for respective varieties. Additionally, independent data collected under WS conditions during four stages of development namely, tillering (Ti), panicle initiation (PI), anthesis (AT) and grain filling (GF), of Nerica 4 were used to test model performance. Radiation use efficiency (RUE) values for Nerica 4 (2.10 g MJ^{-1}) and Nerica 10 (2.20 g MJ^{-1}) were equal. A comparatively high RUE value for the short-duration variety was associated with a low canopy extinction coefficient, a stay-green attribute and semi-dwarfness. Simulated grain (head dry matter) and top dry matter yields during crop growth under WS agreed reasonably well with measured data (D = 0.89, RMSE = 2.51 t ha^{-1}, MAE = 49.75%, MSD = 24.65%) over two seasons, indicating acceptable model performance. However, accurate estimation of grain yield with WS at PI was more challenging, as this stress altered phenology and leaf morphology. The model can be used to explore improved management practices to increase yield and WUE under irrigated and rainfed conditions in different localities.

Key words: Crop modelling, panicle initiation, radiation-use efficiency, Specific leaf area, SWB-Sci.

5.0 Introduction

In rainfed upland rice (*Oryza sativa* L.) agro-ecosystems, soil water conditions are very variable (Parent et al. 2010). Unpredictable periods of water stress (WS) in uplands are caused by uneven distribution of rainfall, intrinsic low water storage capacity of some soils, and high evaporation from bare soil during early crop growth (Shrestha et al. 2013). While rice is generally very sensitive to mild water deficits (Fukai and Lilley 1994), considerable effects of WS on growth, but with no real effect on grain yield have been observed (Boojung and Fukai 1996). Sensitivity to stress depends on the development stage (Wopereis et al. 1996; Heinemann et al. 2011), and most importantly on soil water availability. Asch et al. (2005) reported that a constant soil water deficit across the soil horizon as opposed to progressive soil drying adversely affected rice growth.

In most rice producing regions of sub-Saharan Africa (SSA), this important crop is produced under rainfed upland conditions (ARC 2007). Most African upland rice growers are small-scale producers and face great risk of early-, mid- or late-season drought, depending on rainfall distribution. Successful rice cultivation in moisture-limited conditions is very likely to depend on supplementary irrigation because of increasing incidences of intermittent. Stress at any growth stage has variable effects on rice growth and ultimately on yield and yield components (Wopereis et al. 1996; Boojung and Fukai 1996). Farmers need to mitigate impacts of seasonal WS on rice productivity, for instance through the implementation of appropriate cropping calendars. Sowing dates are dictated by the onset of rain (Becker et al. 2007 cited by Shrestha et al. 2011), which is also typical of SSA, and by availability of labour for farm operations.

Modelling is a potentially useful diagnostic tool for planning production and for understanding a cropping system (Wopereis et al. 1996). Reviews such as those by Farooq et al. (2009) and Akinbile et al. (2011) reported that the highest rice yield losses are frequently caused by WS. However, accurate, variety-specific information on phenological development required to evaluate yield loss is unfortunately lacking for most rice growing regions (Peng et al. 1994). Crop model parameters required for accurately simulating upland rice growth and to make recommendations on related agronomic practices is generally lacking for upland rice, owing to inadequate field-scale rice research (Campbell et al. 2001; Boschetti et al. 2006). Most crop models use parameters for mostly lowland rice germplasm taken from a few areas (Humphreys and Timsina 2003; Shrestha et al. 2013). Use of data not specific for a variety can result in poor prediction of crop growth and development, and consequently grain yield.

Determination of crop model parameters for commonly grown NERICA® varieties in SSA (Jones et al. 1996) can contribute to improving rice productivity in rainfed uplands through building and applying modelling frameworks. For example, the use of models to assess WUE of rice varieties in growing areas and characterise incidences of seasonal WS will aid in capitalising agronomic practices to improve rainfall efficiency. Among the popular NERICA varieties, Nerica 4 has a longer duration than Nerica 10 (Lamo et al. 2010). The longer duration means its seasonal water requirement is likely to be relatively higher. While crop simulation models have been widely applied to lowland rice cropping systems in other geographic regions, evaluations on upland rice are lacking, likely due to the unavailability of genetic coefficients for these varieties in data bases of most models (Timsina and Humphrey 2003). Crop simulation models use basic modules for phenological development, biomass accumulation rate and partitioning between plant organs, the soil water balance and nutrient uptake in the estimation of crop yield (Ritchie 1990).

This study chose the Soil Water Balance (SWB-Sci) model (Annandale et al. 1999) for the following reasons. The model is generic and mechanistic (Annandale et al. 1999), meaning that specific crop parameters need to be determined. The model has been successfully used for other purposes in rainfed and irrigated agronomic crops, fruit tree and pasture crops (Annandale et al. 2011; Ghezehei et al. 2015; Tesfamariam et al. 2015, Mathobo et al. 2018). However, this model has not previously been parameterised for rice.

The main aim of this study was to parameterise and evaluate the SWB-Sci model in order to predict effects of WS on crop performance of two upland rice varieties. Specific objectives were to, (i) determine crop-specific parameters for the medium-duration (Nerica 4) and short-duration (Nerica 10) varieties under upland field conditions, and (ii) evaluate the ability of SWB-Sci, once calibrated using data from stress-free conditions, to simulate scenarios of WS at different development stages of Nerica 4. The hypotheses tested were, (i) SWB-Sci can robustly simulate effects of WS on upland rice variety growth and yields, and (ii) the model can simulate dry matter production and phenology with stress during reproduction. Nerica 4 was deemed as appropriate for the WS study because of its longer duration of growth phases.

5.1 Materials and methods

5.1.2 Brief introduction of SWB-Sci model and justification

The SWB-Sci model was described in detail in chapter 2 (literature review), but in context of this chapter some aspects will be pointed out. The Soil Water Balance (SWB-Sci) model is based on an improved generic crop version of the NEW Soil Water Balance (NEWSWB) model (Campbell and Diaz 1988). The SWB-Sci model is a mechanistic, generic crop model that was originally developed as a real-time irrigation scheduling tool (Annandale et al. 1999; Annandale et al. 2003). Parameters for rice were not determined prior to this study. Although a crop factor approach in the model could be used, there would be uncertainty in appropriateness of the data base (existing information is for lowland rice) to upland rice ecotypes. The model has been widely applied, for instance for simulations of N (Tesfamariam et al. 2015) and P dynamics (Van der Laaan 2009). It uses tested approaches like the FAO Penman-Monteith (1948) grass reference equation to compute evapotranspiration (ET) (Allen et al. 1998) and the Tanner and Sinclair (1983) approach for dry matter accumulation. Crop phenology is simulated as a function of thermal time, calculated from mean daily and cardinal temperatures of the crop.

5.1.3 Field studies and conditions

Field experiments conducted at the University of Pretoria's Hatfield Experimental Farm (25°45'S, 28°16'E; 1370 m a.s.l) were used to determine crop-specific parameters. Climatic and soil conditions at Hatfield, and agronomic practices during field experiments are described in detail in previous chapters (3 and 4). Variety Nerica 4 was grown in a rain-out shelter and Nerica 10 in an open field since different treatments were planned and the shelter (approx. 22 m long X 11 m wide) was not enough to accommodate both varieties. It was paramount to use large sample size of plants for the growth analyses to reduce error. In addition, regular destructive harvesting (8–10 sampling dates per season) meant that crop area would be reduced considerably, and yet a minimum micro-plot size is needed for realistic yield estimation at final harvest.

Nerica 4 was grown during the summers of 2013/2014 and 2014/2015, and Nerica 10 during the summers of 2014/2015 and 2015/2016. Growing seasons of Nerica 10 were very distinct, with respect to rainfall distribution (biased to early season rain in 2014/2015 and to late season rain in 2015/2016) and the second season was also warmer than the first. A small plot (1.0 m X 1.0 m) of Nerica 4 was established adjacent to the rain-out shelter crop in 2014/2015 for root sampling. The small plot and some treatments in the open field and in the rain-out shelter experiments were well-watered and adequately fertilised and agronomic practices were optimised to prevent water and nutrient stresses and pests as described in Chapter 3 and 4.

5.1.4 Soil water content, plant growth analysis, phenology and fractional interception

Profile volumetric soil water content (θ) at 0.2 m depth intervals was measured with a calibrated neutron probe water meter, Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). Irrigation to field capacity to a depth of 0.4 m was given twice weekly using a high-density drip irrigation system from about 10 DAE to physiological maturity for the well-watered control.

For stress treatments, irrigation was only withheld during the development stage of interest. In the open field study, irrigation frequency was less than four days since the last water input through rain, or irrigation.

Plant growth variables were measured at least weekly from three replicate plots up to physiological maturity, as described here. Rice plants from all plots were observed for phenological stages to determine thermal time and duration of growth stages. Plant samples from a 0.25 m X 0.5 m area (n = 14 plants) were cut at ground level and separated into leaves, stems, panicles and grains. During sampling, influence of open spaces after destructive sampling on inter-plant competition for water and light was limited by always sampling at opposite sides of the plot away, from a recent biomass harvest. Roots were not sampled from the rain-out shelter and in the open field trials, but in the small plot as described in the section on determination of root biomass and fraction. Green leaves were passed through a Licor-3100 leaf area meter (LiCor, Lincoln, Nebraska, USA) for calculation of leaf area index (LAI). Samples were oven-dried at 65^{o}C for 72 hours, weighed and DM yield was determined by weighing. At harvest maturity when nearly all grains were brown, grain yield was measured from a net plot area measuring 1.75 m X 1.5 m (rain-out shelter study) and 1.25 m X 1.0 m (open field study), while yield component analysis was based on plants sampled from a 0.25 m X 0.5 m area. Grain and straw yields were weighed and sub-samples of each were oven-dried for determination of moisture content. Grain yield was corrected to 12 g kg^{-1} moisture content.

Interception of Photosynthetically Active Radiation (PAR, 0.4–0.7µm) by the canopy was determined at least three times every month by measuring photosynthetic photon flux density above the canopy and at ground level with a 1 m long Decagon Sunfleck Ceptometer (Decagon devices, Pullman, Washington, USA). For ground level readings, the ceptometer was placed mid-way between two plant rows. Four points were measured diagonally across in each plot and the average value was computed.

5.1.5 Computation of parameters

Most parameters were estimated following procedures published in the manual for the model (Annandale et al. 1999). Cardinal temperatures of rice and values for minimum leaf water potential were sourced from literature (Shrestha et al. 2011). A brief description of some parameters follows.

Phenology and thermal time

Growing degree days (GDD, ^{o}Cday) was calculated by summing "heat units" from sowing to 50% emergence (germination), and to the growth stage of interest. Daily thermal time was calculated as mean of daily minimum and maximum temperature less the base temperature. The base temperature (T_{base} = 8.2 ^{o}C), optimum temperature (T_{opt} = 22.0 ^{o}C) and cut off temperature (T_{cut} = 42 ^{o}C) were adopted for upland rice varieties (Shrestha et al. 2011) which closely related to ones in our study.
In the SWB-Sci, GDD are required for stages namely, emergence, flowering, transition period from vegetative to reproductive growth and physiological maturity. All these stages were observed and for physiological maturity, dry matter accumulation, besides colour of grains, was used to estimate the stage. Since phenology was observed daily, the transition period (^{o}C d), was determined, based on flowering duration (first flower appearance to about 100% flowering) from growth analysis. Tillering in rice is spread over time and data on tiller development was used to confirm the estimated transition period.

Canopy extinction coefficients (K_{PAR} and K_S)

Intercepted photosynthetic photon flux density of the crop was calculated as the difference above and below canopy ceptometer readings. Fractional interception (FI) for PAR was calculated as the ratio between ceptometer readings of above and below the canopy, averaged for each plot.

$$FI_{PAR} = 1 - \frac{PAR_{below}}{PAR_{above}} \quad (5.1)$$

The extinction coefficient (K_{PAR}) was estimated using Monsi and Saeki (1953) equation 5.2, analogous to Lambert-Beer's law.

$$FI = 1 - e^{-K_{PAR}*LAI} \quad (5.2)$$

Exponential regression of FI against LAI was performed by customising the model in CurveExpert Professional© software version 2.3.0 (Hyams Development, Chattanooga, Tennessee, USA). Canopy extinction coefficient (K_{PAR}) was determined from curve fit (CurveExpert Professional®2.3.0) using a customised equation. The resultant slope of the regression equation is K_{PAR}. Since the ceptometer measures PAR flux, K_{PAR} was then converted into canopy extinction coefficient for solar radiation (K_s) required for partitioning of ET into soil evaporation and crop transpiration. The equation by Campbell and van Evert (1994) was used to convert K_{PAR} to K_s:

$$K_s = K_{bd}\sqrt{a_s} \quad (5.3)$$

$$K_{bd} = K_{PAR}/\sqrt{a_p} \quad (5.4)$$

$$a_s = K_{PAR}/\sqrt{a_p a_n} \quad (5.5)$$

where K_{bd} - the canopy radiation extinction coefficient for 'black' leaves with diffuse radiation, a_s - leaf absorptance of solar radiation, a_p -leaf absorptance of PAR (assumed as 0.8) and a_n – leaf absorptance of near infrared radiation (0.7–3 µm) is assumed to be 0.2 (Gourdriaan 1977).

Specific leaf area (SLA)

Area (m^2) of green leaves sampled from a known ground area was divided by the leaf dry mass (kg) to obtain SLA on each date. A plot of SLA over time declined exponentially. A mean value was calculated for the period before flowering, 0–75 DAE for Nerica 4, and 0–60 DAE for Nerica 10, as leaf senescence had not yet commenced.

Root biomass and root fraction

A core sampling method designed for rice (Kondo 2003 cited by Kato et al. 2006) was used to measure root biomass at 52, 59, 67 and 75 DAE from about the middle of the vegetative to flowering stages. Roots were taken from the small plot adjacent to the shelter for confirmation of rooting depth during 2014/2015. Root cores were taken within an area of 0.25 m X 0.25 where plants were also sampled for comparison of root DM and TDM yield.

Roots were extracted approximately 10 cm from either side of two plant rows, as rice roots are mostly concentrated around this distance from rows (Kato et al., 2006). Six cores (50-mm height, 50-mm inner diameter) were stacked into a sampling probe and driven into the soil. The soil sampler was equipped with six cores and one plate to cover the top part of the cores. Roots were sampled to about 500 mm soil depth and soil cores were divided into 0–100, 100–200, 200–300 and 300–400 mm segments. On occasions when the soil was too hard to take a complete sample, cores were taken at 200 mm soil depth (two cores) increments. To ease root extraction, the crop was irrigated on days of sampling to wet the soil. A total of six replicate cores (three on either side of a row) at each soil depth was taken on each day. Soil cores were enclosed in plastic bags and carefully washed with water to remove roots. Roots were oven dried at 70^{o}C for at least three days. Dried samples were then weighed on a scale (precision 0.001 g). Root dry matter was calculated on mass per sampling area basis (kg m^{-2}) to relate with above ground biomass on area basis. Surface area of the cores was equal to 0.00197 m^{2}. Mean root DM yield at each depth was calculated from the six sampling cores. The fraction of DM in roots was estimated.

Radiation use efficiency and dry matter water ratio

To estimate RUE, accumulated intercepted solar radiation ($\sum FI_i * R_{Si}$), where is R_{Si} is daily solar radiation and FI_i is estimated intercepted fractional interception on a specific day (i = 1,…n), was calculated. Fractional interception on days after sowing when a ceptometer was not used (due to e.g. cloudy weather) was estimated by fitting a cubic polynomial regression ($ax^2 + bx + c$) to data on each plot. Coefficients a, b and c were different for each season. Calculated FI values from the polynomial regression were compared with observed data on respective days to establish accuracy of the equation.

The SWB-Sci model can calculate radiation or water limited yields (Annandale et al. 1999). Radiation use efficiency (RUE) was estimated as the slope of the linear regression line relating biomass accumulation (kg m^{-2}) and accumulated daily solar radiation (MJ m^{-2} day^{-1}) intercepted (Monteith 1977) by the rice crop. Top dry matter (TDM) was only considered in the calculation of RUE, but the fraction of total DM in the roots was used in interpreting RUE values. Otherwise, considering root biomass would have biased comparisons between the varieties. Dry Matter water ratio (DWR) a conversion from transpiration (T), corrected for VPD to DM production, was calculated as the ratio of DM yield to T corrected for seasonal average VPD (Tanner and Sinclair 1983). Evapotranspiration (ET) was used instead of T in the calculation of DWR as T was not actually measured. The SWB-Sci model considers the lower of the two parameters in simulating dry matter production.

After deriving the parameters, values were adjusted within reasonable limits so that simulated values closely matched with observed data, a process called calibration. Logical adjustments were done for a parameter at a time while considering the match between time course simulations of TDM, Harvestable DM, LAI, FI and soil water deficits and the observed values. The calibration was done using data from three replicate plots under water and nutrient stress-free conditions.

5.1.6 Model testing and validation

The performance of the model was tested using independent data sets collected from similar and different treatments during other seasons. Data from N non-limiting rates of 120 and 160 kg N ha^{-}

[1] during 2015/2016 were considered for Nerica 10, while for Nerica 4, stress treatments in addition to a well-watered control in 2013/2014 were used. Statistical indicators namely, index of agreement (D), relative mean absolute error (MAE), root mean square error (RMSE) and coefficient of determination (R^2) were used to estimate errors and determine model bias (Willmott 1981). SWB-Sci generates these indicators when comparing simulated values with observed data. Indicators were calculated separately for final harvestable DM and TDM because a single set of statistics for these two variables is generated from the model.

5.2 Results

5.2.1 Crop parameters for the rice varieties

Estimated values of RUE, calculated from TDM alone up to physiological maturity, for the medium-duration variety Nerica 4 in two growing seasons (0.0021 and 0.00188 kg MJ^{-1} of R_s intercepted) were slightly different from the values for the short-duration variety. The values for Nerica 10 (0.0021 kg MJ^{-1} of R_s intercepted) were very similar during the two seasons. It is noted that during 2014/2015, when both varieties were grown, the RUE value for Nerica 10 was 0.0022 kg MJ^{-1} more than the value for Nerica 4. The higher RUE is confirmed by the steeper slope of the relationship between leaf area duration between sampling periods (x) and TDM (y) for Nerica 10 ($y = 74.01 + 86.15x,\ R^2 = 0.72$) than for Nerica 4 ($y = 55.13 - 83.86x,\ R^2 = 0.70$). Dry matter accumulation during the grain-filling period for instance during 2014/2015 changed considerably for Nerica 4 (approx. 1.2–1.8 kg m^{-2}) compared to that for Nerica 10 (approx. 0.7–0.8 kg m^{-2}). This change in DM accumulation during the late phase is associated with remobilisation of reserves from mostly leaves and results in accelerated leaf senescence. Leaf senescence post-anthesis was evident and quick in Nerica 4 as opposed to the "stay green" attribute of Nerica 10.

It was noted that total intercepted R_s at PI and first flowering for the medium-duration variety (Nerica 4) was greater than for the short-duration (Nerica 10) (data not shown), because LAI values at the same development stage were greater for Nerica 4. While canopy size for Nerica 10 was smaller at PI, it is likely that utilisation of intercepted Rs was quite high during post-flowering stages (due to stay green attribute) resulting in a similar RUE to that for Nerica 4.

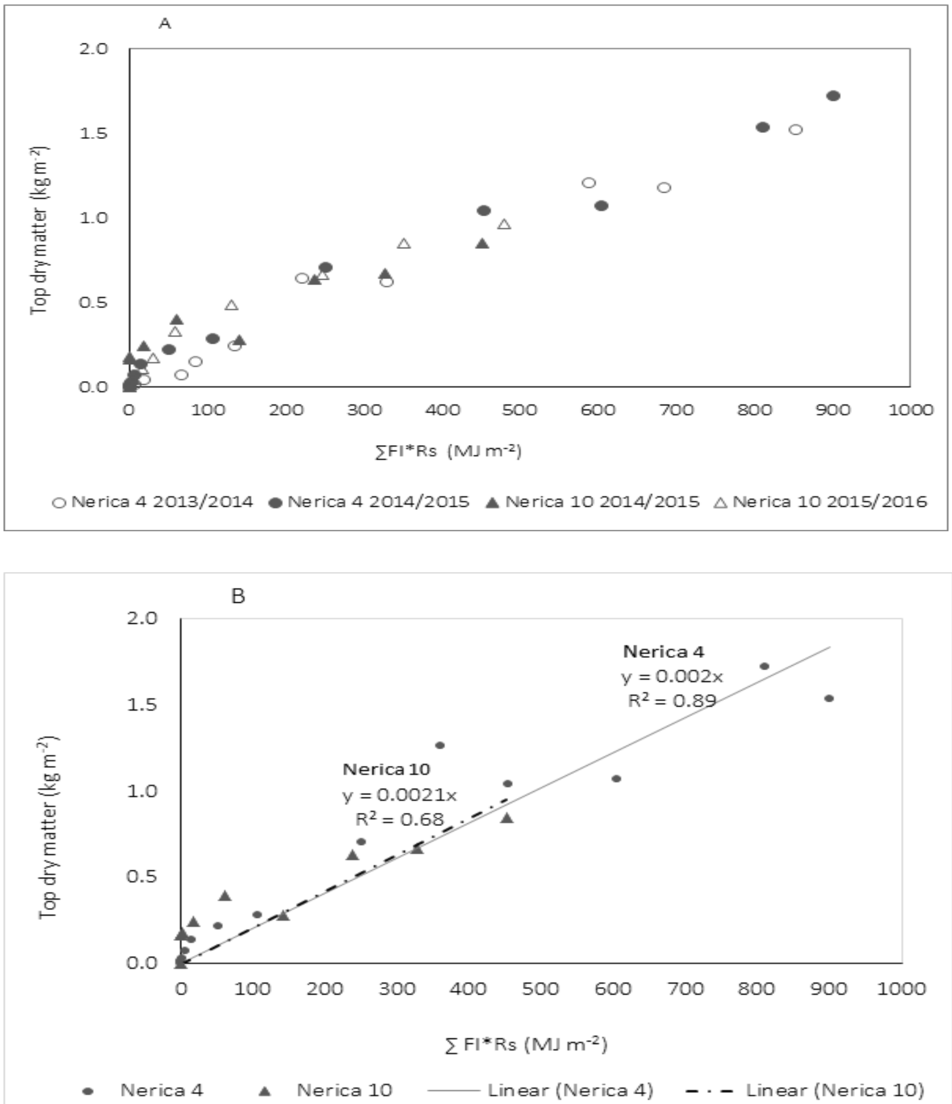


Figure 5.1 (A) Relationship between cumulative intercepted solar radiation (R_s) and top dry matter (TDM) of the two rice varieties measured during two growing seasons and (B) fitted linear relationship between cumulative R_s and TDM, showing estimated RUE values of the two varieties.

Variability in the data was too small, as a uniform crop stand and equal plants m^{-2} was achieved, to cause considerable error in estimated mean biomass. During sampling, influence of open spaces after destructive sampling on inter-plant competition for water and light was omitted by always sampling opposite side of the plot from a recent biomass harvest. The values of RUE at harvest were slightly lower than at maturity (data not shown) because of reduction in dry matter through natural senescence and respiration during the period (15–24 days across seasons) when the crop was left to dry after maturity.

Table 5.1 shows crop parameters measured under stress-free growth conditions (no water and no nutrient limitations and without pests) during 2013/2014–2015/2016 summers at Hatfield Experimental Farm, South Africa. Input parameters determined from literature and previous SWB research were: stress index (0.99), root growth rate (3.0), base temperature (8 ^oC), optimum temperature (22 ^oC), cut off temperature (42 ^oC) and minimum leaf water potential (-800 kPa) were taken from literature (Dingkuhn et al. 1999; Asch et al. 2005; Annandale et al. 2009).

For simulations of N dynamics of Nerica 10, a default value of 0.45 typical for C3 crops was taken as the slope for dilution curve of biomass and N (Van der Laan 2009). Grain N partitioning coefficient of 1.0, root N concentration (0.01 kg kg^{-1}) and increased root activity biomass (0.2) were taken from SWB data base. The NP ratio (5.5), optimal P concentration (kg kg^{-1}) values at emergence (0.045), vegetative growth (0.0018) and reproductive growth (0.001) were taken from Yoshida et al. (1976) and Fageria et al. (2010). Although P simulations were not performed, the values are needed for the model to run.

Table 5.1 Selected input parameters for two upland rice varieties after calibration in SWB-Sci.

Parameter† (units)	Symbol or abbreviation in SWB-Sci	Value for each variety	
		NERICA 4	NERICA 10
Extinction coefficient for solar radiation (R_s)	K_s	0.60	0.50
Dry matter water ratio (Pa)	DWR	7.0	9.0
Radiation use efficiency (kg MJ^{-1} of intercepted R_s)	RUE	0.0021	0.0022
Emergence day degree (°Cday)		149	131
Flowering day degree (°Cday)		1200	980
Maturity day degree (°Cday)		1950	1759
Transition day degree (°Cday)		330	400
Leaf senescence (°Cday)		700	1240
Maximum height (m)		0.94	0.57
Maximum root depth (m)		0.4	0.6
Stem to grain translocation (% dry matter)	Stem to grain transl.	0.15	0.15
Specific leaf area (m^2 kg^{-1})	SLA	4.0	3.2
Leaf-Stem partitioning	Leaf-Stem PART	0.138	0.19
TDM at emergence (kg m^{-2})		0.009	0.016
Maximum grain N concentration (kg kg^{-1})		na	0.021

The bulk of root biomass sampled was found in the top 0.3 m of the profile, and this trend is likely to remain the same after 75 DAE (Figure 5.2). Fine root hairs were rarely found in 0.3–0.4 m soil layer during samplings before first flower. The drop in mean root DM at 70 DAE is just variation between samples as indicated by the error bars or variations between depths. It is noted that root growth tends to flatten after 65 DAE, which suggests that roots had attained maximum depth by then, which is 10 days before flowering. However, thereafter an increasing trend in root biomass in the 0.3–0.4 m soil layer suggests that roots continue to grow post-flowering. The contribution of roots in 0.3–0.4 m layer to total root DM is very small and as such root growth did not change considerable after 65 DAE. Total root DM to a depth of 0.4 m, initially increased from 0.046 kg m^{-2} at 52 DAE to 0.231 kg m^{-2} at 67 DAE before attaining a stable value of 0.202 kg m^{-2} around flowering. Estimated ratio of root:total DM declined from 0.6 to 0.48 over the sampling period. Notwithstanding, root growth post-flowering can have a positive significant impact on water and nutrient uptake. If root biomass was considered in the calculation of RUE, then RUE would be approximately twice the calibrated values (Table 5.1) for both the varieties.

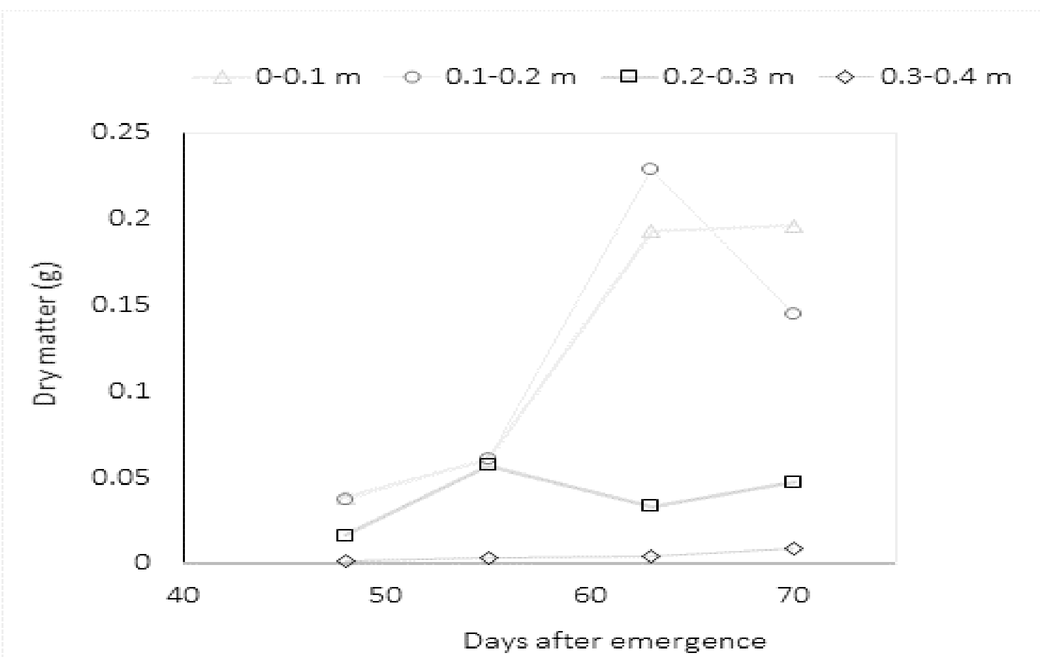


Figure 5.2 Root dry matter yield of variety Nerica 4 over time at different soil depths.

Besides RUE values, the two varieties differed in other parameters, notably K_s and duration of leaf senescence. Canopy for Nerica 10 did not achieve closure to the same degree as Nerica 4. Maximum FI was attained at the start of flowering, and was approximately 60% for Nerica 10 and 80% cover for Nerica 4 (Figure 5.3). However, the short-duration variety (Nerica 10) maintained a functional green canopy after flowering for longer than Nerica 4 but as mentioned before, its LAD was shorter than for Nerica 4. Because of its comparatively "open canopy", the value of K_s was lower for Nerica 10 than for Nerica 4, but estimated thermal time for leaf senescence was greater for Nerica 10. The "stay green" attribute was clearly visible post-flowering of Nerica 10, and this was also seen in the practically constant measured LAI values from destructive sampling. Panicles of rice varieties used drooped during ripening as opposed to most cereals thereby shading lower canopy. Thus, the increase in measured fractional interception of PAR after peak LAI can be contributed to panicle shading.

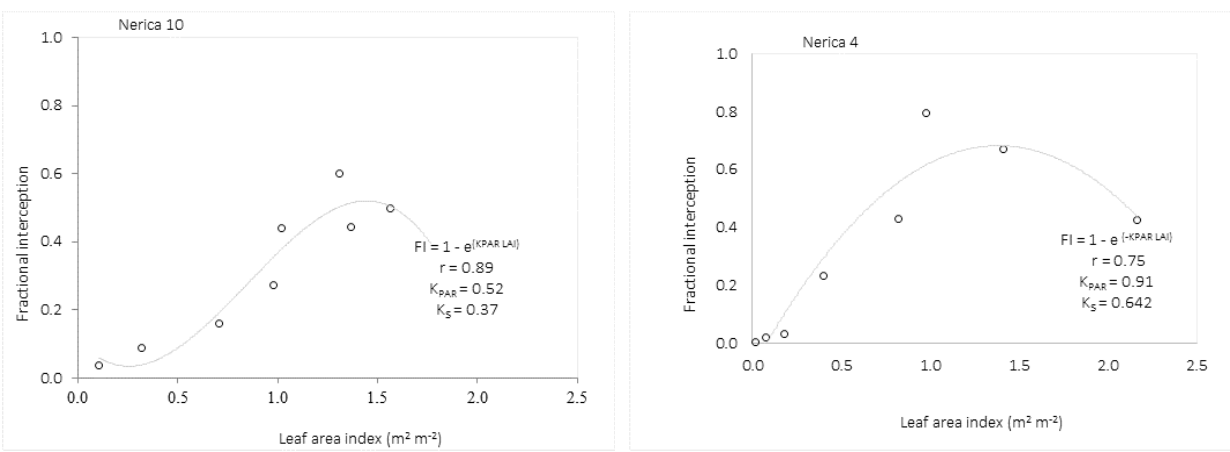


Figure 5.3 Relationship between leaf area index and fractional interception of photosynthetically active radiation (FI_{PAR}) for short (Nerica 10) and medium (Nerica 4) growth period rice varieties in 2014/2015.

5.2.2 Model calibration and validation results for potential growth conditions

Parameters for the two varieties used in calibration of SWB-Sci model are presented in Table 5.1. It was noted that for Nerica 10, SLA ($m^2\ kg^{-1}$) was variable between seasons because for the same development stage, leaf area ($m^2\ m^{-2}$) was smaller in 2014/2015 than 2015/2016, but DM ($kg\ m^{-2}$) was quite similar. The final values of parameters after calibration were close to values estimated from the calibration data before adjustment. Figure 5.4 shows model simulations and measured values for well-watered, adequately fertilised treatments during 2014/2015 (calibration data).

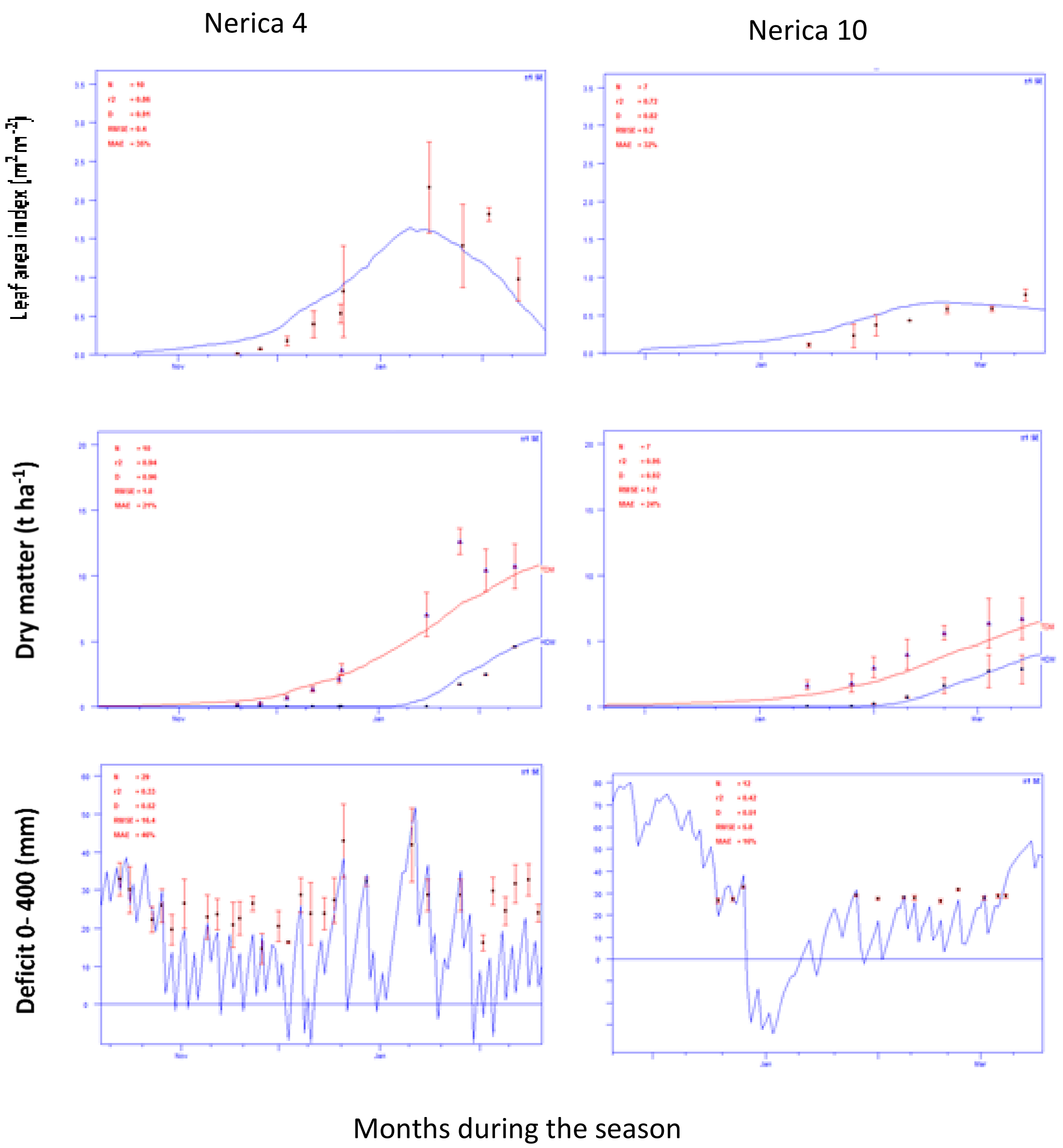


Figure 5.4 Model simulations (lines) and measured values (points) for (A) leaf area index, (B) head and total top dry matter yields (HDM and TDM) and (C) soil moisture deficits for Nerica 4 (left) and Nerica 10 (right) for well-watered, nutrient non-limiting conditions at Hatfield, South Africa (calibration data set 2014/2015). Vertical bars represent standard deviation bars on each sampling date.

Overall, using statistical indicators, there was a reasonable agreement between simulated and observed growth data (Table 5.2), with the error in prediction during the season generally low. However, the LAI-time course for Nerica 4 after a peak value was attained, was slightly overestimated, with the model simulating later canopy senescence than what was observed. In contrast, the model simulation of LAI for NERICA 10 was better than for Nerica 4, according to RMSE and MAE% values in Table 5.2. This difference in the precision with which LAI is simulated can be attributed to differences in canopy growth of the varieties. The LAI-time curve for Nerica 10 approached a near linear-plateau following peak value ('stay green') unlike that for Nerica 4 which was characterised by rapid decline (accelerated leaf senescence).

Model verification using independent (verification) data for well-watered conditions in 2013/2014 (Nerica 4) and in 2015/2016 (Nerica 10) indicated that predictions of crop growth generally compared well with observed data (Table 5.2). Achieving a good fit of simulated and measured LAI in 2015/2016 was difficult because great differences in canopy growth. Inaccuracy of the parameter SLA of Nerica 10 during growth was the cause of under estimation of LAI curve.

Table 5.2 Calibration and test results from SWB-Sci for selected parameters of the two varieties under well-watered conditions using statistical indicators in 2013/2014 and 2014/2015 summers.

Variety, growth parameter	Calibration data				Independent data			
	r^2	D	RMSE	MAE (%)	r^2	D	RMSE	MAE (%)
Nerica 4								
LAI (m^2 m^{-2})	0.84	0.89	0.4	33	0.90	0.75	1.0	44
Dry matter (t ha^{-1})	0.94	0.96	1.8	21	0.92	0.73	4.9	54
FI for R_s (%)	0.48	0.74	0.2	43	0.93	0.87	0.2	28
Deficit (mm)	0.23	0.36	23.1	69	0.2	0.33	21.4	73
Crop height (m)	0.95	0.96	0.1	14	0.99	0.99	0.0	4
Nerica 10								
LAI (m^2 m^{-2})	0.72	0.82	0.2	32	0.92	0.92	0.3	26
Dry matter (t ha^{-1})	0.95	0.92	1.2	24	0.99	0.88	1.6	32
FI for R_s (%)	0.81	0.63	0.2	52	0.90	0.84	0.1	52
Deficit (mm)	0.42	0.51	5.8	16	0.15	0.02	43.8	102
Crop height (m)	0.95	0.95	0.0	6	0.94	0.93	0.1	12

FI stands for fraction interception of radiation; Error of mean (n = 3 replicates).

5.2.3 Model validation under water stress conditions

Test results for independent data from four WS treatments showed overall model performance was satisfactory for most parameters (Figure 5.5). Grain yield at harvest under WS treatments in two seasons (n = 8 points) was well predicted (D = 0.89, RMSE = 2.51, MAE = 49.75%, MSD = 24.65 %). Modelled value of grain yield (5.2 t ha^{-1}) of Nerica 4 in 2013/2014 should be considered correct because measured grain yield was reduced by birds. Simulation of LAI under water stress showed means were underestimated by about 0.6–1.1 m^2 m^{-2} (RMSE) during 2013/2014 across all treatments. Performance with measured data in 2014/2015 was similar and thus is not shown

The model underestimated the peak value of LAI under stress as illustrated for two stress treatments around Ti and PI (Figure 5.5). However, general LAI-time response and head dry matter yield of Nerica 4 for stress around PI or late vegetative growth was well simulated. Based on a general pattern (fit of simulated to observed data for the two parameters), grain yield and top dry matter yield were well predicted under Ti and PI stress. Error of prediction (RMSE = 1.90 t ha^{-1}, averaged for seasons) of DM yields was comparable to other treatments. Accurate estimation of LAI under water stress around Ti and PI stage will require more refining of crop parameters to account for new tillers. The model could not detect regrowth of canopy after relieving stress. The contrast in simulations of the model for PI stress from the other stages could also be associated with a unique modification in leaf morphology- leaves wilted and twisted during PI and consequently leaf surface area and fractional interception greatly reduced.

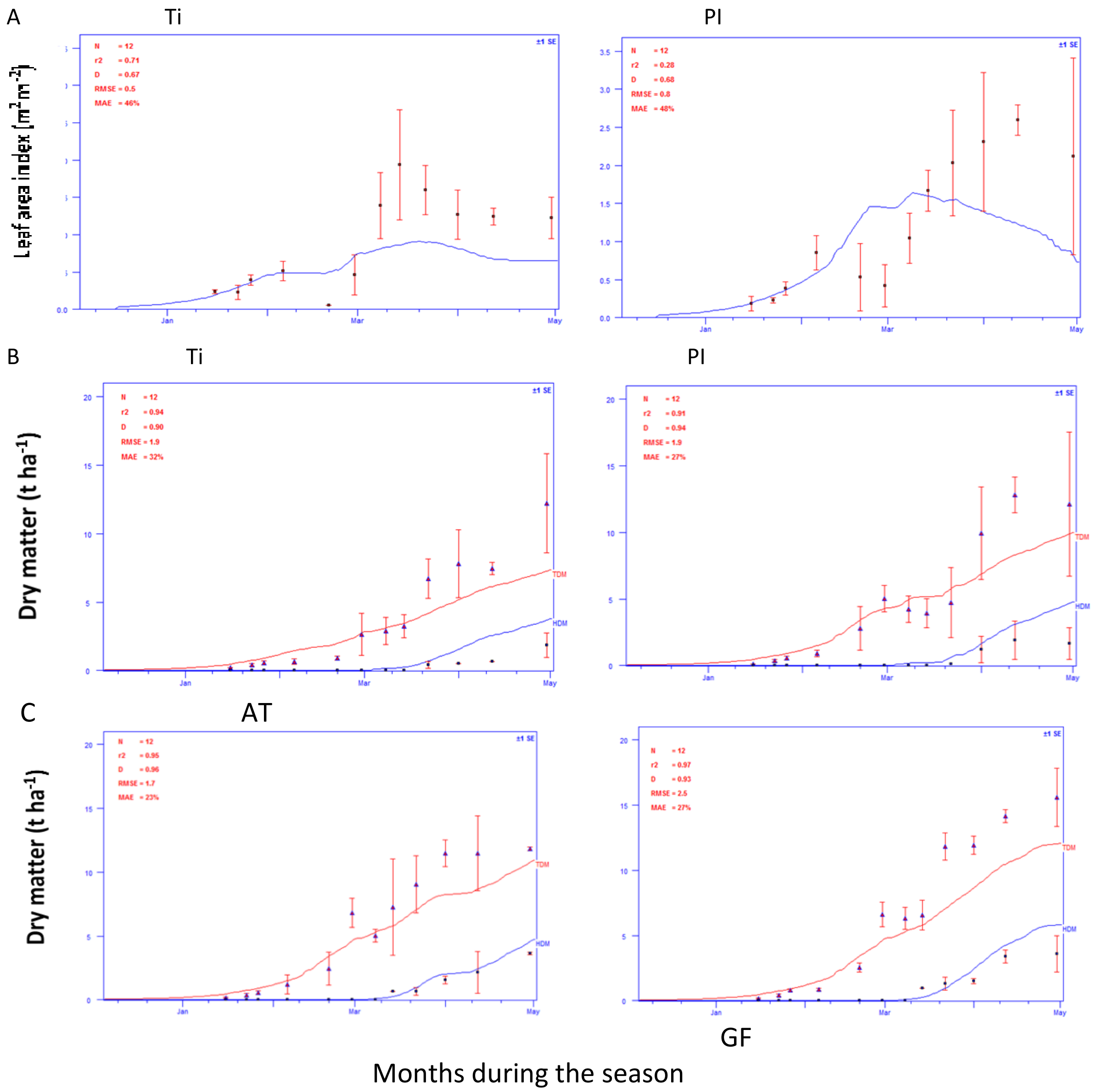


Figure 5.5 Selected SWB-Sci model simulations of (A) leaf area index and (B) top dry matter and grain yield of Nerica 4 for independent data with stress during tillering (Ti), panicle initiation (PI), anthesis (AT) and grain filling (GF) during 2013/2014. Standard deviation bars are for observed data (n = 27) while curves show simulated response.

5.2.4 Model performance under nitrogen-limited conditions

The results of simulations under three N rates, 0, 40 and 80 kg N ha^{-1} are shown in Figures 5.6 and 5.7. Simulated LAI values matched well with observed data ($R^2 > 0.65$, $D > 0.74$, RMSE < 0.2 and MAE < 45%) and overall, the pattern of leaf growth was well simulated. During early growth stages, simulated LAI were slightly higher than the observed values for some treatments especially in 2015/2016 season. However, the simulated values are less than 0.5 standard deviation from measured values in all seasons. The slight overestimation is due to inaccuracy of the parameter SLA during early growth and because leaf growth varied markedly between the seasons.

Maturity dates were slightly overestimated by about seven days in 2014/2015. Compared to observed flowering dates, the model simulated late flowering (+14 days) in 2015/2016 and early flowering (-8 days) in 2014/2015 on average. As a result, the simulated HDM in 2015/2016 was slightly higher than measured compared to that in 2014/2015 (Figure 5.7).

Figure 5.7 shows that simulated dry matter yields were very close (R^2 = 0.90–0.96 and D = 0.89–0.97) to measured values. The slight overestimation in TDM and HDM, notably in the early growth was as a result of slight overestimation of LAI. It is noted that harvest date in 2015/2016 was delayed by approximately 11 days, because late season rains interfered with ripening and drying of the crop. The yields measured at harvest were then considered for maturity dates when comparing simulated with measured data for that season.

Paired t-test results showed that simulated LAI, grain yield and TDM were not significantly different ($p > 0.01$) from measured data at the 99% confidence level. Thus, the calibrated model can be used for predicting growth and yields of upland rice under N limited conditions in other growing areas with adequate empirical data on soil chemical and physical properties.

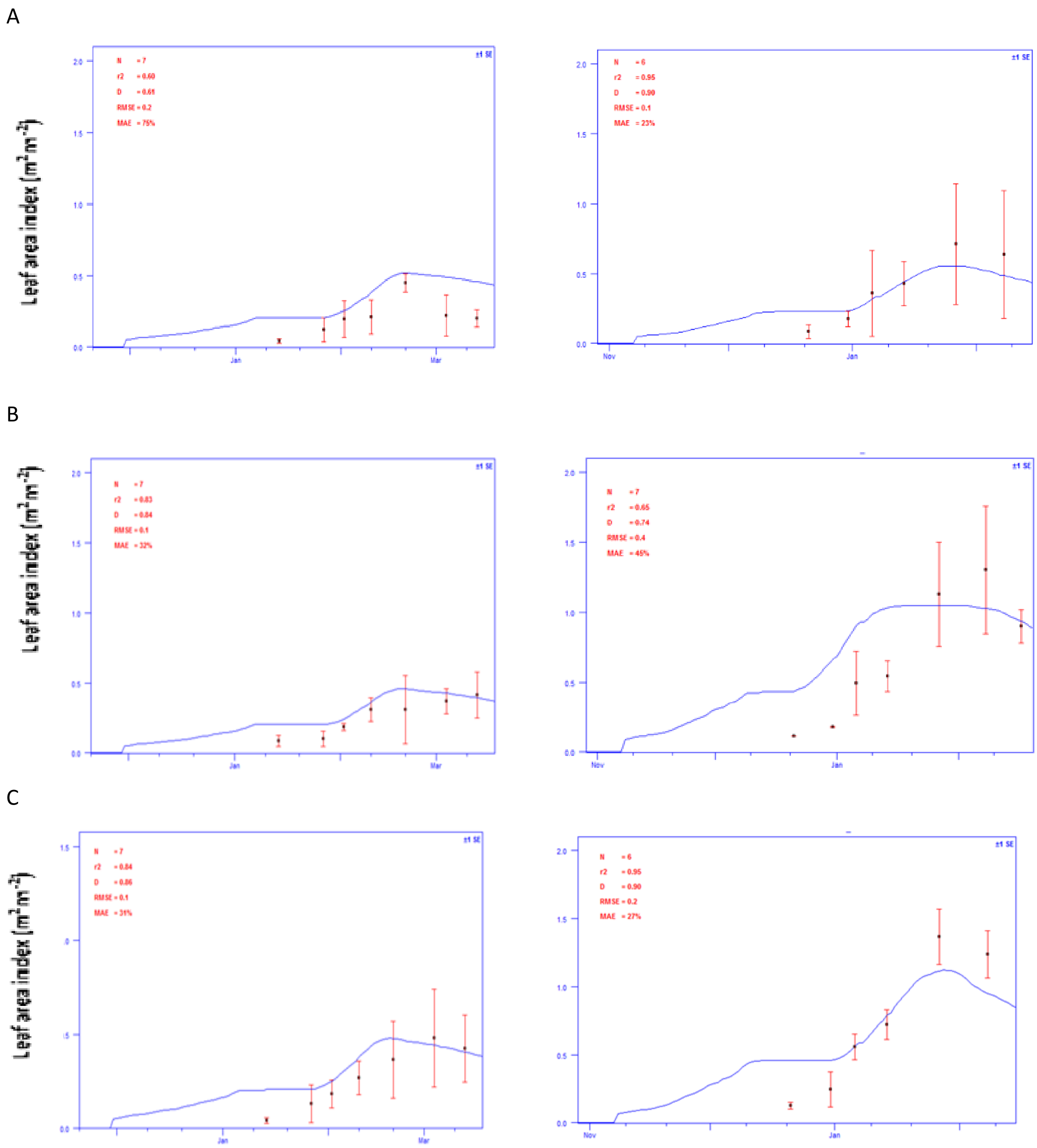


Figure 5.6 Model simulations (lines) and measured values (points) for leaf area index for Nerica 10 for nitrogen limited rates: (A) 0, (B) 40, and (C) 80 kg N ha^{-1}, well-watered conditions in 2014/2015 (left) and 2015/2016 (right) at Hatfield, South Africa. Vertical bars represent standard deviation for three replicates of measurements.

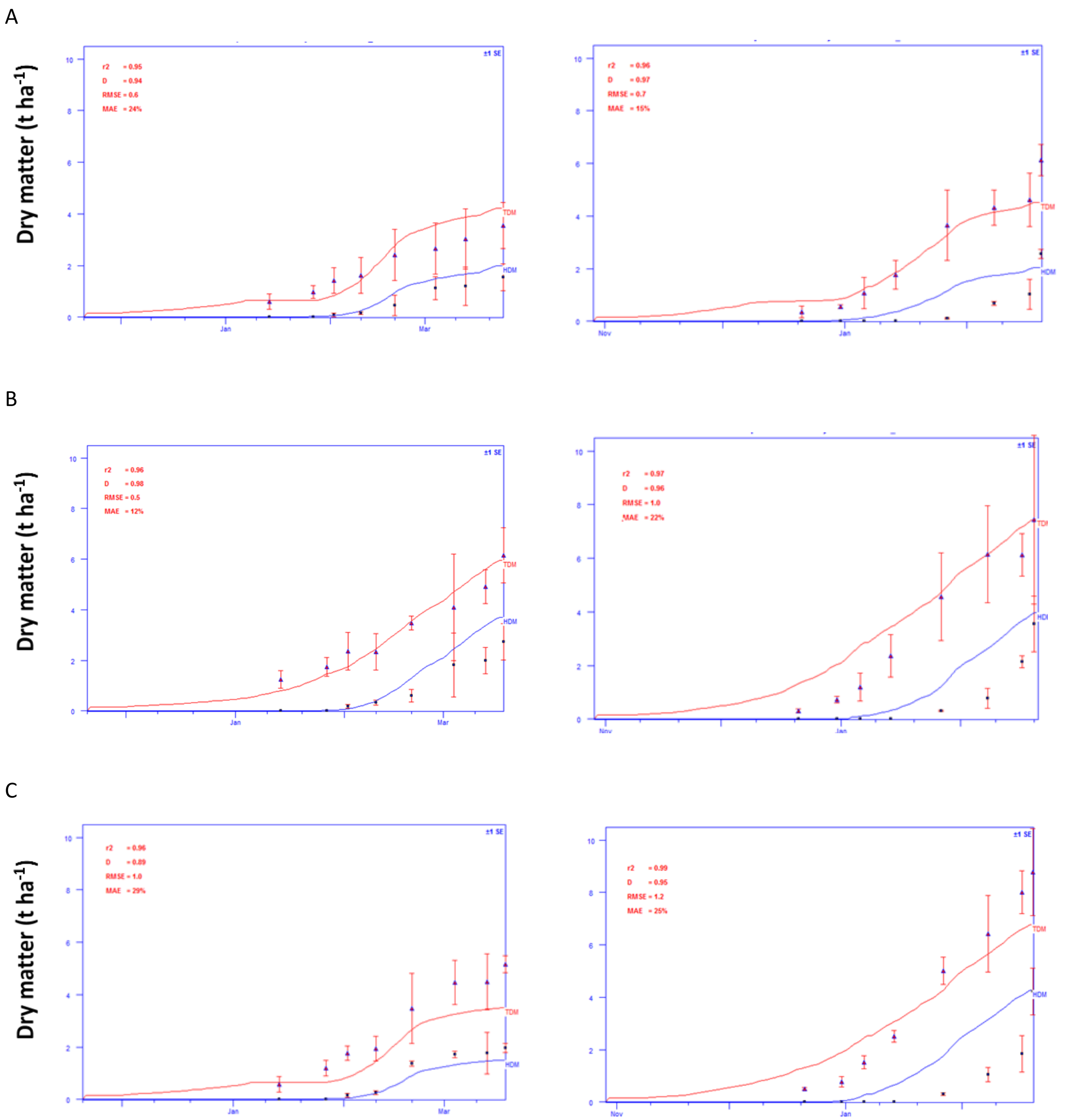


Figure 5.7 Model simulations (lines) and measured values (points) for total top dry matter yields (HDM and TDM) for Nerica 10 for nitrogen limited rates: (A) 0, (B) 40, and (C) 80 kg N ha^{-1}, well-watered conditions in 2014/2015 (left) and 2015/2016 (right) at Hatfield, South Africa. Vertical bars represent standard deviation for three replicates of measurements.

5.2.5 Sensitivity of yield simulations to rooting depth during panicle initiation stress

Plants only during stress at PI stage grew deeper roots below 0.4 m depth, beyond maximum depth of roots under well-watered conditions. This was confirmed by a considerable decline in θ in the 0.4–0.6 m layer during stress at this stage (data not presented). It was important to find out if this modified root adaptation was useful in explaining model simulations of growth parameters under stress at PI, but using the same set of crop parameters. Increasing root depth in model simulation improved precision of measurement of DM yield (RMSE and MAE reduced and R^2 values increased) (Table 5.3). However, it was noted from growth curve that grain yield tended to be overestimated in both seasons. This observation may be useful when predicting rice yield under rainfed conditions with a distribution biased against mid-season or late vegetative growth of the crop.

Table 5.3 Model response for dry matter yield (top and head) to increase in rooting depth under water stress at panicle initiation.

Statistical indicators ǂ	0.4 m		0.6 m	
	2013/2014	2014/2015	2013/2014	2014/2015
R^2	0.90	0.91	0.92	0.99
D	0.93	0.94	0.96	0.94
RMSE (t ha^{-1})	1.9	1.9	1.6	2.0
MAE%	28	27	23	24

ǂ Statistics for n = 12 and 10 observations (dates of measurements) during crop growth in each season

5.3 Discussions

5.3.1 Biological significance of crop parameters

Radiation use efficiency values of the varieties were similar despite being different genetically and phenotypically. During PI, TDM was quite similar between the varieties, but cumulative intercepted R_s was obviously more for the medium-duration than for the short-duration variety. Furthermore, results showed that there were some periods during which biomass production of Nerica 4 levelled off. As for Nerica 10, increases in TDM were steady for most of the growth period. This observation should not be regarded as variation in samples because the standard deviation values were very small. Looking at the absorption of R_s during late growth phase (post-anthesis), it was higher for Nerica 10, which maintained a greener canopy for longer than Nerica 4. The stay-green growth habit of Nerica 10 explained why RUE was slightly higher than that for the medium-duration variety. The findings of the present study agree with those of Campbell et al. (2001) which showed that high leaf senescence during post-anthesis decreased RUE.

Generally, there is scarce information in literature on growth parameters for upland rice genotypes. Crop parameters of upland rice varieties were not documented prior to this study. New Rice for Africa (NERICA®) are widely grown in sub-Saharan Africa (Jones et al. 1997). Varieties of Nerica are traditionally grown in farming systems in the tropics. Elsewhere, in a field experiment conducted in Japan at a study site located 8°6'N, on the margin of humid sub-tropical and temperate environments, better yield performance of Nerica than indigenous Japonica varieties under rainfed conditions was reported (Matsunami et al. 2009). Based on that study, it is not therefore surprising to measure high values of especially RUE and root biomass, given that the present study was also done in the subtropics.

The slight differences in RUE values between the present study and values reported in literature is because of differences in crop morphology, latitudinal differences and growing conditions between studies. Nerica varieties have erect or upright deep-green leaves (visual observations) which is a unique leaf morphological feature, rarely observed among one of the donor parents (*Japonica* subspecies) of Nerica (Jones et al. 1996). This kind of morphology is associated with better radiation penetration into the lower canopy (Boschetti et al. 2006) and is not limited to early development stages. Consequently, a high efficiency of utilising solar radiation for dry matter production is not surprising for Nerica varieties, as mutual shading is minimal. In other latitudinal zones, Bouman et al. (2006) reported 1.70–1.72 g MJ^{-1} absorbed PAR in aerobic rice in northern China (40°02'N, 116°10'E). By calculation, these values are approximately 0.85–0.86 g MJ^{-1} of intercepted R_s, which is low compared to values in the present study. Clerget et al. (2013) reported slightly higher RUE values of 0.95–1.1 g MJ^{-1} of intercepted R_s in aerobic rice at maturity in Los Baños, Philippines (14°11'N, 121°15'E). Values of RUE in the present study are close to high values in lowland flooded rice (Bouman et al. 2006) because stresses were omitted in this study. Besides growing conditions, the difference in RUE values between the present study and those for aerobic or dry land varieties for other studies could also be attributed to differences in varieties growth duration in part. For instance, Clerget et al. (2013) reported 654 and 694 °Cd to panicle initiation in two cropping seasons which is comparatively shorter than 930 and 1119 °Cd to the same development stage for Nerica 10 and Nerica 4, respectively in the present study. In contrast, Bouman et al. (2006) used Han Dao (local name for dry land rice), varieties with similar growth period, (105–115 days and 130–140 days) in a similar climate zone to the present study, and they obtained 1.62 and 1.71 g MJ^{-1} of intercepted PAR. Campbell et al. (2001) reported very high RUE values of up to 5.66 µg J^{-1} (5.66 g MJ^{-1}) absorbed PAR for LAI between 2 and 4 in irrigated lowland rice which though rarely reported, suggests that RUE is very variable in rice.

New rice for Africa varieties are targeted for low input systems (Jones et al. 1997) in the tropics, but high RUE values suggest upland Nerica varieties have a high yield potential under supplementary irrigation (which has not been demonstrated before). In the tropics, existing elite rice varieties under irrigation assimilate only about 2.2 g above ground dry mass per MJ^{-1} of intercepted PAR (Dingkuhn et al. 2015), which is approximately 1.1 g per MJ of R_s intercepted, assuming a ratio (1: 0.5) of PAR waveband/Rs (Lange et al.2012). In agreement with the review by

Dingkuhn et al. (2015), the measured RUE values for Nerica in the subtropics is about 41% greater than the generic RUE values in literature. The difference in RUE values between the tropics and subtropics is because radiation is often a limiting factor in the tropics due to generally more days of cloudy cover

Specific leaf area is very variable over the crop cycle and depending on the stage of sampling, different values can be measured. In the present study, mean values of SLA were calculated for the first growth phase, from seedling to just before reproduction, during which leaf senescence is almost negligible. Considerable leaf senescence occurred some days before flowering even under non-limited conditions (Yin et al. 2010) and SLA estimation in the late stages with destructive sampling is thus subject to this error. Studies such as those by Asch et al. (1999) and Dingkuhn et al. (1998), which reported high SLA values ranging 20–36 m^2 kg^{-1} in other rice ecotypes were measured during the first 30 days after emergence. The early growth in some rice varieties is characterised by high seedling vigour and tillering ability of a variety (Rebolledo et al. 2013), which influences SLA. In fact, during plant growth sampling about 30 DAE, values of SLA for Nerica 4 were close to the range reported by Asch et al. (1999).

Dingkuhn et al. (1999) reported extinction coefficients ranging 0.5–0.6 in African rice in Côte d'Ivoire, in the tropics. These values were considered by the authors as not typical of unstressed rice, meaning higher values possible. In case of the present study, the K_s values (0.5–0.7) are comparatively high (but since no specification as K_{PAR} or K_s was made and could be made without published information), because there were no stress conditions.

5.3.2 Model performance

For upland rice, crop models have never been parameterised, calibrated and validated. This pioneer study successfully applied the SWB-Sci model for upland rice and generated information that can be used for other rice crop models. The varieties used in this study are widely grown in

Sub-Saharan Africa and success in rice production in uplands is partly ascribed to this germplasm (ARC 2007). Therefore, results of this study can be used in upland rice growing areas. The calibrated model predicted growth and yield of upland rice under well-watered and stress conditions satisfactorily except grain yield under late vegetative stress (Table 5.2). The model will be useful in predicting water uptake, use and efficiency of rice in uplands.

Apparent decline in LAI post-flowering for Nerica 10 was absent as the variety exhibited a stay-green attribute even around maturity. Results on SLA and leaf senescence have implications on the choice of crop models that use a single value for entire season during parameterization. The SWB-Sci model like other models such as APSIM-ORYZA (Zhang et al. 2004), CropSyst (Stöckle et al. 2003) and WARM (Confalonieri et al. 2005) uses a single mean SLA value for an entire crop cycle. Validation results showed that this suits well within a season but not between growing seasons for Nerica 10. Leaf expansive growth of this variety varied between seasons. Poor simulation of LAI-time curve has been previously reported with other models even under potential production conditions. Zhang et al. (2004) reported that under estimation of LAI in APSIM-ORYZA was associated with inaccuracy in prediction of SLA during late growth period.

5.4 Conclusions

Most crop model parameters like RUE were similar between varieties of different durations. The study determined RUE of upland rice varieties is high and this suggests untapped genetic yield potential of these varieties. The germplasm is developed for rainfed conditions. The parameterised SWB-Sci model for well-watered, nutrient non-limiting simulated well growth, water uptake and DM yield under stress during most development stages and under N-limiting conditions. The lack of good prediction of LAI-time curve under PI stress was explained by alteration in crop phenology and consequently partitioning of DM between leaves and stems. However, under open field conditions, WS duration during growth may not last for several days as was the case in our study.

With additional parameterisation, the model will be very useful in explaining growth and yield of upland rice under rainfed conditions.

CHAPTER 6

QUANTIFYING YIELD GAPS OF EQUATORIAL UPLAND RICE CROPPING SYSTEMS AND STRATEGIES FOR IMPROVEMENT

This Chapter is under preparation as article style for submission to an accredited journal. The authors are: I.N. Alou[ab], J.M. Steyn[a], J.G. Annandale[a] and M. van der Laan[a].

[a] Department of Plant and Soil Sciences, University of Pretoria, Private Bag X20 Hatfield, 0028 South Africa

[b] National Agricultural Research Organisation (NARO), Bulindi ZARDI, P.O. Box 101 Hoima, Uganda

Abstract

In equatorial climatic areas, rainfall follows a bimodal (BRF) and a unimodal (URF) pattern, and two upland rice (*Oryza sativa* L.) crops are possible annually. Current actual grain yields (Y_a) of rice in uplands in sub-Saharan Africa (SSA) are below 1.5 t ha^{-1} on average. Most famers blame low rice yields on seasonal water stress (WS). Available literature shows that attainable yield (water- and nutrient- [nitrogen specifically] limited yield, Y_t) vary widely (0.34–3.86 t ha^{-1}) in some countries. It is unclear what the relative contribution of water limitations and other limiting factors are to below potential yields of rice (Y_P) and what measures can resource limited farmers take to close these gaps. The main objective of this study was to estimate rice yields, Y_P and suggest adaptive cropping strategies for improving the system productivity. The parameterised, corroborated SWB-Sci model was used to predict growth, phenology and yields of upland NERICA® rice varieties widely grown in Africa. Over the simulation period (2008–2012), measured Y_t was approximately 34% and 17% of the simulated Y_P of the short- (Nerica 10) and the medium-duration variety (Nerica 4), respectively. The general assumption that yield gaps of rainfed rice are principally due to WS are flawed for URF zones and only true for the Eastern Semiarid zone for the BRF region. The ratio of water-limited (Y_w) to Y_P for Nerica 4 was different between the first (0.49) and second growing season (0.61) in a URF region as well, indicating that there is yield merit of growing rice in the second over the first season. Three broad rice yielding zones for rainfed crop, low, medium and high were identified. Findings suggest: (i) the overall contribution of WS to yield gap is likely less than 50%, but this gap varies widely between zones, (ii) yield gaps differ between growing seasons, but surprisingly for Nerica 4, gaps are very similar at sites near the equator and (iii) it is feasible to achieve yield improvements through fallowing in certain areas. The implications for different rice cropping systems on rice production and opportunities to improve yields through adaptive strategies by zone are discussed.

Key words: Adaptive management, cropping systems, yield gaps, reference yields, SWB-Sci model

6.0 Introduction

Water stress (WS) or drought is one of the primary constraints to crop production and food security worldwide (Farooq et al. 2009). Economic yield loss from drought can range from 30 to 40% in less severe conditions, to 81% in extreme cases, depending on rainfall pattern, atmospheric demand for water and water storage capacity of soils (Farooq et al. 2009). Generally, crop yields are adversely affected when soil water content declines to less than 20% plant available water (PAW) during reproductive growth (Allen et al. 1998). In rice, depending on growth stage and severity of WS, grain yield can be reduced by 60–92% under severe stress and by 30–55% under moderate stress (Basnayake et al. 2006; Lafitte et al. 2007). While in a study by Boojung and Fukai (1996), WS had no apparent effect on grain yield but on growth, Oikeh et al. (2009) reported considerable yield loss in upland rice, even when dry spells occurred during vegetative growth. Vulnerability of a crop to WS is highly site-specific due to interactions in the soil-plant-atmosphere continuum. A single factor such as soil depth or texture or rainfall pattern is often insufficient to fully explain the impact of WS.

Rice (*Oryza sativa* L.) is an important food crop grown worldwide, with about 41% of global production being rainfed (ARC 2007; Global Rice Partnership 2013). In many parts of Africa, rice is mostly an upland rainfed crop, covering at least 45% of the rice area (Lodin et al. 2005; Global Rice Science Partnership 2013). Per capita consumption of rice was estimated to increase at 5.5% annually, making it the highest rate among crops over a 10-year period (USDA 2013), and is estimated to increase by 130% by 2035. From 2010 data, on average 40% of rice consumed in Africa in recent years was imported (Saito et al. 2015). Fulfilling the growing rice market demand is thus a major challenge and opportunity for local producers who are predominantly smallholder farmers.

Rice growing areas in equatorial Africa have a huge potential for diverse cropping systems and upland ecosystems could represent the future rice basket. Equatorial tropical climatic regions are endowed with favourable rainfall patterns (two rainy seasons per year) with a distinct dry season in-between (Philips and McIntyre 2000), and crop growth is rarely limited by extreme temperature. Soil drying during dry seasons results in low PAW at sowing and may partly explain low rice yields in rainfed conditions in the tropics, compared to subtropical zones (Kato and Katsura 2014). Rice is directly dry-seeded, in diverse upland soils often with minimal fertiliser input (ARC 2007; Kijima et al. 2008; Kaizzi et al. 2014), and sowing occurs at onset of a rainy season. The majority of farmers lack access to weather information, making it difficult to plan sowing dates. In low input rainfed rice, nutrient limitations are interwoven with WS, but George et al. (2002) revealed that production potentials among locations in Asia with similar management systems were largely driven by rainfall pattern, onset and duration of the season. During favourable seasons, Onaga et al. (2013) reported that supplementary irrigation and adequate fertilisation increased rice yields by 55% and 40% respectively under rainfed conditions, compared to unfertilised controls. Frequency of wet events affects crop water balances (Sadras and Rodriguez 2010) and seasonal rainfall amount alone is insufficient for yield assessment. Furthermore, high evaporation losses under short dry spells can reduce seasonal water use efficiency. In addition to quantifying yield gaps, it is important to assess occurrence of WS during the growing season to indicate or suggest how to align rice cropping systems to rainfall patterns.

Most tropical areas of Africa are characterised by two wet seasons and this is also typical of Uganda (Philips and McIntyre 2000). Two annual crops are feasible per year, one during the first rainy season (March–May), and the second during the second rains (August–November) (Mubiru et al. 2012). Rainfall regime is also a result of the modulation effect of topography and surface water bodies in the Great Lakes Region; which results in a unimodal rainfall pattern (URF) further north (about 2^{o}N) in Uganda. The same effects result in a bimodal pattern (BRF) in Uganda's south and transition zones in the northeast (Mubiru et al. 2012; Nsubuga et al. 2014). Pentads (five-day periods) for rainfall onset range from 16 to 23 in URF and from 6 to 20 in BRF (Mubiru et al. 2012). Based on the number of pentads, pre-season rainfall is likely more in the URF than in the latter regime. It is noteworthy that classification of rainfall patterns does not allude to the number of growing seasons in a calendar year, but to the number of rainfall peaks in a year. Depending on sowing date during the second season, the growing season may extend into another calendar year. According to Mubiru et al. (2012), wet pentads (five-day rainfall > 10 mm) in places within URF are more (67–68) than in BRF areas (27–32) before withdrawal of rainfall, indicating longer rainy periods for URF areas. Despite two growing seasons, rice is mostly grown during the long rainy season (August–November or June–October), depending on the latitudinal location of an area. The first season in general is short and an even good seasonal distribution is critical for achievement of good rice yields. Thus, farmers regard it risky to grow rice during the first season (NEMA 2004), which may not be a challenge for farmers in the URF agroecological zones (AEZ). It means that double rice crops (DCS) per annum are rare in certain locations. However, the opportunity for farmers to improve system productivity is through conservation agriculture. For example, fallowing to conserve water from the first season and then plant rice in the second season on a wet profile.

Uganda, like other SSA countries, requires rice imports estimated at a cost of US $ 12 million per year (more than 25% of annual supply) to satisfy local demand (FAO 2004). However, it is unclear if preference to seasons (rice only grown in a good season) is specific to some AEZs (biophysical limitation) or is influenced by other market related factors. For example, farmers tend to look for better prices of surplus rice (farmers are typically semi-subsistent producers) towards the festive Christmas season, which coincides with the end of the second growing season. Another argument for season preference is that farmers lack adequate storage facilities for grains, especially from the first season. To sustain rice production and improve yields, it is important to understand if seasonal yields are largely affected by WS in the two growing seasons in time and space.

The impact of WS on rice yields (assuming nutrients are non-limiting) and contribution to yield gaps can be comprehensively investigated using crop simulation models. Crop simulation models integrate the impact of soil, crop or genetic traits and weather variables on crop yield (Passioura and Agnus 2010). Several crop simulation models such as CroSyst, APSIM-ORYZA and DSSAT have been applied in rice and other cropping systems (Bouman et al. 2001; Timsina and Humphreys 2003). Investigations of this kind are widely reported in lowland rice (Amarasingha et al. 2015; Inthavong et al. 2014), but are scarce for rice grown on upland soils.

Estimates of actual rice yields (yield limited by abiotic and biotic factors) (Y_a) ranging from 1.0 to 1.5 t ha^{-1} (ARC 2005) are anecdotal and not related to site-specific conditions. Thus, it is often difficult to accurately show realistic yield gaps, notably Y_a/Y_W ratio, which indicates the gap under rainfed conditions, for small-scale farmers where Y_a are not defined by site and season. Models can be used to estimate Y_P and $Y_{W,}$ provided daily-time step weather, environmental and crop management data exist (Van Wart et al. 2013), and subsequently models can be used to estimate the relative contribution of different biophysical factors to yield. Attainable yields (Y_t) can be determined from rainfed, without fertiliser (especially nitrogen) treatments, especially from experiments managed by researchers. Reference yields should be carefully defined, for instance a low yield with fertilisers under rainfed conditions may result a low $Y_{w,}$ compared to Y_t. Estimates of yield gaps or relative yield (Y_t/Y_P) and (Y_t/Y_w) affords understanding of the contribution of nutrient and water stresses, or other factors to Y_P.

This study chose the SWB-Sci model to investigate rice yield gaps and as a reasoning tool to support decisions on improving the cropping system in equatorial areas, because the model is generic, mechanistic and user-friendly (Annandale et al. 2011). The model has been successfully applied under rainfed conditions in several studies to accurately predict water use and in some cases dry matter (DM) production and other variables for vegetables, cereals, pastures and trees (Annandale et al. 1999; Annandale and Jovanovic 2000; Tesfamariam et al. 2015; Ghezehei et al. 2015). Since simulation studies were done for rainfed conditions, choice of the model was thus appropriate. Performance of models to predict growth and processes under stress conditions is, however, a common challenge (Boojung 2000; Mall and Agarwal 2002), because assimilate partitioning between plant organs, which occurs under stress, is often inaccurately simulated. Reasons for poor performance of crop models under stress were not specifically stated in most studies. Timsina and Humphreys (2003) stated reasons for poor performance as: inherent model assumptions, lack of adequate empirical variety-specific data for parameterising and testing a model. For past work in lowland rice, the need to locally calibrate a crop simulation model was already emphasised as one way to improve predictions.

This study was guided by a leading assumption in literature that water and nutrient stresses (especially nitrogen) are the primary limitations of crop yields in African smallholder agriculture (Van Wart et al. 2013; Tittonell et al. 2013). The relative contribution of these two primary limiting factors to yields is still arguable in several cropping systems. Hypotheses tested are guided by literature on crop production characteristics in the tropics (Philips and McIntyre 2000; Mubiru et al. 2012). Considering that a wet period is longer in the URF than BRF before cessation of rainfall and since URF has just one distinct dry season (Mubiru et al. 2012), it is expected that rice varieties of medium duration will better fit or suit the URF compared to the BRF. Furthermore, as pre-season rainfall is more in the URF than in BRF, WS may not be a serious rice yield limitation in URF. From ecological context, it can be speculated that farmers in locations with a URF (~ 3^{o} N) have no yield advantage in growing a medium-duration rice variety in the second over the first rainy season, while those in locations with a BRF (~ 0.10^{o} S–2.06^{o} N), will benefit.

The objective of this study was (i) to simulate yields and quantify yield gaps of upland rice in equatorial regions and (ii) to make recommendations on agronomic strategies that can be implemented to potentially improve cropping system productivity. The hypotheses tested were: (i) yield gaps due to WS are larger in the first than second growing seasons in the BRF region and (ii) within a season, the yield gaps for the medium- and short- duration varieties are similar in URF zone.

6.1 Materials and methods

This section comprises of experimental and simulation studies.

6.1.1 Study site and rationale for choice of plant material

Field experiments were conducted using two upland rice varieties (Nerica 4 and Nerica 10) at the University of Pretoria's Hatfield Experimental farm (25°45' S, 28°16' E; 1370 m asl). Variety Nerica 4 was grown during the summers of 2013/2014 and 2014/2015 in a rain-out shelter and variety Nerica 10 in an open field during the summers of 2014/2015 and 2015/2016.

Soil in the shelter was a sandy clay with a field capacity (FC) of 283 mm m^{-1} and permanent wilting point of 163 mm m^{-1}, while the open field site had a sandy clay loam with FC of roughly 230 mm m^{-1} and PWP of 120 mm m^{-1}. Soils at the farm are locally classified as a deep Hutton form (MacVicar et al. 1977), equivalent to loamy, kaolinitic, mesic, Typic Eutrustox with a coarse-textured topsoil (FAO soil classification 1970). Experimental details were described in detail in Chapter three.

Rice progenies are widely adopted in rice systems in Africa and expected to expand in rice cultivation areas (Africa Rice Centre 2007). Nerica varieties are of the most popular upland rice varieties among farmers in Uganda (Lamo et al. 2010).

6.1.2 Justification for treatments and agronomic practices

The choice of treatments for experiments described in Chapter 3 was to provide agronomic data under varied water and N conditions for establishing crop phenology and growth parameters and for model testing purposes. For the rain-out shelter trial, the timing of WS treatments mimicked incidences of early, mid and late season stress. Rain events were thus excluded during stress periods, which ensured that WS was achieved at specific phenological stages. This would have been difficult if sowing dates were staggered (Boojung and Fukai 1996). The N limiting, well-irrigated trial was conducted to simulate WS and N deficiency interactions on canopy growth, phenology, DM production and crop water use.

6.1.3 Why the SWB-Sci model?

The SWB-Sci model used in this study has been published (Annandale et al. 2011) and was described in the literature review (Chapter Two) of this thesis. The SWB-Sci model permits estimation of DM yield under both potential (non-limiting) and WS conditions, because it uses two approaches to simulate DM production, the Monteith (1977) radiation-limited growth model and the Tanner and Sinclair (1983) gas exchange theory for dry matter accumulation. Biomass production is either radiation or water limited, and the model takes the lower of the two. Application of the model in past studies to other crops and plant species was successful under rainfed conditions (Ghezehei et al. 2015; Tesfamariam et al. 2015) and under well-irrigated conditions (Annandale et al. 2000). It is noteworthy that SWB-Sci has since its development been widely tested under African conditions.

6.1.4 Study sites for model simulations

6.1.4.1 Parameter computation and estimation

Data from well-watered, adequately fertilised treatments and independent data from stress treatments were used to validate and parameterise the model, as described in Chapter 3. Measurement of soil input parameters for calibration were described in Chapters 3 and 4 of this thesis. Hatfield Experimental Farm soil parameters were measured before, during and at the end of the growing seasons. Profile soil water content at 0.2 m intervals to 1 m depth was monitored at least once weekly using a neutron water meter probe (Model 503DR CPN Hydroprobe, Campbell Pacific Nuclear, California, USA). Soil water deficit of the root zone was then calculated to determine the planned irrigation amount. For the various sites in Uganda, soil water holding characteristics were calculated from the sand, silt and clay fractions of each soil layer, using a soil water textural-based calculator in the SWB-Sci model (Annandale et al. 2011).

Distribution of the different sites in Uganda is presented in Figure 6.1. Sites represent the diverse agroecological zones (AEZ), which relate to agroecological conditions in Uganda, including rice growing areas and production characteristics (Wortmann and Eledu 1999; Kaizzi unpubl. 2016). The zones are: Eastern Semi-Arid (ESAR), Eastern Savannah Mid-altitude (ESM), Mid-Western Zone (MWZ) also referred to as Lake Albert Crescent (LAC), Lake Victoria Basin (LVB), Montane or Highland Farming System (HFS), Northern Moist Farming systems (NMF), South-Western Semi-arid farmlands (SWS) and West Nile Zone (WNZ). The sites are numbered alphabetically as in the location map and belong to the following AEZs: NMF: sites 1, 4, 11 and 12; SWS: sites 2, 10, 15 and 20; LVB: sites 3, 9, 17, 18 and 23; ESM: sites 7, 8 and 14; LAC: sites 5, 13 and 16; and ESAR: sites 19, 21 and 22.

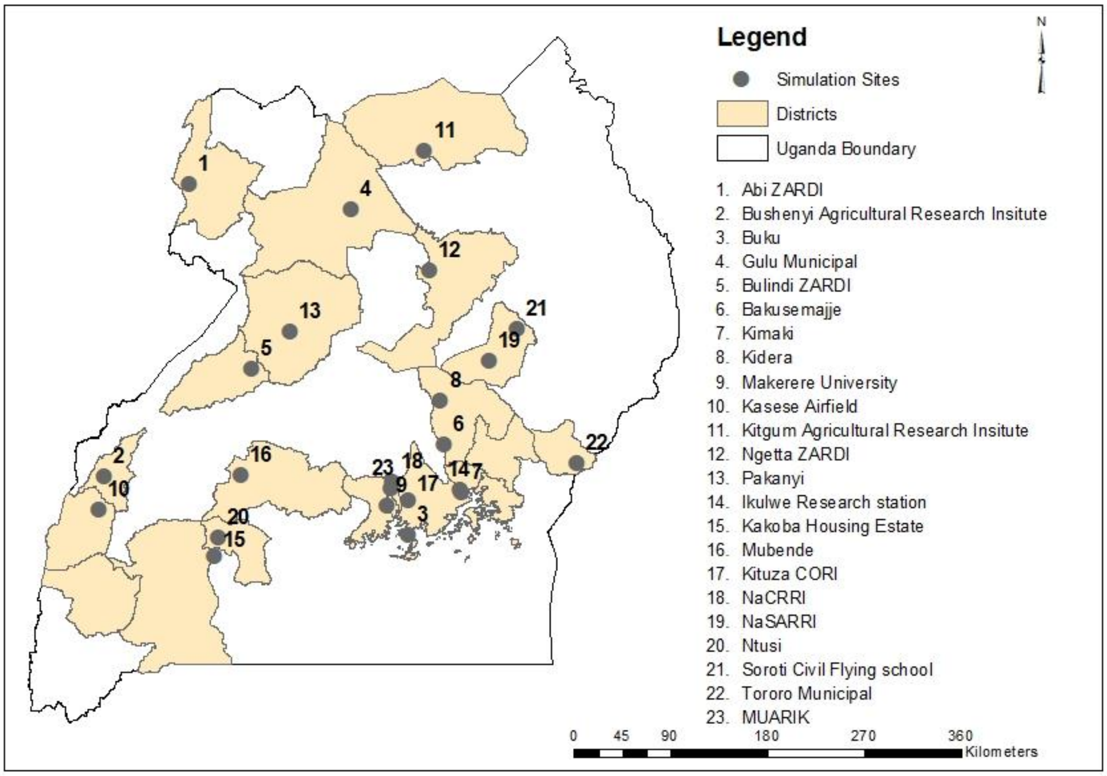


Figure 6.1 Map of Uganda showing distribution of sites used in the yield gap study.

Soils are of different inherent productivity potentials (FAO Soil Classification 2004) and this was reflected in differences in Y_a and Y_t from published literature. Recent studies done at most of the sites in Uganda by Kaizzi et al. (2012) report that soils are deep and effective root depth is always greater than 1.0 m, implying there is no restriction to root growth of crops. Upper soil layers in simulation sites varied from coarse-textured (70% sand and 14% clay) to fine-textured (46% clay and 30% sand), resulting in a range of different water retention characteristics between sites. Data on soil textural composition for the sites considered was available for mostly the top 0.4 m depth, and in few cases, for a 1.0 m soil profile (Alou et al. 2012; Onaga et al. 2012; Kaizzi et al. 2014; NARO institutions, unpubl. data). The majority of soils in Uganda are classified as ferralsols, highly weathered soils, characterised by the absence of distinct horizons (Isabirye et al. 2004). This feature means that changes in soil textures in the profile are gradual and hence water holding characteristics do not drastically change with depth. The study thus assumed soil water characteristics for depths below 0.4 m to be the same as values in upper soil layers, and this was not a concern because rice roots are mostly found within the top 0.4 m of the soil profile (Okami and Kato 2010). This was also observed for Nerica varieties in our trials, following root sampling in 2014/2015. For all sites, soil water was simulated to a depth of 0.6 m, representing maximum root depth.

The names of weather stations at the simulation sites are presented in Tables 6.1, 6.2 and 6.3. The numbers in brackets are the same as in the location map (Fig. 6.1). It is noteworthy that the weather stations used are located in the different Districts of Uganda. The coordinates presented are for the stations and not the district.

Table 6.1 Locations and weather stations, daily minimum and maximum air temperatures, mean annual rainfall, typical soils and range of sowing dates in the ESAR and ESM used in the yield gap study (Kaizzi et al. 2014; Nsubuga et al. 2014).

Station name	Location	Elevation (m a.s.l.)	Soil group /texture	Min T (°C)	Max T (°C)	Rainfall (mm yr^{-1})†	Season sowing dates (range)
NaSARRI (19)	1.53° N, 33.43° E	1140	Acric ferralsols (SCL)	16.0–23.6	23.8–37.0	839	8 March–1 April, 23 July–25 Aug.
Soroti Flying Academy (21)	1.53 ° N, 33.43° E	1140	Lixic ferralsols (SL)	12.0–23.5	18.2–36.6	909	27 Feb–28 March, 25 June–28 July.
Tororo Municipal offices (22)	0.68° N, 34.16° E	1170	Acric ferralsols (SL)	11.5–20.9	22.4–36.3	1219	01 March–4 April, 1 Aug.–1 Sept.
Iganga Municipal (6)	0.83° N, 33.05° E	1128	Petric plinthsol (SCL)	12.0–22.2	17.6–38.2	1177	23 March–11 April, 2–30 Aug.
Kimaki Airfield (7)	0.43° N, 33.20° E	1175	Lixic ferralsols (CL)	12.0–22.2	19.6–38.2	823	22 Feb–5 April, 20 July–28 Aug.
Kiige, Kidera (8)	1.20° N, 33.02° E	1103	Lixic ferralsols (CL)	7.0 – 19.6	21.6–39.7	924†	5–30 March, 13 Aug–1 Sept.
Ikulwe Station (14)	0.45° N, 33.18° E	1173	Lixic ferralsol (CL)	15.5–20.3	26.0–35.3	2774†	5–30 March, 13 Aug–1 Sept.

SC, sandy clay; SCL, sandy clay loam; SL, sandy loam; CL, clay loam; L, loam. †Mean for these sites computed for a four-year period for which weather data was available; ESAR, Eastern Semi-Arid; ESM, Eastern Savannah Medium-altitude.

Table 6.2 Locations and weather stations, daily minimum and maximum air temperatures, mean annual rainfall, typical soils and range of sowing dates of sites in the Mid-Western Zone or Lake Albert Crescent and Lake Victoria Basin used in the yield gap study (Kaizzi et al. 2014; Nsubuga et al. 2014).

Site /Station name (*)	Location	Elevation (m asl)	Soil group /texture	Min T (°C)	Max T (°C)	Rainfall (mm yr^{-1})[†]	Season sowing dates (range[‡])
Bulindi ZARDI (5)	1.46° N, 31.44° E	1157	Acric ferralsol (C)	6.0–23.0	14.0–39.5	1076	17 March–12 April, 9 Aug–23 Sept
Pakanyi/Masindi district headquarters (13)	1.77° N, 31.77° E	1140	Leptosol (SCL)	13.8–22.1	22.8–35.2	1288	16 March–8 April, 29 July–4 Sept
Mubende district headquarters (16)	0.58° N, 31.36° E	1000	Nitisol (L)	11.7–18.3	24.0–31.4	1179[†]	1–29 March, 16 Aug–10 Sept.
Buku / Entebbe airport road (3)	0.08° N, 32.75° E	1155	Petric Plinthsol (CL)	10.0–23.7	20.0–34.6	848	1 March–1 April, 6 Aug – 26 Sept.
Makerere University Hill (9)	0.32° N, 32.57° E	1240	Petric Plinthsol (CL)	13.2–20.6	20.2–33.5	977	22 Feb–1 April, 7 Aug– 9 Sept.
Kituza CORI (17)	0.36° N, 32.75° E	1207	Acric Ferralsol (SCL)	13.8–20.5	18.2–33.2	1368[‡]	7 Feb– 8 March, 18 July–25 Aug.
MUARIK (23)	0.46° N, 32.61° E	1200	Acric ferralsol (Kandiudalfic) SCL	14.0–22.0	19.8–38.0	1099[‡]	28 Feb– 5 April, 7– 28 Aug.
NaCRRI (18)	0.52° N, 32.61° E	1155	Acric ferralitic SCL	11.5–19.7	21.9–34.6	1090	12 March–19 April, 2 Aug–8 Sept.

[‡] mean for these sites computed for a four-year period for which data was available.

Table 6.3 Locations and weather stations, daily minimum and maximum air temperatures, mean annual rainfall, typical soils and range of sowing dates of sites in the Northern Moist Farmlands and South-Western Semi-arid zones used in the yield gap study (Kaizzi et al. 2014; Nsubuga et al. 2014).

Station name (*)	Location	Elevation (m asl)	Soil group /texture	Min T (°C)	Max T (°C)	Rainfall (mm yr^{-1})†	Season sowing dates (range‡)
Abi ZARDI (1)	3.00° N, 30.92° E	1261	Arenosol (SL/ SCL)	11.6–21.8	19.5–39.5	1323	8 March– 16 April, 24 July– 23 Sept.
Gulu District Headquarters (4)	2.79° N, 32.27° E	1070	Plinthosols (L)	10.0–17.8	22.5–37.3	1013	23 Feb–28 April, 22 July– 1 Sept.
Ngetta ZARDI (12)	2.28° N, 32.93° E	1079	Petric Plinthsol (SC)	9.5–21.5	24.0–37.0	1445‡	27 Feb–11 April, 11 June– 21 July.
Kitgum ARI (11)	3.28° N, 32.89° E	929	Leptosols (SL)	12.0–23.5	21.5–40.6	705	27Feb– 10 April, 15 June– 01 Nov.
Ntusi, District Headquarters (20)	0.06° N, 31.17° E	1234	Ferralsol (SCL)	13.0–19.2	17.8 - 33.2	362	28 Feb–28 March, 26 July–25 Aug.
Kakoba Housing Estate (15)	0.10° S, 31.13° E	1420	Ferralsol (SCL)	11.0–15.4	22.4–32.5	703	25 Feb–25 March, 15 Aug–22 Oct.
Bushenyi ARI (2)	0.56° N, 30.21° E	1610	Acrisol (SC)	10.0–18.3	17.7–30.0	1040	14 Feb–27 March, 13 Aug–30 Sept.
Kasese Airfield (10)	0.29° N, 30.17° E	958.9	Ferralsol (CL)	12.7–22. 3	22.1–36.4	1774	28 Feb–25 March, 5 Aug–30

Bushenyi ARI, Bushenyi Agricultural Research Institute; Kitgum ARI, Kitgum Agricultural Research Institute

6.1.4.2 Drainage factors

Typical water potential (kPa) values for FC and PWP, as well as drainage factors (dimensionless) for the different soil types were adopted (FAO 2004) and set in the soil unit of SWB-Sci. The water potential value for PWP was set at -1500 kPa and for FC according to soil texture class: -33 kPa for clay, - 20 kPa for clay loam, -15 kPa for sandy loam, and -10 kPa for sandy clay loam. Respective drainage factors considered for the various textural classes ranged as follows: 0.20–0.3 for fine textured soils and 0.5–0.8 for coarse textured soils. Coarse-textured soils were mostly sandy loams and thus 0.5 was the common drainage factor used.

6.1.4.3 Growth and secondary yield data

Plant growth analysis and derivation of crop parameters was described in Chapter 5. There were no plant growth analysis data for simulation sites in Uganda, but data on final grain yield (at approximately 14% moisture content) and in some cases, top dry matter production was available. Therefore, model validation for simulated parameters such as leaf area index (LAI), soil water content and fractional interception (FI) at Uganda sites could not be achieved. Data on plant height and phenology of varieties under rainfed conditions was rarely available, except for one site at Bulindi Zonal Agricultural Research and Development Institute (Bulindi ZARDI) for three seasons.

6.1.4.4 Weather data sources

For the Pretoria site, daily weather data was obtained from an automatic weather station at the University of Pretoria's Hatfield Experimental Farm. Weather data for the period 2008–2012 for simulation sites in Uganda was mostly sourced from research and or academic institutions and partly from district stock farms and airports. Although preferable, long-term weather data for at least 10 years (20 growing seasons) could not be afforded due to limited financial resources. Most experimental sites where past studies were conducted were located within 0.5 km of the weather stations, thus proximity to the fields ensures reliability of rainfall data. Data on solar radiation (R_s) for most sites in Uganda was lacking from records provided. Solar radiation was therefore estimated internally in the SWB-Sci model, based on the diurnal temperature range from the weather station data and latitude and altitude of the site (Allen et al. 1998; le Roux et al. 2016). Approximation of R_s for fields in simulation sites from SWB-Sci was assumed to be with minimal error, because the topography around weather stations and fields is generally homogenous. Daily temperatures missing in records for short periods (about three days) were estimated by the ordinary kriging method or interpolation (Borga and Vizzaccaro 1996).

6.1.5 Simulation study

6.1.5.1 Features of sites in Uganda

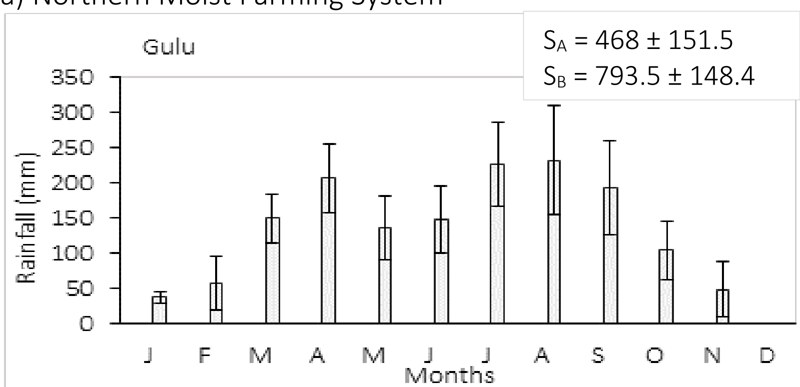
The distribution of simulation sites in Uganda is presented in Figure 6.1. Simulation sites differ in annual rainfall amounts and distribution (unimodal or bimodal), and soils (light to heavy types), and elevation (929–1420 m a.s.l), as reported previously. This study examined several types of literature sources, including socio-economic studies and project reports in Uganda. However, it was inappropriate to cite all publications or sources in this chapter because a combination of sources was used to obtain comprehensive information of one site. Most of the sites had records on reference yields, some information on crop management like sowing and harvest dates, and input use and soil characteristics mostly for the top 0–40 cm and 0–60 cm layers (Tables 6.1, 6.2, & 6.3). The main literature sources used were, Isabirye et al. (2004), Alou et al. (2012), Kaizzi et al. (2012), CABI International (2013), Okanya and Maass (2013), Otim et al. (2015) and Basamba et al. (2016). Although rice cultivation is nationwide, the major upland rice producing areas are in the Hoima and Masindi districts, in the LAC or MWZ (Lodin et al. 2005). Iganga, in the eastern region, is an upcoming upland rice growing area from a traditional lowland system (Kijima et al. 2008).

6.1.5.2 Latitudinal location, rainfall regime and growing seasons

The most distinguishing feature of these AEZs is rainfall regime. There are three broad zones, namely, unimodal rainfall in the northern region (~ 3° N), bimodal in the majority of locations close to the equator (~ 0. 10° S–2.06° N) and a transitional zone (1°–3° N) (Mubiru et al. 2012). Classical examples of each rainfall regime from long-term weather data (Manjaliwa et al. 2015) are shown in the appendix (Figure A6.9). These regimes notably URF could not all be well depicted using period (2008–2012) of available data (Figure 6.1). On annual basis, rainfall follows a URF at Abi Zonal Agricultural Research and Development Institute (Abi ZARDI) (3.00° N), Gulu (2.79° N), Kitgum (3.28° N) and Ngetta ZARDI (2.28° N). It is noteworthy that Abi ZARDI in Arua District falls under WNZ, but receives URF. Similarly, Kasese is at the fringes of the SWS and much of the district is classified as HFS. Thus, for grouping in regions in Table 6.1c, Abi ZARDI is put in the NMF and Kasese in the SWS. The LVB has quite different rainfall conditions, for instance Makerere Agricultural Research Institute Kabanyolo (MUARIK) and Namulonge Crop Resources Research Institute NaCRRI (NaCRRI) are distant from Lake Victoria, compared to Entebbe and exhibit long dry spells according to rainfall data. A bimodal distribution is characteristic of the rest of the southern hemisphere of Uganda, for instance at Mbarara and Ntusi. The far east of Uganda (Soroti and Serere) are transitional zones but tend towards BRF. The National Semi-Arid Resources Research Institute (NaSARRI) in the Serere District, being close to the Nile River and Lake Victoria, has quite different rainfall conditions.

Figure 6.2 shows monthly rainfall averaged for the five-year period. The dry season in URF zones usually lasts from December to March and according to Mubiru et al. (2012), may extend to early April, while in BRF zones, June–July and December–February are distinct dry months. These dry periods result in a pattern characterised by two peaks of rainfall for a BRF regime and one peak for a URF regime, as demonstrated in Figure 6.2. Rainfall peaks around May in the first season and October in the second in a BRF regime and between August and October for a URF regime. These two also differ in annual rainfall, as indicated by standard deviation bars. Total rainfall widely varied between 605 and 1728 mm yr^{-1} between simulation sites during the five-year period (data not shown). On average, over the 2008–2012 simulation period, the NMF with a URF pattern received more rainfall (1012–1445 mm yr^{-1}) than the BRF systems (839–1218 mm yr^{-1}) (Tables 6.1, 6.2 & 6.3). In Figure 6.2, amount of rainfall received in each season (S_A for the first season and S_B for the second) is based on sowing window. Seasonal rainfall varied more during the second season (indicated by s.d values) under a URF compared to a BRF. The length of the rainy period also varies between zones and within zones.

a) Northern Moist Farming System



b) Eastern Semi-Arid Zone

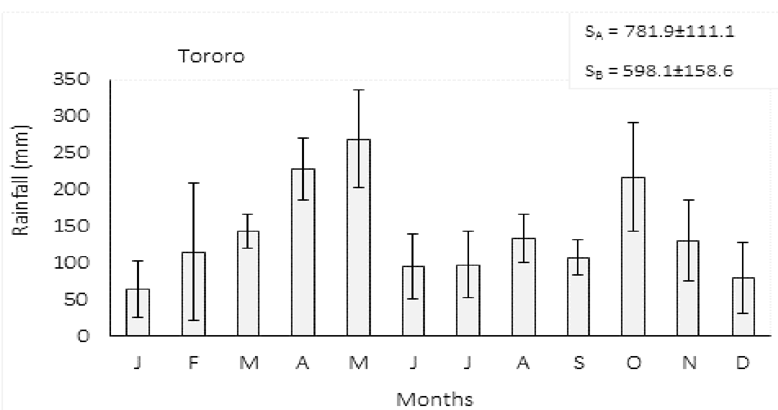


Figure 6.2 Monthly mean rainfall ± standard deviation from 2008 to 2012 at selected simulation sites in Uganda representing, unimodal (a) and bimodal annual rainfall regime (b). Site names inset graphs. Standard deviation bars (n = 5 years).

The onset and cessation of rainfall in terms of pentads (five-day periods, DOY 1 to DOY 5 is pentad one) during a year differentiates the two rainfall regimes (Mubiru et al. 2012). Consequently, the annual length of a growing period in a URF (300–340 days) is longer than in a BRF (200–250 days) regime. This means that for upland rice, which is commonly dry-seeded, sowing dates can differ by over a month between early- and late-planting among farmers. Risks of prolonged dry spells are high during the first growing season (March–May) for areas near the equator because of the short growing season (70–100 days) (Mubiru et al. 2012).

6.1.5.3 Data sources and yield characteristics

Sites which had complete information on soil properties, and rice crop management from various sources (Tables 6.4 and 6.5), include among others, Minyamoto et al. (2012), Onaga et al. (2012), Kaizzi et al. (2014), NARO institutions and unpublished reports (www.naro.go.ug). Maximum grain yields of each variety were available from replicate plots for some sites. Standard errors to indicate variability in measured data could not be computed for some sites. Grain yields for each variety varied highly between seasons within a site, even at the same nutrient application rates. The number of rice fields per site ranged between two and seven and also varied in soil type (Tables 6.4 and 6.5). Sites with insufficient data on rice yield and crop management, but with information on soils and daily weather records, were used in simulating Y_P and Y_W to increase the spatial coverage of the simulation study for testing hypotheses on water-limited yield gaps. This was deemed relevant to increase spatial scope of simulations to include most of the principal rice growing areas in Uganda (Kaizzi et al. 2016), despite lacking measured reference yields. This was required in line with our specific interest of obtaining yield distribution and descriptive in each AEZ for testing hypotheses. However, on-farm trials were not close to weather stations, so accurate rainfall amounts were not available for validation. These included experiments done by researchers at Ikulwe in the Mayuge District, Kwera and Kizaranfumbi in the Hoima District. Crop management and weather data for Ikulwe and Bulindi ZARDI covers some studies done in 2013 and 2014. Long-term rice yield data was lacking because until 2005, upland cultivation was uncommon, and rice was not a priority crop in the government of Uganda's Poverty Eradication Plan (MAAIF 2009). Some sites lacked rainfall data for one or two seasons for the five year data period and hence, the number of runs were not equal between sites. However, this limitation of unequal runs was considered in statistical analysis.

Table 6.4 Maximum rice yields, production characteristics and location of experimental sites in the Northern Moist Farmlands and the Eastern Savannah Medium Altitude agro-ecological zones in Uganda used in model validation.

Agro-ecological zone	Site-district	Location and elevation (m asl)	Soils† types (no. fields)	Grain yields of NERICA 4† (Mg ha^{-1})	Grain yields of NERICA 10† (Mg ha^{-1})	Reference or source
Northern Moist Farmlands	Abi- Arua	3.28° N; 30.93° E 1215	Ferralsols SCL (n =2), SL (n = 2)	1.10–4.51	1.01–4.70	Abi ZARDI comprehensive NERICA project report 2012 (unpubl.)
Eastern Savannah Medium Altitude	Bakusekamajja-Iganga	0.836° N, 33.05° E 1128	Petric Plinthsol SCL (n = 2)	3.28–4.72	2.61–3.74	Onaga et al. (2012)
	Ikulwe-Mayuge	0.45° N, 33.18° E 1173	Lixic Ferralsol CL (n =2) SCL (n =1)	1.5–4.48	0.6–3.00	Ikulwe satellite BugiZARDI reports (unpubl. data)

Soil texture class of each site are indicated by: C=Clay; C* (same textural class but different percentage of clay fractions thus different water holding capacities), CL= Clay Loam; SL= Sandy Loam; SCL= Sandy Clay Loam.

Table 6.5 Maximum rice yields, production characteristics and location of experimental sites in the Mid-Western Zone and the Lake Victoria Basin in Uganda used in model validation.

Agro-ecological zone	Site-district	Location and elevation (m asl)	Soils† types (no. fields)	Grain yields of NERICA 4† (Mg ha^{-1})	Grain yields of NERICA 10† (Mg ha^{-1})	Reference or source
Mid-Western Zone/ Lake Albert Crescent	Bulindi-Hoima	1.466° N, 31.44° E 1157	Acric Ferralsol C* (n = 8) CL (n =1)	3.28–4.72	2.61–3.74	Alou et al. (2012); Kaizzi et al. (2014)
	Kwera-Hoima‡	2.06° N, 32.83° E 1054	Arenosol SCL (n = 1)	(5.18)	(5.18)	Kaizzi et al. (2014)
	Kizaranfumbi-Hoima‡	1.81° N, 32.96° E 1084	Petric plinthsol CL (n = 2)	(4.97)	(4.97)	Kaizzi et al. (2014)
	Pakanyi- Masindi	1.77° N, 31.78° E 1147	Leptosol SCL (n = 2)	5. 13–6.07	4.06–4.97	Onaga et al. (2012)
Lake Victoria Crescent	Kalagala-Luweero	0.61° N; 32.61° E 1160	Acric ferralsol SCL (n = 2)	5.32–6.73	2.31–2.81	Onaga et al. (2012)
	Namulonge-Wakiso	0.53° N, 32.62° E 1155	Acric Ferralitic SCL (n= 6)	2.70–5.04	2.00–5.59	Goto et al. (2012), Minyamoto et al. (2012), Onaga et al. (2012)

Soil texture class of each site are indicated by: C=Clay; C* (same textural class but different percentage of clay fractions thus different water holding capacities), CL= Clay Loam; SL= Sandy Loam; SCL= Sandy Clay Loam. ‡ Sites with yields were averaged across varieties and were not used in model validation due to also lack of weather data from a close station.

6.1.6 Model validation

Validation of model performance across simulation sites was done for grain yield and phenology. Validation was limited to yield data from sites with nearby weather stations because the further the field for which yield is simulated from a station, the more likely the error in yield prediction due to spatial variability in rainfall data. Paired data of simulated and observed grain yield were compared for each variety in respective seasons using a t-test.

6.1.7 Evaluation of model performance

Performance of the model during testing and validation was assessed using statistical indicators of estimation errors (Willmott 1981; Legates and McCabe 1999; Moriasi et al. 2007). The degree of agreement (D), the square of the coefficient of determination (R^2) for goodness of fit, root mean square error (RMSE), mean squared deviations (MSD%) and mean absolute error (MAE %) and normalised RMSD (root mean squared deviations) for growth parameters and yields were calculated. The equations below were used to calculate each statistical parameter for paired data of simulated and observed grain yield.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n-1}} \quad \text{.........(6.1)}$$

$$D = 1 - \frac{\sum_{i=1}^{n} (Si - Oi)^2}{\sum \left[\left(S_i - \bar{X} \right) + \left(O_i - \bar{X} \right) \right]^2} \quad \text{.........(6.2)}$$

$$MAE\ (\%) = \frac{100 \times \sum_{i=1}^{n} (S_i - O_i)}{n \times \bar{X}} \quad \text{.........(6.3)}$$

$$MSD = \frac{\left[\sum_{i=1}^{n} (S_i - O_i) \right]^2}{\bar{n}} \quad \text{.........(6.4)}$$

where, O_i and S_i are the paired observed and simulated values for grain yield, respectively, $\overline{x}$ is the sample mean of observed values, and n is the number of observations or replications.

The acceptability of the model predictions was tested using the Student's *t*-test at the 0.05 and 0.01 levels of significance by comparing O_i and S_i values for the two varieties. Both one-tailed and two-tailed distributions were used as secondary data on yield collected from different sites and not for equal periods.

6.1.8 Scenario analysis for yields and cropping systems

6.1.8.1 Water-limited and potential yields

The components of the soil water balance (swb), rainfall, runoff, evaporation, transpiration and percolation or drainage, were measured and or estimated from input data and parameters in the SWB-Sci model. However, the swb for a season or day depends on initial profile water content (θ_i) which is a function of soil water deficits from the water balance equation (Allen et al. 1998). There was no literature on seasonal dynamics of θ for Uganda to improve decisions on what a typically dry or wet soil profile is. Thus, three different levels of θ_i (mm m^{-1}) were used for rainfed conditions in Uganda to simulate Y_w. Varying levels of θ_i during the simulation allows one to capture factors such as tillage operations and length of land preparation and most importantly soil type, which influence θ_i. Other modeling frameworks (Sadras and Rodriguez 2010) for example, followed a similar approach to simulating wheat yield when data on θ_i were lacking. It should be noted that no specific hypothesis was formulated on θ_i and this approach was followed to determine Y_w distribution. The fraction of PAW (f_{PAW}) in the soil profile at sowing was varied as 0.25xPAW–0.75xPAW, where f_{PAW} is 25%, 50% and 75% PAW for a specific soil type. Plant available water was calculated as the difference between upper (FC) and lower drained limits (PWP). Estimation of soil water held at PWP was as well based on soil textural composition, even though PWP varies according to crop cover. Consequently, θ_i was calculated as the sum of soil water at PWP and f_{PAW}% X PAW. Sadras and Milroy (1996) considered 40–50% PAW as the threshold range of soil water for demand-limited transpiration in crops. Thus, the chosen levels of θ represent favorable and extreme conditions of soil water availability at the start of a season. For potential growing conditions, θ_i was set to FC of a soil type each time a simulation was performed for a combination of sowing dates and initial soil water contents at a site.

Simulated yield data was a result of full factorial combinations of two sowing dates per season, three levels of θ_i and two growing seasons per year. Per site (n = 22), a total of approximately 48–60 multiple simulations were performed for each rice variety during the simulation period (2008–2012), depending on the number of seasons with complete weather data. Water-limited yield was not simulated for periods with missing daily rainfall for more than two days in a season. Several sites except those in Table 6.2 had no reports of rice experiments to allow use of actual sowing dates. Thus, pentads of rainfall from DOY 1 to DOY 366 or to DOY 365 were calculated in Excel to aid in choosing sowing dates. Ogallo (1989) defined a wet pentad in Uganda is one with 10 mm or more with at least three rainy days (> 30 mm of rain), to determine start of the season. Sowing dates were within the planting window and the window differs between the second season (34–44 days) and the first one (< 35 days) (Mubiru et al. 2012). The first and second sowing dates were selected in every season and year for a site. In common cases, first and second sowing dates in a season were separated by approximately two or three rainfall pentads, which was equivalent to a duration of 10–30 days between sowing dates. In rare cases, a 'wet' pentad was considered even if cumulative rainfall for three days was slightly lower than 30 mm. This criterion is in accordance with other drought and meteorological studies (Mubiru et al. 2012). Thus, sowing dates in Tables 6.1 a, b & c apply to a range (the earliest to latest possible selected date) across a four- or five-year period in each growing season.

Data were disaggregated by the three soil water availability levels. Minimum, first quartile (Q1), median, and third quartile (Q3) values of yields were calculated in Microsoft Excel. Box-plots and whisker charts were plotted by calculating the lengths of boxes and whiskers to characterise yield distribution. The lengths of boxes were calculated, hidden (=Q1), lower (=

median – Q1) and upper boxes (= median – Q3), and of the top (= Max – Q3) and bottom whiskers (= Q1 – Min). In a few cases, at about three sites where Y_W seemed poorly estimated, the data was excluded, but this did not change median values and yield outlook.

To visualise the spatial distribution of water-limited yield gaps, data of Y_W/Y_P ratios of Nerica 4 over the simulation period were presented in thematic maps using ArcGIS software (ArcGIS Release 10.1, Environmental Systems Research Institute, Redlands, CA). According to Passioura and Angus (2010), crop yields approach a ceiling are at least 80% of the Y_P. Data were first divided into four quarters, (i) 0–0.26, (ii) 0.27–0.53, (iii) 0.54–0.80 and (iv) 0.80–1.0, corresponding to large, medium, small and negligible gaps due to water limitations, respectively. For each site, frequency was calculated as a percentage of yield ratio in each quarter over the total number. Classification of data was based on natural breaks (Jenks method) to maximise the differences between quarters (yield gaps), whereby the colour ramp of a dot on a map depends on the value. The colour ramp (a diverging colour scheme) was done in ArcGIS.

6.1.8.2 Double and single cropping systems for zones

Suitability of a DCS involving two rice varieties in a year to agroecological conditions was assessed based on total annual grain yield (AY) and chances of realising poor or good yields over the simulation period were also assessed. Yields regarded as 'poor' or 'good' was based on outcome of yield distribution at a site. Options for DCS were, (i) a medium-duration variety (Nerica 4) with a high yield potential in both seasons, and (ii) a short-duration variety (Nerica 10) during the first 'short' wet season and Nerica 4 during the second wet season. Some farmers may opt for the second cropping system in view of increasing AY because the first season is short (NEMA 2003), while option one may be more suitable in URF zone.

For a single cropping system, the argument for (i) fallow in the first season and plant Nerica 4 in the second season against the argument (ii) no rice in the first season and Nerica 4 in the second season was explored. The most common practice is the second option. Farmers plant other crops like maize (*Zea mays* L.) and sweet potatoes (*Ipomoea batatas*) in the first season (Minyamoto et al. 2012). For the latter option, it was therefore assumed that if a crop was grown in the first season, soil water would be depleted to low levels at sowing time of rice in the second season. The first option may result in increased AY in low rainfall areas because introducing a fallow in the first season may increase θ at planting in the second season.

For simple comparisons, simulations for a fallow plus rice (F–R) and no fallow-rice (R) system started with an equal initial soil water content (θ_i = 25% PAW) in the first season. This level of θ_i is typical of areas in the equatorial regions. For example, data from Agricultural Model Intercomparison and Improvement Project (AgMIP) showed that in some sites near the equatorial region, soils contained 30% PAW at sowing (Falconnier et al. 2019).

Total AY for a cropping system was calculated as the sum of typical yield during the first and second growing seasons. Again, typical yield was considered as the median value at respective sowing dates. The probability of realising extremely poor- (< 25th percentile) and very good- (> 75th percentile) AY was assessed using four levels or quarters of yield distribution analogous to a sectioning method (Addiscott and Wagenet 1985). In this method, ordered yield distribution within a zone was subdivided into four sections and frequencies within each inter-quartile range was calculated. Opportunity (if any) of AY with slight delayed sowing (but within planting window) in a growing season was assessed using algorithms in Excel.

$IF((AY_1 - AY_2) > 0, \text{"Yes"}, \text{"}No\text{"})$

where subscripts 1 and 2 represent early and late (delayed) sowing periods, respectively in season. The number of cases when early or delayed sowing resulted in better AY over the simulation period were counted and summarised as proportions within a zone.

6.1.8.3 Key assumptions in inferring reference yield data

Grain yield at national level for an average rice farmer in SSA ranges between 1.0 and 1.5 t ha^{-1} (ARC 2007). Although many survey reports published realistic figures, few measured data were site-specific and segregated by variety, thus such sources were not considered. This study therefore had a small sample size for Y_a. The little data available on Y_a represent the rice cropping system and yield gaps quantified will be widely applicable. It was assumed that pests and diseases had negligible effect on measured Y_a because Nerica has been reported to have high weed competitiveness and resistance to blast and other pests (Asch et al. 1999; Maji et al. 2011). Yield variations due to local sowing practices were ignored by using medium plant densities of 100 plants m^{-2}, which is recommended and commonly used among upland rice farmers (ARC 2007). This assumption was also held during comparison between O_i and S_i data with model validation.

When pests and diseases are controlled, Y_t are largely constrained by water availability and nutrients in most cropping systems (Timsina and Humphreys 2003). Again, site-specific data on Y_t was limited to researcher-managed experiments, and thus yield data from unfertilised treatments under rainfed conditions were used to infer to Y_t. The achievable yield under rainfed conditions without irrigation, the Y_w (van Ittersum et al. 2013) was defined by maximum yields with adequate fertilisation from rainfed, researcher-managed studies. There were no data on Y_P of rice in equatorial regions such as measured yield under non-limiting growth conditions to confirm our simulations of Y_P from the model.

6.1.9 Statistical analysis

The relative yield ratio of simulated Y_w/Y_P was calculated for each run at a specific sowing date over the whole simulation period. A median value of simulated Y_w for three levels of θ_i at each sowing date was used because median is a typical measure of a population parameter. Arithmetic mean was deemed not a suitable measure of a population because yield can be skewed or asymmetrical.

A yield gap was calculated as the yield ratio subtracted from one (1- Y_w/Y_P) (Tittonel and Giller 2013; Richards et al. 2016). Planned comparisons between seasons within a zone were done using the Student's *t*- test for paired groups of data. In describing water-limited yield gaps, quartile ranges, 0–25% (Q1), 26–50% (Q2), 51–75% (Q3) and 76–100% of Y_w/Y_P (Q4), were used to define large, medium, small and negligible gaps, respectively.

The General Linear Model (GLM) procedures in SAS® 9.3 version 6.1.7061 (SAS Institute Inc., Cary NC, USA) for Windows was used to analyse effects of sources of variation, namely, agro-ecological zone, season, variety and interactions between the factors. Differences in yield gaps were assessed with zones, variety and season as the main factors and sites as replicates within a zone, analogous to a Randomized Complete Block Design. Statistical procedures were used to test if yields and gaps are specific to AEZ, and if within a zone they differed between seasons in the medium-term simulation period. The unbalanced design (Type III error for sum of squares/ ss3) was used because the total number of simulations were not equal (±24) between some sites, which was due to an unequal periods of available weather data. *Post-hoc* Tukey tests were used to separate mean values of yield ratios for interaction or main effects which were significant.

Total annual yield (AY) and proportion of realising 'poor' yield (< 25th percentile) and 'good' (> 75th percentile) was used to evaluate suitability of the rice cropping system (a single or a double rice cropping per year) to an AEZ. The probability of 'poor' or 'good' AY was also considered, because simulated Y_w varies across seasons (largely due to rainfall) and this results in a wide range in AY.

6.2 Results

6.2.1 Model performance for predicting grain yield and phenology

Simulated Y_w grain yield in comparison to measured data is shown in Figure 6.3. Statistical indicators of model performance for the two varieties, inset Figure 6.3 overall showed acceptable model performance. It was noted that some observed yield data (n = 7) had higher certainty were compared with simulated yield, largely from one site in Uganda (Bulindi ZARDI) after cross-checking against seasonal rainfall data. For this site, moderately high grain yield ranging from 2.0–5.47 t ha^{-1} were reported with relatively low rainfall amount. Either rainfall data were incorrect, or yield data are correct or vice versa.

Across seasons, simulated Y_w was better predicted for Nerica 4 than for Nerica 10 for the same sites. The difference in accuracy with which yield of the two varieties was predicted was associated with incidence of WS. Water stress mostly coincided with reproductive growth of Nerica 10.

Comparisons of simulated and observed data using the Student's t-test revealed statistical similarity (p > 0.05) between paired data sets for each variety, as desired for continuity with application of the calibrated model to scenario simulations. Model bias was equally positive and negative – simulated grain yields were slightly above the observed yields in 19% of typical cases and yield was underestimated in approximately 24% of cases (data not shown). Underestimation of yields was common during growing seasons when WS developed around the middle of the growing season. Sites like Bulindi ZARDI and NaCRRI were dominated by dry spells between 45 and 69 DAS on average during the season, which coincided with late vegetative growth of varieties. Model corroboration in high yielding areas of Uganda was not possible. Grain yields (5 t ha^{-1}), well above the median values of 2.72 t ha^{-1} and 2.75 t ha^{-1} of varieties were measured on-farm at Kiziranfumbi, and Kwera (Hoima District) and Pakanyi (Masindi District), which unfortunately did not have weather stations in close proximity (< 5 km).

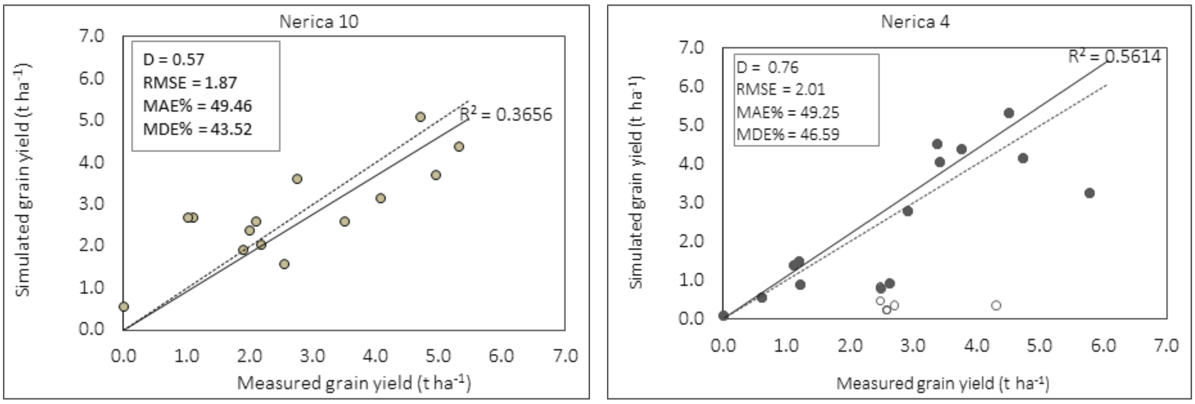


Figure 6.3 Comparison of simulated water-limited yield of rice varieties and measured data for research sites in Uganda. The dashed line is the 1: 1 line, and the data points represent mean grain yields in each season from 10 experimental sites across agro-ecological zones over the period 2008–2012.

Estimated crop duration from sowing to maturity (GDD) from the Hatfield site in South Africa was, as expected, very close to the calculated thermal time for maturity of upland rice varieties in Uganda. Simulated GDD to first flowering, anthesis and maturity under well-watered conditions in the Hatfield trial was roughly equal to thermal time to these stages in Bulindi ZARDI, the only site with measured phenology, (1.466° N, 31.44° E; 1157 m asl), in Uganda. It is noteworthy that rice trials in Bulindi ZARDI were rainfed compared to Hatfield which were under well-watered conditions, but observed GDD to reach the crop stages marginally differed (±100 GGD) between the sites.

6.2.2 Distribution of modelled water-limited yields as related to zones and water availability

Yield characteristics varied highly between AEZ, and unique yield distribution can be identified from the box-plot whisker charts (Figures 6.4 & 6.5). For instance, simulated yields at most sites were generally skewed or asymmetrical about the mean except in the NMF. Across all sites, data above the third quartile (within 25% of highest yields) were few and were usually less than 15% of the total simulations at a site (data not shown). Such extreme yields were for seasons during which received very high amounts of rainfall. Consequently, crop duration was comparatively longer by about 10 days due to likely overcast conditions.

Variation in simulated yield between zones was anticipated but most important is the inter-seasonal variation within zones as influenced by soil water availability. Typical yields as indicated by median values with respect to θ_i changed less for sites at NMF than other zones. On average, median values of both varieties are highest at sites in the NMF (2.4–8.2 t ha^{-1}) compared to sites in the LVB (1.2–6.9 t ha^{-1}) across all θ_i levels. Median yields for SWS (0.6–2.9 t ha^{-1}) were lowest, but excluding Bushenyi District Farm Institute (Bushenyi DFI), followed by the ESM (1.9–4.7 t ha^{-1}) and the ESAR (2.4–6.0 t ha^{-1}). Bushenyi DFI lies on a relatively higher altitude than the mean altitude of sites in the same zone. Consequently, median Y_w of 5.6–6.8 t ha^{-1} across varieties are high, owing to a longer growing period.

Simulated Y_W in the ESAR and SWS are generally low, even for the short-duration variety compared to levels in other AEZs (Figures 6.4 & 6.5). Simulated Y_W slightly varied over seasons in the ESAR and ESM as indicated by equal lengths of the whiskers due to fairly distributed rainfall.

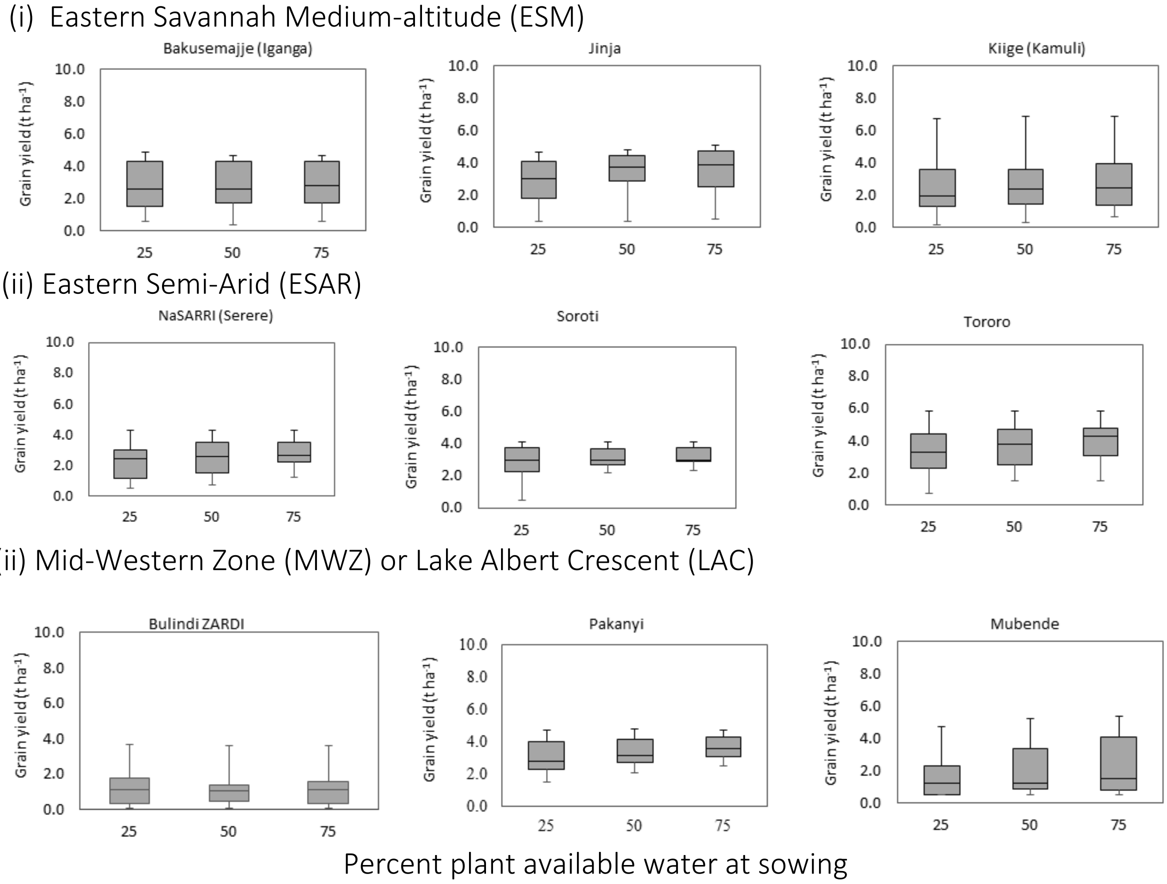


Figure 6.4 Range and distribution of simulated water-limited yields of Nerica 10 disaggregated for initial soil water content for selected sites in the (i) ESM, (ii) ESAR and (iii) LAC over 2008–2012 period (8 ≤ seasons ≤ 10). Box plots indicate first and third quartiles (25th and 75th percentiles) and dark horizontal line through the box is the median value.

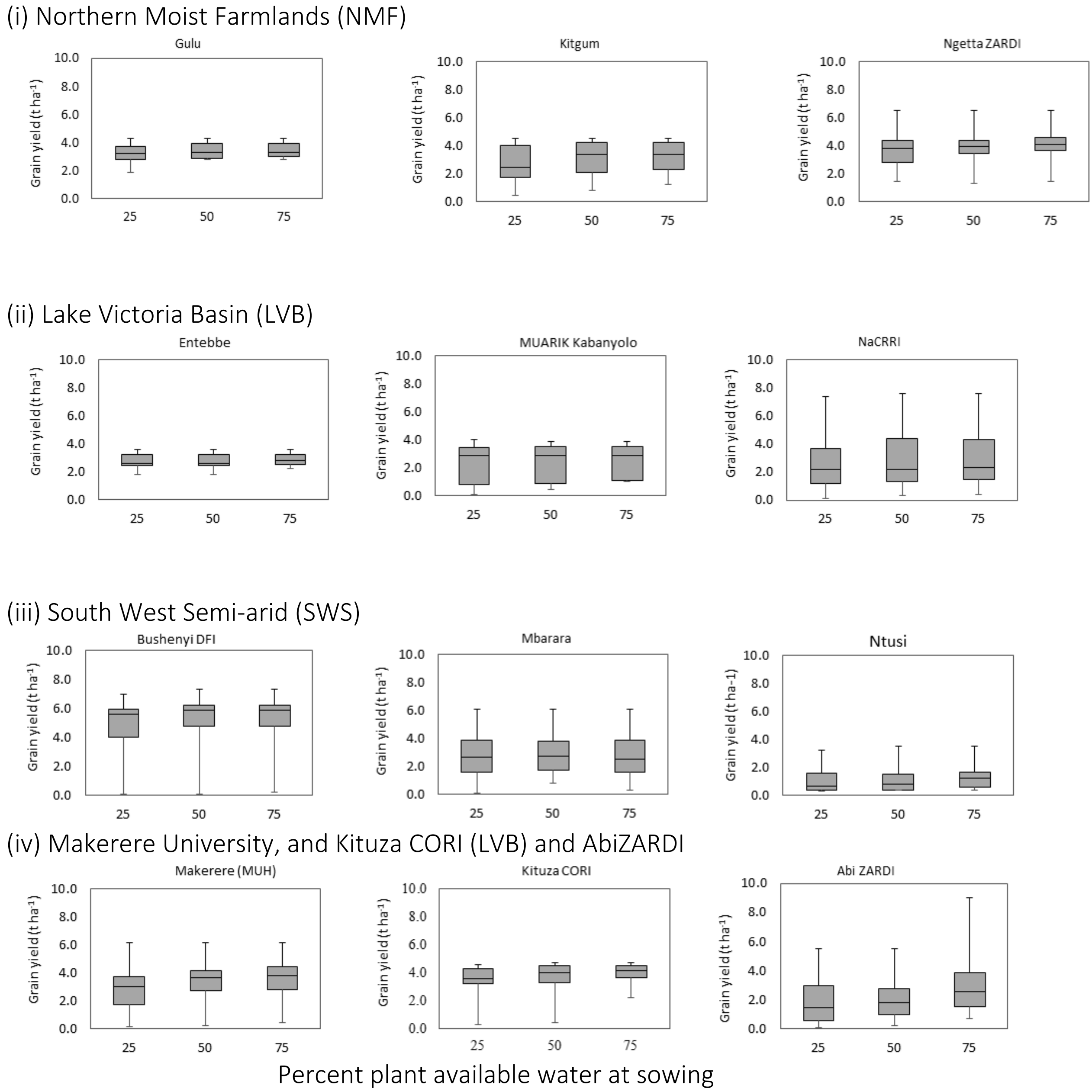


Figure 6.5 Range and distribution of simulated water-limited yields of Nerica 10 disaggregated for initial soil water content for selected sites in the (i) NMF, (ii) LVB and (iii) SWS over 2008–2012 period (8 ≤ seasons ≤ 10). Box plots indicate first and third quartiles (25th and 75th percentiles) and dark horizontal line through the box is the median value.

Modelled rice yields varied considerably between seasons over the five-year simulation period. However, variation in Y_W at sites under the NMF was less as indicated by equal lengths of whiskers (Figures 6.5 and 6.7). This corresponded to a similar rainfall distribution during growing seasons at Gulu, Kitgum and Ngetta ZARDI, which are characterised by a unimodal annual rainfall pattern (Figure 6.2). Therefore, compared to other sites, conditions of water availability are less diverse between sites in the NMF. Temporal analysis revealed, (i) rice growth at these sites was less affected by WS and (ii) no severe early stress was detected from simulations with an initial dry profile or soil water content starting at 25% PAW (data not shown). In contrast, seasonal yields generally were very variable in other regions of the country. For example, in most sites closest to the equator (0.5° S–1° N) as represented by the SWS and the LVB zones (Figures 6.7), the range of yield data was wide and amount of data in the extremes, < Q_1 and >Q_3, was larger (data not presented).

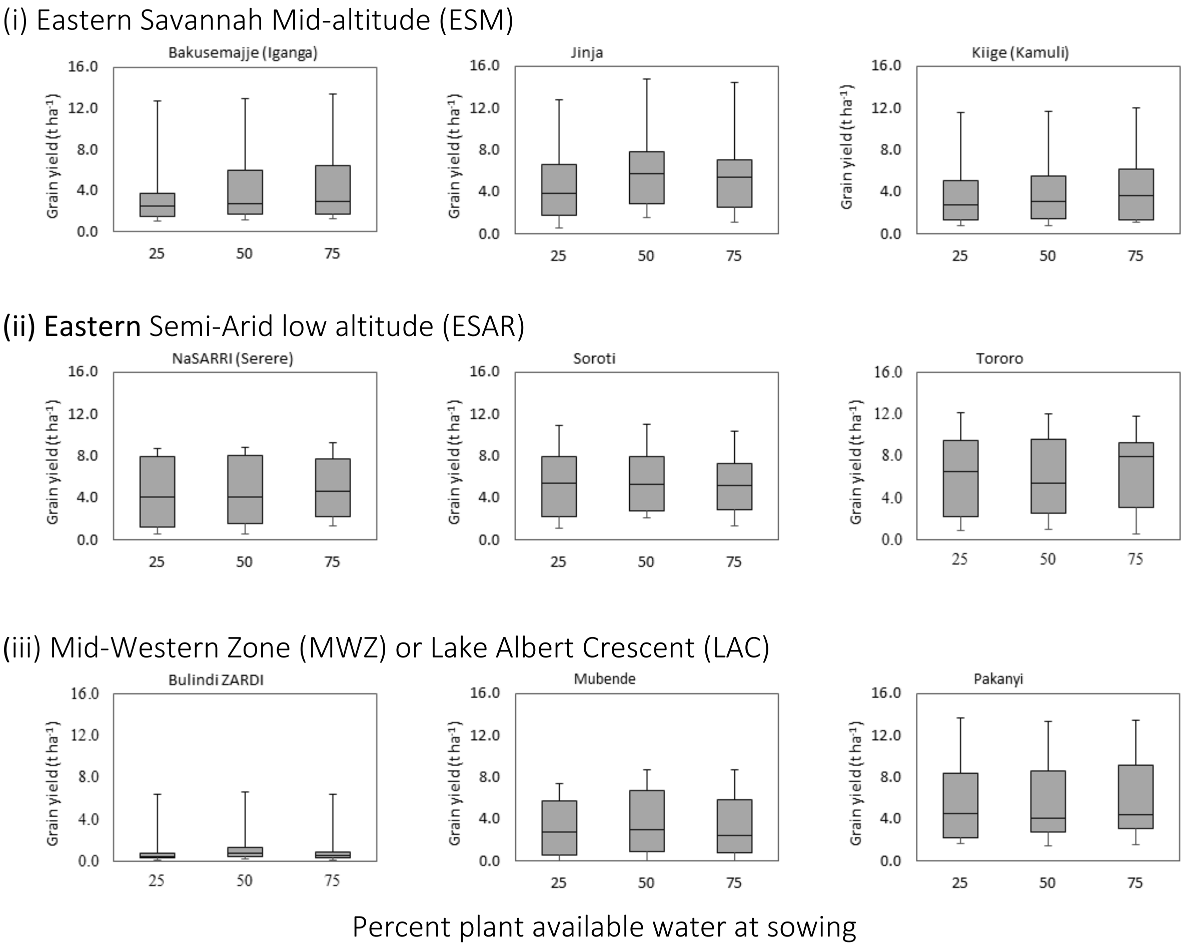


Figure 6.6 Range and distribution of simulated water-limited yields of Nerica 4 disaggregated for initial soil water content across selected sites in agro-ecological zones (i) ESM, (ii) ESAR and (ii) LAC over 2008–2012 (8 ≤ seasons ≤ 10). Boxes indicate first and third quartiles (25th and 75th percentiles) and the dark line through the box is the median value.

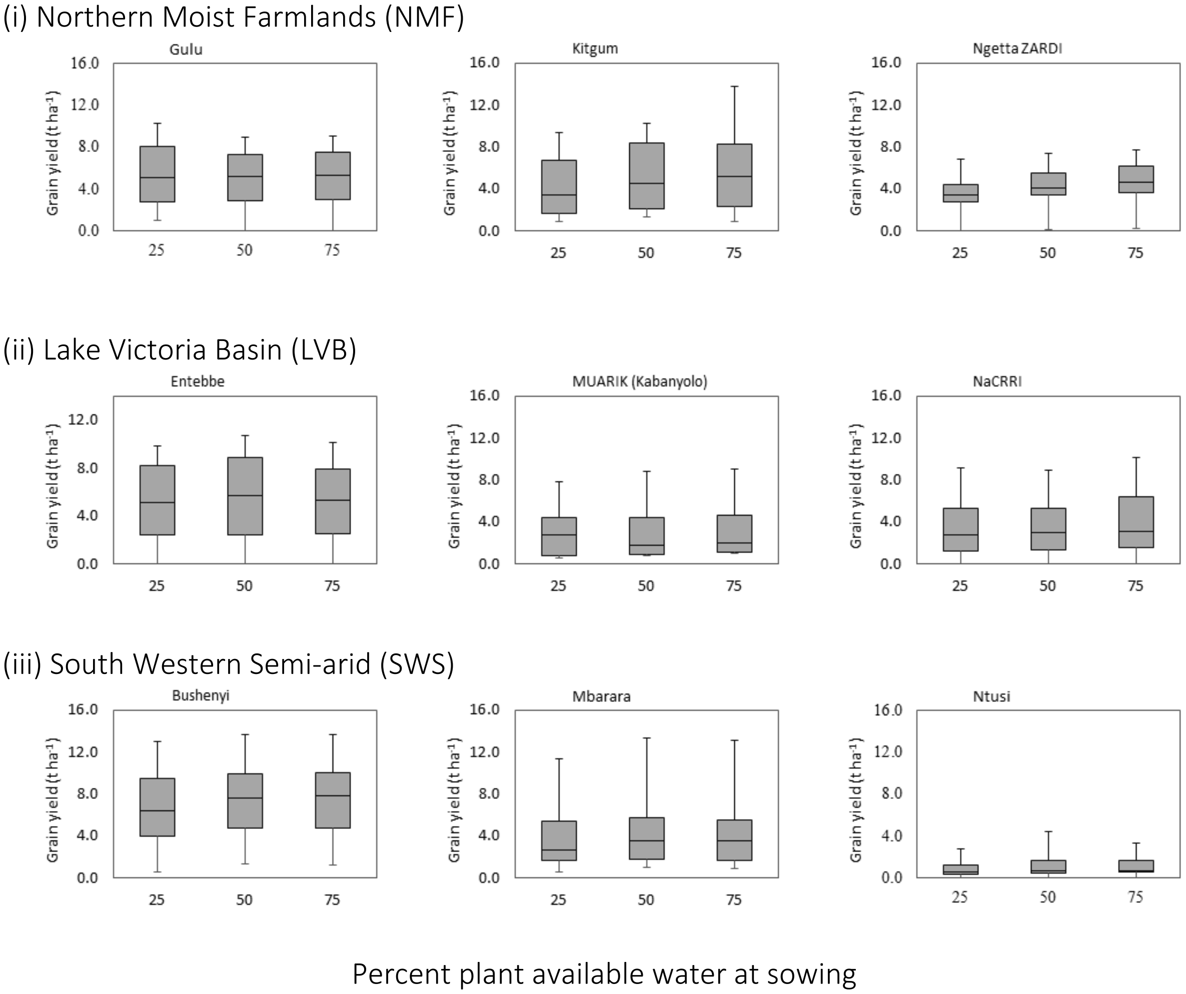


Figure 6.7 Range and distribution of simulated water-limited yields of Nerica 4 disaggregated for initial soil water content across selected sites in agro-ecological zones (i) ESM, (ii) ESAR and (ii) LAC over 2008–2012 (8 ≤ seasons ≤ 10). Boxes indicate first and third quartiles (25th and 75th percentiles) and the dark horizontal line through the box is the median value.

During the simulation period, cases of prolonged dry spells were rarely detected. Under severe water shortage (about 50% of the average normal seasonal rainfall), grain yields ranged from 0.2 to 0.6 t ha^{-1} in extreme cases. Consistent to the expected WS effects on rice yields, the model detected reduction in grain yield with stress during late vegetative growth. However, under prolonged dry spells (lasting for at least 30 days) and low seasonal rainfall at certain sites, simulated grain yield was low relative to simulated top dry matter of the medium-duration variety (Nerica 4). It is expected that such prolonged WS during late vegetative growth affects the grain yield of the medium-duration variety (with a longer reproductive stage) more than that of the short-duration. Overall grain yield was likely under simulated in 25% of the total simulation scenarios in two research sites, 16 out of 60 cases at NaCRRI (LVB) and 12 out of 48 cases at Ntusi (SWS). Simulated yields were likely low in 18 out of 60 cases at Mubende (LAC), due to WS coinciding with vegetative growth. There were no measured local Y_t and Y_w during seasons of interest at these sites to confirm a possibility of model correctness or precision of simulation.

6.2.3 Potential yields

Potential rice yields estimated at different sowing dates between growing seasons were quite similar for most sites (data not shown). Table 6.6 shows mean values of simulated Y_P for different AEZs. Potential yields were rarely well above the simulated average at a site. During seasons characterised by comparatively low minimum daily temperatures and prolonged dry spells resulting in a slightly longer crop duration, simulated Y_P values were higher. There was no data on growth under non-limiting conditions to aid in validating simulated Y_P.

6.2.4 Local reference yields and gaps aggregated by rice variety

Actual yields measured on farms and from experiments conducted under poor agronomic practices such delayed weeding varied from 0.34 to 2.6 t ha^{-1} across sites. The wide range in Y_a is also because agronomic practices investigated differed from secondary data sources. Median values were 0.45 t ha^{-1} for Nerica 10 and 0.76 t ha^{-1} for Nerica 4. It is noteworthy that Y_a was considered for only eight sites which had available measured data. Otherwise, descriptive statistics for Y_a could be slightly different for a larger sample size. The Y_a/Y_P on median terms is 30% and 13% of Y_P of the varieties indicating a gap of approximately 70% (due to biotic or abiotic constraints) for maximum yields of Nerica 4.

Yields from treatments without fertilisers from rainfed experiments (Y_t), are also limited by WS, also widely varied. As a fraction of potential yield, Y_t/Y_p ranged from 0.04 to 0.58 for Nerica 4 and from 0.12 to 0.59 for Nerica 10. Median yield of the medium-duration variety was severely reduced more than yield of the short-duration variety.

Fractional yield (Y_w/Y_P) values of Nerica 10 (0.37–0.98) are higher than for Nerica 4 (0.08–0.86). The higher Y_w/Y_P ratio values for Nerica 10 suggests that WS limited yield of Nerica 4 more, compared to Nerica 10 or the benefit of irrigation (if practiced) is more for Nerica 4 than for Nerica 10.

Measured Y_t data from researcher-managed experiments and simulated Y_P, analysis suggests that yield gaps arising from water and nutrient (largely N) limitations, which is typical of most small-scale growers or resource-constrained farmers, were approximately 56% (Nerica 4) and 49% (Nerica 10) (median values) over the simulation period. As expected, simulated Y_w were significantly ($p = 0.026$, two-tailed t-test) higher for the medium-duration (Nerica 4) than for the short-duration variety (Nerica 10) over years of experimentation. It was difficult to estimate the improvement in grain yields under rainfed conditions due to nutrient application level, without data on soil nutrient status for Uganda sites. However, yield gains from fertilisers of a rainfed crop could be affected by a lower observed water-limited yield (Y_{wo}) relative to simulated Y_W for a specific sowing date. The Y_{wo}/Y_w ratio values in Q1 were below 0.76 (Nerica 4) and 0.86 (Nerica 10), suggesting that yield improvement with fertilisation under rainfed systems was relatively better for the medium- than for the short-duration variety. This suggestion exempts cases of uncertainty with measured data from Uganda, as previously noted in Section 6.2.1.

With fertiliser application, mean yields varying from 0.67 to 4.97 t ha^{-1} were measured under rainfed conditions across sites over the study period (Table 6.2). These best yields measured in researcher managed trials at 80–150 kg N ha^{-1}, 30–60 kg K ha^{-1} and 30–60 kg P ha^{-1} represent Y_w. In most seasons, no significant yield gains were realised with rates above 80 kg N ha^{-1}, suggesting that WS suppressed attainment of maximum Y_w. For example, as expected yield gaps narrow with removal of limiting factors, but, the larger median ratio Y_t/Y_w than Y_w/Y_P for

Nerica 4 (Figure 6.8) was due to mid-season WS which depressed yield response under fertiliser. Consequently, Y_W was closer to Y_t, ideally $Y_w >> Y_t$, and the median ratio Y_W/Y_P slightly increased.

Simulation of nutrient- (largely nitrogen) limited and water- limited yield (Y_t) for Uganda sites could not be achieved without data on initial N conditions, field and crop management and detailed soil properties. Nitrogen was assumed as the main yield-limiting nutrient because grain yield measured with all three (N+P+ K) nutrients was not different from the yield without P+K with only N under rainfed conditions. Since simulated Y_w compared well with measured data, the yield ratio (Y_t/Y_P) and the gap thereof thus alluded to nitrogen and water limitations.

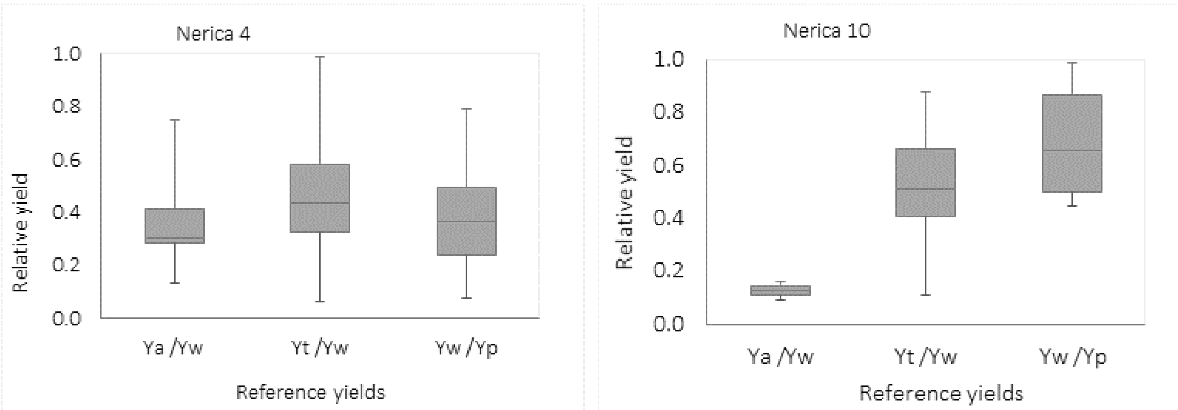


Figure 6.8 Relative ratios between actual (Y_a), attainable (Y_t), and simulated water-limited yield (Y_w), and between Y_w and simulated potential yield (Y_p) of upland rice varieties from eight diverse sites (each 2–4 seasons). Measured data on Y_a were from three sites and eight seasons.

6.2.5 Yield gap is intrinsic to rainfall regimes and not consistent between seasons

The range and distribution of Y_w/Y_P values within an AEZ from multiple simulations is shown in Figure 6.9. Means at the sites are not presented because sites were treated as 'replicates' in the statistical (GLM) model for hypothesis testing in line with the objective. The ratio of Y_w/Y_p was significantly ($p < 0.0001$) higher in the NMF which receives URF than in all other zones except ESAR, indicating a lower mean water-limited yield gap.

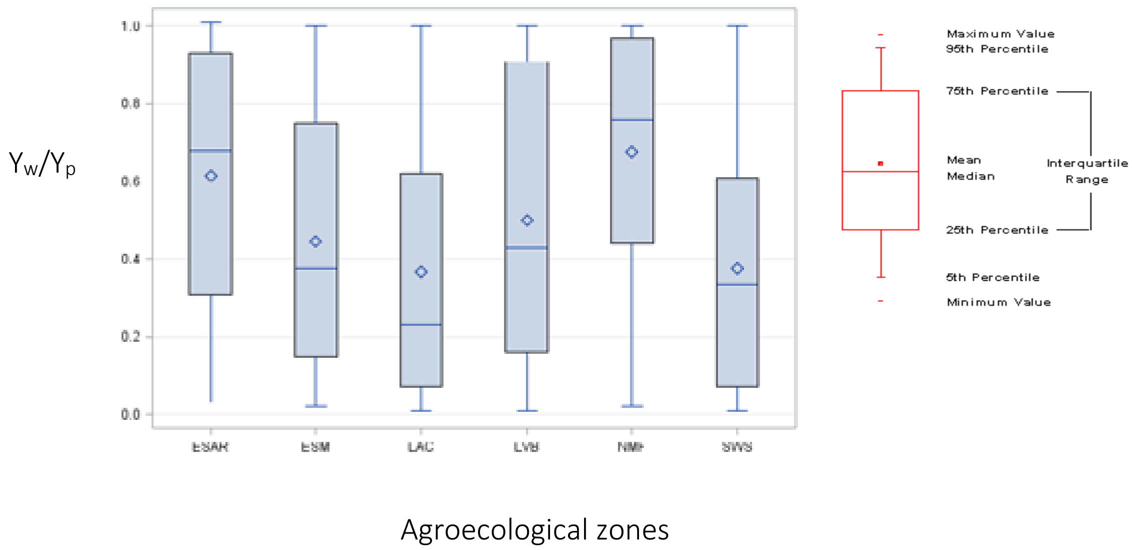


Figure 6.9 Range of distribution of relative yields (Y_w/Y_p) for different agro-ecological zones: Eastern Semi-Arid (ESAR), Eastern Savannah Moist (ESM), Lake Albert Crescent (LAC) or Mid-Western Zone, Lake Victoria Basin (LVB), Northern Moist Farming system (NMF) and South-Western Semi-arid (SWS) over 2008–2012 period. Relative yields are across sowing dates. Error bars are between 5th and 95th percentiles within zones across sites and varieties.

Table 6.6 shows the degrees of freedom and sources of variation of Y_W/Y_P. As expected, Y_w/Y_P ratio values were highly significantly different ($p < 0.0001$) between zones, between growing seasons and the interaction effect was significant, indicating differences in yield gap due to WS are specific to zones. Some of the AEZs, namely, (i) Lake Victoria Basin and Eastern Savannah Moist, (ii) South Western Semi-arid, and Eastern Savannah Moist and Mid-Western and (iii) Eastern Semiarid and Northern Moist Farming systems, had statistically similar Y_w/Y_P. Based on this analysis, AEZs can be classified into three broad yielding areas: high (NMF and ESAR), medium (LVB, ESM) and low (SWS and MWZ).

Table 6. 6 Analysis of variance for relative water-limited (Y_W) to potential yield (Y_P) between seasons, variety and zones across sites in Uganda.

Sources of variation	Degrees of freedom	Type III SS	Mean Square	F Value	Pr > F
Zone	5	24.67801603	4.93560321	57.80	<.0001
Season	1	6.12426351	6.12426351	71.72	<.0001
Variety	1	31.01949492	31.01949492	363.28	<.0001
Zone*season	5	3.66642277	0.73328455	8.59	<.0001
Season*variety	1	0.00468367	0.00468367	0.05	0.8149
Zone*season*variety	10	0.77792059	0.07779206	0.91	0.5219

It was hypothesised that water-limited yield gap alone estimated from Y_W/Y_P ratio, for the short-duration variety (Nerica 10) does not differ between short and long rain seasons. Findings completely reject this postulation in some AEZs (LVB, NMF and SWS) because differences in the mean Y_W/Y_P ratios of the variety were significant between seasons (Table 6.7). The ratios are higher (> 0.66) in the NMF and marginally differed between seasons indicating the contribution of WS to yield was small over the simulation period.

In contrast to the study expectations, yield gaps due to WS singly in the NMF, characterised by URF, are similar between seasons. The Y_W/Y_P ratio values in the NMF are high, just like in the ESAR compared to ratios for other AEZs, especially for the short-duration variety.

Across seasons, the modelled data supports study expectations of yield gap differences, even though not in absolute terms (Table 6.7). Grand mean ratios (Y_W/Y_P) for the second season B (0.55) and for the first A (0.44) across AEZs are both below 0.66, which can be regarded a large yield gap. The hypothesis that potential improvements in yields during the first growing season (A) are hindered by WS was supported by lower Y_W /Y_P ratios (high yield gaps) of Nerica 4 than of Nerica 10 across most AEZs (Tables 6.7 and 6.8). The same hypothesis was, however, rejected for SWS where Y_W/Y_P of the short- and medium- duration variety are approximately equal and below threshold value of 0.66. The ESM and NMF systems have a low risk of WS reducing yields during the first season (Tables 6.7 and 6.8). This finding demonstrates the possibility of farmers to fit short-duration varieties during the first growing season against the tradition and norm of forfeiting the season.

Table 6.7 Mean (± SE) values of simulated potential yields (Y_P), and water-limited relative yields (Y_w) of two varieties for growing seasons (A and B) and range of attainable/potential yields in the ESM, LVB and NMF in Uganda.

Agroecological zone, seasons	Potential grain yield of varieties (t ha^{-1})		Y_w/Y_p		Y_t/Y_p (range of varieties) †
	Nerica 4	Nerica 10	Nerica 4	Nerica 10	
Eastern savannah moist (ESM)•					
A	12.69 ± 0.28	4.82 ± 0.11	0.21 ± 0.03	0.52 ± 0.03	0.19–0.34
B	12.91 ± 0.17	5.60 ± 0.14	0.37 ± 0.03	0.67 ± 0.03	0.17–0.26
Lake Victoria basin (LVB)•					
A	12.22 ± 0.16	3.99 ± 0.28	0.35 ± 0.03	0.58 ± 0.03*	0.18–0.50
B	12.76 ± 0.22	5.00 ± 0.32	0.37 ± 0.03	0.70 ± 0.03*	0.25–0.38
Northern Moist Farming system (NMF)°					
A	10.06 ± 0.22	3.61 ± 0.16	0.49 ± 0.03**	0.75 ± 0.03**	0.05–0.12
B	11.09 ± 0.16	4.50 ± 0.14	0.61 ± 0.03**	0.86 ± 0.03**	na

Symbols in superscript (°•□) beside names of AEZs show zones with similar grand means of Y_w/Y_p of varieties and significantly different from other zones by GLM procedures.
Within a zone, means of Y_w/Y_p are significantly different between seasons at, * $p < 0.05$ and ** $p < 0.01$ for each variety by Student's t-test.
na, not applicable.
SE is the standard error of the mean (n = 26–32).

Table 6.8 Mean (± SE) values of simulated potential yields, and water-limited relative yields of two varieties between growing seasons (A and B) and range of attainable/potential yields in the ESAR, LAC and SWS in Uganda.

Agroecological zone, season	Potential grain yield of varieties (t ha^{-1})		Y_w / Y_p		Y_t / Y_p (range of varieties) †
	Nerica 4	Nerica 10	Nerica 4	Nerica 10	
Eastern Semi-arid Mid altitude ESAR)°					
A	10.67 ± 1.16	3.56 ± 0.13	0.49 ± 0.03**	0.78 ± 0.03	na
B	11.39 ± 1.25	4.57 ± 0.15	0.43 ± 0.03**	0.75 ± 0.03	na
Lake Albert Crescent (LAC)□					
A	12.09 ± 0.33	5.16 ± 0.34	0.15 ± 0.03*	0.43 ± 0.03	0.11–0.94
B	12.64 ± 0.45	5.78 ± 0.41	0.33 ± 0.03*	0.53 ± 0.03	0.04–0.47
South Western Semi-arid (SWS)□					
A	14.16 ± 0.19	6.26 ± 0.20	0.14 ± 0.03**	0.34 ± 0.03**	0.13
B	14.19 ± 0.25	6.60 ± 0.14	0.40 ± 0.03**	0.62 ± 0.03**	na

Symbols in superscript (°•□) beside names of AEZs show zones with similar grand means of Y_w/Y_p of varieties and significantly different from other zones by GLM procedures.
Within a zone, means of Y_w/Y_p are significantly different between seasons at, * $p < 0.05$ and ** $p < 0.01$ for each variety by Student's t-test.
na, not applicable.
SE is the standard error of the mean (n = 26–32).

Eastern Semi-Arid mid altitude (ESAR) and the NMF have a relatively low risk (≤51% water-limited potential gap) of WS reducing yields during the first season. Spatial distribution of water-limited gaps using Nerica 4 as a case are shown in Figure 6.10. At certain sites, notably, 4 and 11 in the NMF and 19, 21 and 22 in the ESAR, yields were not always limited by water shortages (Figure 6.10, map D). The frequencies of Y_W/Y_P above 0.8 were noted in between 27 and 38% of the cases. Over the 2008–2012 period, some seasons had evenly distributed rainfall in these sites. Furthermore, large yield gaps ($Y_W/Y_P < 0.26$) were simulated in less than 40% of the cases or scenario combinations in the ESAR and less than 65% cases in the NMF. This means that improving Y_W above the current observed levels can be achieved through addressing other limitations (excluding WS) to rice yields such as crop management.

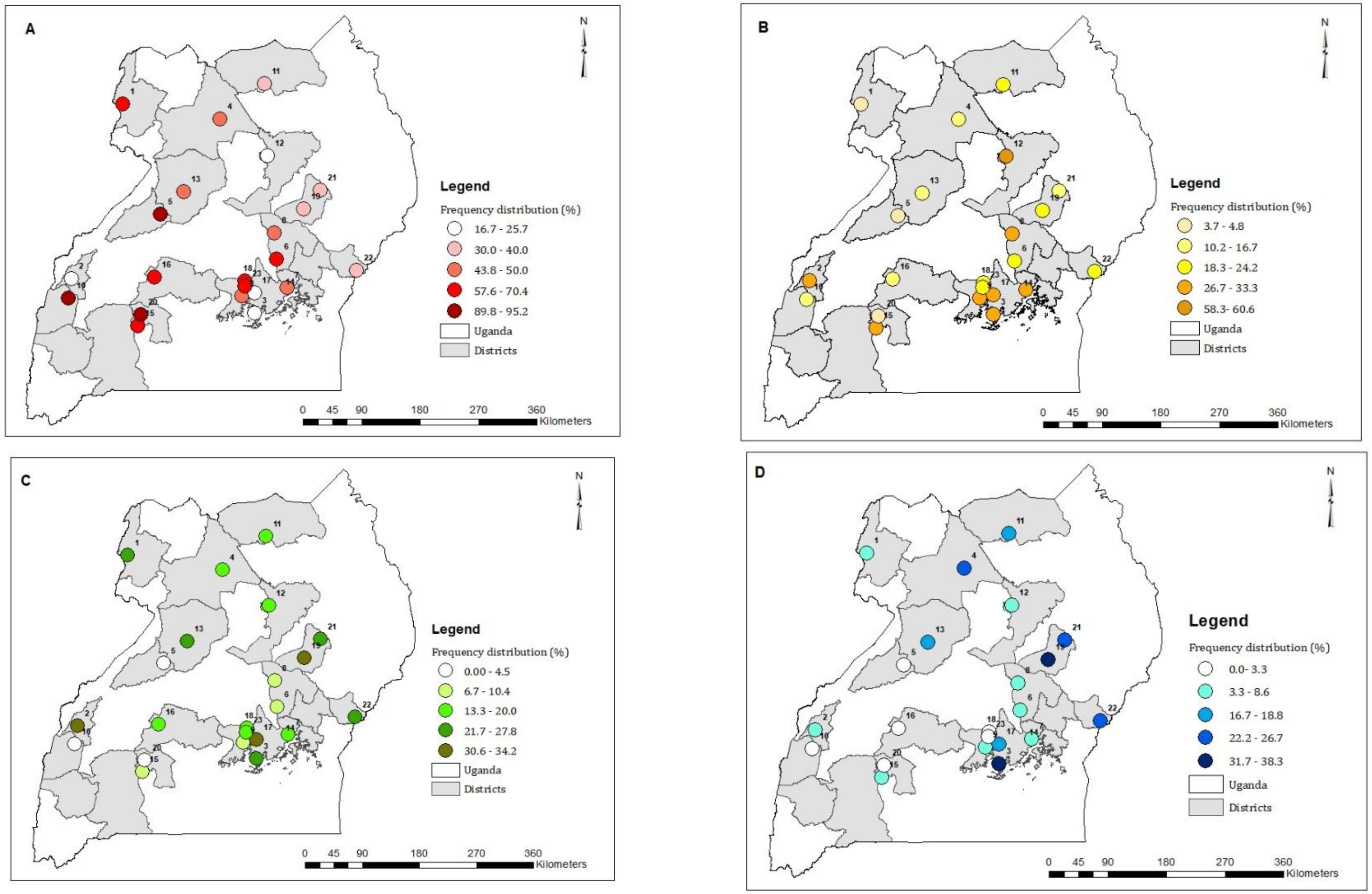


Figure 6.10 Frequency distribution (%) of water-limited to potential yield ratio in yield classes: 0–0.26 (A), 0.27–0.53 (B), 0.54–0.8 (C) and 0.8–1.00 (D) over the simulation period corresponding to yield gaps: large (A), medium (B), small (C) and negligible (D).

6.2.6 Yield merit and opportunities to improve yields under different cropping systems

In the previous sections, it was noted that yield gaps are specific to AEZs and varied between seasons. The spatial variability and magnitude of Y_w/Y_P and Y_t/Y_w ratios in particular related to rainfall distribution, soil water content at sowing, duration and yield potential of the variety. These conditions present opportunities for improving rice cropping system productivity, which will be discussed in this section.

Total annual yield (AY, t ha^{-1} yr^{-1}) under double cropping systems (DCS), did not differ significantly ($p > 0.05$, Student paired t-test), except for NMF. Annual yield for Nerica 4_a-Nerica 4_b (Nerica 4 in seasons A and B) ranged from 0.3 to 22.4 t ha^{-1} yr^{-1} and for Nerica10_a -Nerica 4_b (Nerica 10 in season A followed by Nerica 4 in season B) ranged from 0.3 to 18.4 t ha^{-1} yr^{-1}) across AEZs. The proportion of AY above 75th percentile ('good' total yield) under Nerica 4_a - Nerica 4_b system was notably high in the NMF compared to the other AEZs (Table 6.7). Furthermore, modelled data revealed that chances of a higher AY with delayed sowing (AY_d) than with immediate sowing (AY_i) are significant ($p < 0.01$, Student's t-test) in the NMF and SWS as well. This finding demonstrates the possibility of improved annual rice yields by shifting sowing dates away from the traditional dates for these two AEZs.

Some management scenarios did not result to an increase in the simulated Y_w under certain conditions. Early (immediate) sowing did not increase the proportion of cases with a higher AY than that for delayed (late) sowing across most AEZs (Table 6.7). The only exception was for the SWS where AY_d, instead, was significantly ($p < 0.05$, Student t-test) higher than AY_i. Sowing early in a planting window, the expected norm, did not necessarily always result in higher AYs, compared to delaying sowing in this AEZ. It was noted that the chances of higher AY_d values than AY_i are more in the SWS than in other AEZs, because rainfall distribution was biased to the mid-season and dry spells predominated the early season. Therefore, sowing based on onset of a rainy season (tactical management) rather than sowing based on historical weather data (strategic management) is very appropriate for the SWS.

The level of θ at sowing even at 75% PAW had a negligible effect on the simulated Y_w in some sites in the LVB and SWS (Figure 6.7). This was associated with soil type (low water holding capacity) and rainfall distribution in different cases. Growing a short-duration variety instead of the medium-duration variety during unfavourable wet seasons did not result in a yield merit. So, during such times farmers can either forfeit the season for fallow or choose a short-duration variety so that labour can be availed for other farm activities.

Table 6.9 Annual yield distribution data and probability of yield differences compared between immediate and delayed sowing across zones under different rice cropping systems over 2008–2012 simulation period.

Agro-ecological zone-Cropping system	Annual yields of cropping systems (%)		Proportion for different AY between sowing periods[†] (%)		F-value for AY_i and AY_d
	<Q1	>Q3	$AY_i > AY_d$	$AY_d > AY_i$	
Nerica 4_a–Nerica 4_b					
Eastern Semi-Arid	0.28	0.24	0.69	0.31	ns
Eastern Mid-altitude	0.27	0.27	0.62	0.38	ns
Lake Victoria Basin	0.23	0.31	0.77	0.23	*
Mid-Western Zone	0.25	0.25	0.77	0.23	ns
Northern Moist Farming	0.26	0.82	0.59	0.41	**
South West Semi-arid	0.23	0.27	0.47	0.53	*
Nerica 10_a–Nerica 4_b					
Eastern Semi-Arid	0.27	0.27	0.62	0.38	**
Eastern Mid-altitude	0.23	0.31	0.58	0.42	ns
Lake Victoria Basin	0.27	0.27	0.69	0.31	ns
Mid-Western Zone	0.25	0.25	0.79	0.21	ns
Northern Moist Farming	0.24	0.26	0.76	0.24	*
South West Semi-arid	0.27	0.27	0.53	0.47	*
$Fallow_a$–Nerica 4_b[‡]					
Lake Victoria Basin	0.27	0.28	0.16	0.14	ns
Mid-Western Zone	0.28	0.26	0.08	0.06	ns
South West Semi-arid	0.28	0.25	0.03	0.02	ns

Annual yield with immediate or early sowing (AY_i) and with delayed or late sowing (AY_d).
Subscripts, a represents the first growing season and b the second in a year. [†] Sowing periods; immediate (after three rainfall pentads) and delayed (at least three rainfall pentads) separated by approximately 15–30 calendar days. Q1 is first quartile (25th percentile) and Q3 is third quartile (75th percentile). Significant at, * $p < 0.05$, ** $p < 0.01$; ns, not significant at $p = 0.05$ but at the 0.1 level of significance by Student's t-test.

Three AEZs, the LVB, the MWZ and the SWS are not suited for two rainfed crops per year over the 2008–2012 simulation period. For all study sites in the LAC and SWS and two sites in the LVB, simulations showed that mid-season WS, especially during the first season, frequently affected rice growth and yields over the years. Simulated Y_w were thus generally low. If fields fallowed in the first season and rice is grown in the second (F–R system), simulations indicated that yield increased compared to growing rice (R system) only during the second season (Figure 6.12). Typical yields indicated by the median increased and amount of data in the 25th percentile generally reduced in a F–R system, compared to R across three AEZs.

Scenarios of fallow–sowing date, fallow early+sow early, fallow late+sow early, fallow late+sow early and fallow late+sow late, did not result in significant differences ($p > 0.05$) in simulated Y_w and AY. However, in 8% of cases in the LVB, 4% in the LAC and 2% in the SWS, fallow early in season A and sow late in season B (fallow early+sow late) resulted in higher AY, with an equal length of the fallow period.

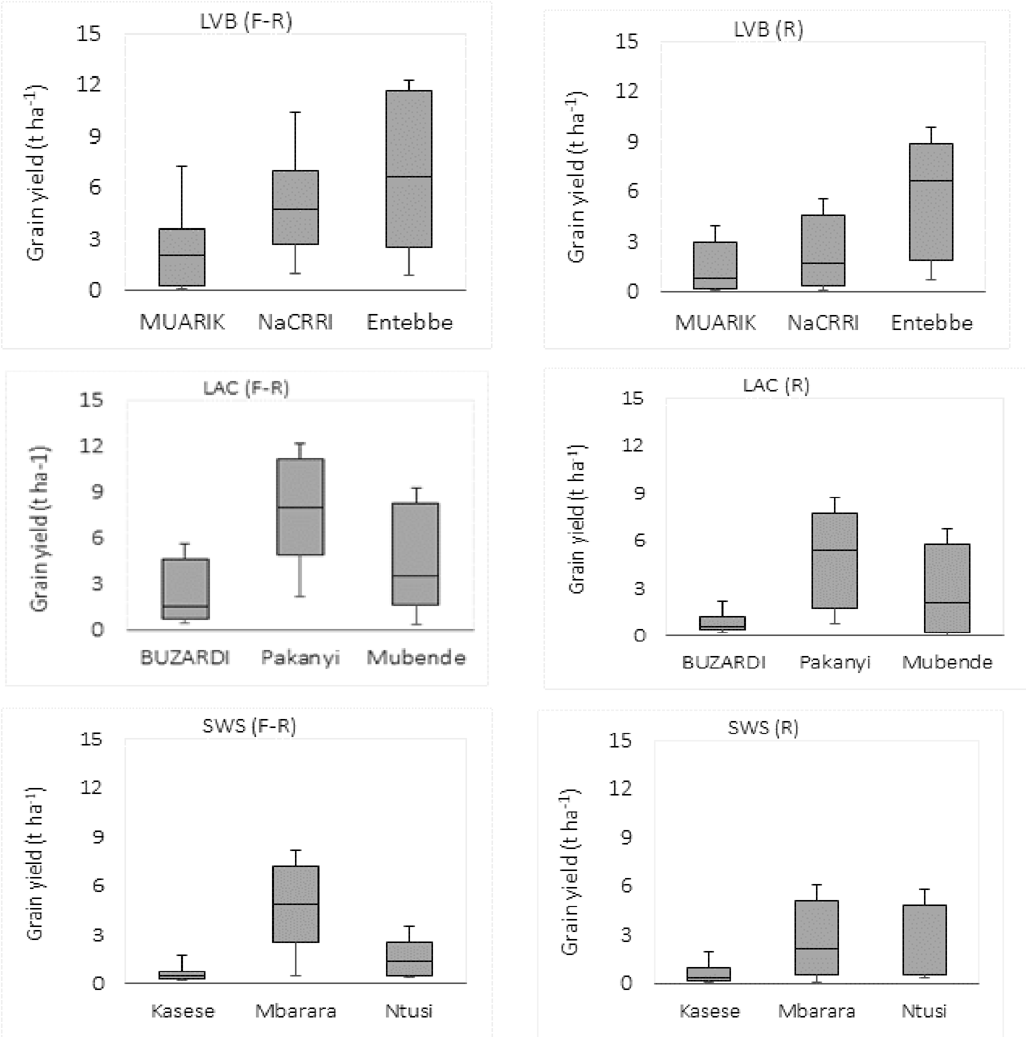


Figure 6.11 Comparison of annual yield of a high yielding variety (Nerica 4) between fallow-rice (F–R) and rice only (R) cropping system, with Nerica 4 during only the second season within and across the Lake Victoria basin (LVB), Lake Albert Crescent (LAC) and the Southwestern Semi-arid (SWS). Quartile box plots (between 25% and 75%) show yield data simulated for sowing-fallow period scenarios.

6.3 Discussion

6.3.1 Model performance and limitations

Accurate modelling of rice growth and yield depends on proper calibration and validation of models with measured field data. Prior to this study, simulation of upland rice yields was difficult due to lack of information on crop growth parameters, water and nitrogen use efficiency of the crop. The parameterised SWB-Sci model predicted rice yield and phenology with acceptable performance, as the statistical parameters were within ranges described in literature (Moriasi et al. 2007). Since the model was successfully calibrated and validated, it could be applied to sites elsewhere. However, inaccurate prediction of yield for some seasons at two sites (NaCRRI and Bulindi ZARDI) in Uganda could be partly attributed to lack of data on variability in observed yield data. Another limitation was, lack of data on time course of growth and duration of development stages in most seasons, except for records on sowing and harvest dates. This emphasises the need to report quite detailed agronomic information in future studies. Related to this, data especially on actual yield was aggregated at administrative levels like sub-regional level (Kijima et al. 2008), making it difficult to detect actual yield gap differences between sites.

The underestimation of yields in many cases at Bulindi ZARDI is not surprising. Soil at the site has an exceptionally high clay content (45–51 %) (Kaizzi et al. 2014), compared to common upland soils where rice is grown. Coupled with low minimum daily temperatures, compared to other simulation sites, these extreme conditions may have modified adaptation of rice to WS, and model predictions could not fully explain this. Studies on threshold levels of soil water depletion for upland rice growth are lacking (Asch et al. 2005; Kato et al. 2006), and therefore need to be determined for different soil types. Rice growth parameters, especially the basic ones like phenology and crop duration needed for accurate yield estimation (Cao and Moss 1997), should be also well documented in such extreme environments.

Available information on rice growth in many African equatorial regions is generic, for example, 100–120 days after emergence is reported as the maturity period, but plant growth analysis data is lacking (Kaizzi et al. 2014). Boojung and Fukai (1996) and Wopereis et al. (1996) reported that rice growth and phenology was altered under rainfed conditions. This means that at AEZ level the variation in rice phenology is likely considerable and this may have affected yield estimation. For future comprehensive modelling studies, detailed soil profile description, mapping and additional weather stations at research institutions should be installed.

6.3.2 Reflecting the estimated rice yield gaps

Proper quantification of crop yield gaps is important in addressing food security and environmental issues on self-sufficiency, profitable crop production and sustainable use of inputs. What yield gaps are relevant in a farming system and which ones to prioritise depends on the production objective (subsistence or commercial) and the type of producers (small-, medium- or large-scale).

This study met the basic requirements in simulating Y_w and Y_P (van Ittersum et al. 2013) and afforded reliable data sources on Y_a and Y_t (Onaga et al. 2012; Kaizzi et al. 2014). Results on Y_a/Y_w ratio in Figure 6.8 are within the estimated relative yields by Richards et al. (2016), which indicate that Y_a on average are between 20 and 25% of the Y_w of crops in SSA. This confirms that simulated Y_w is realistic for rice. At the current Y_a, the gap to achieve Y_w (if only water is limiting yield) is very large (> 70%) for the majority of rice farmers in African equatorial region. Identifying limiting factors in different rice growing areas is the first step to determine what crop management to address in rainfed rice.

Results on relative yields (Figure 6.8) confirm reports of the World Bank (2008) that attainable crop yield (Y_t) on farms is 80% of Y_P. However, the Y_t gap is not easily differentiated from the actual yield gap (Passioura and Angus 2010), as depicted in the present study. Preliminary analysis of relative yields in Figure 6.8 revealed that fertiliser application narrowed the yield gap of Nerica 10 more than that of Nerica 4. This suggests that current fertiliser recommendations (Onaga et al. 2012; Kaizzi et al. 2014) should be revised for varieties, which are of different durations and yield potentials. Scenario analysis confirmed that the Y_w/Y_P ratio, alluding to a water-limited yield gap singly, is different between varieties. Most important, the gap for Nerica 10 is uniform across zones, while for Nerica 4 it varied between zones.

6.3.3 Feasibility of achieving yield improvements and strategic cropping practices

In certain areas rainfall is insufficient to grow rice during the second season. The National Crop Resources Research Institute (NaCRRI 2010) recommended 360 mm per season as the minimum water requirement of Nerica 4, based on pot experiments without detailed protocols. In the present study, with this amount of rainfall, simulated Y_W in research sites ranged between 0.2 and 0.4 t ha^{-1}. It is noted that pot studies do not well account for other components of the swb, which explains the disparity between present study findings and that by NaCRRI (2010). Scenario analysis revealed that an unevenly distributed seasonal rainfall of below 500 mm per season, yields were very variable, but mostly between 0.8–1.9 t ha^{-1}, across varieties.

Introducing a fallow period preceding sowing of rice (F–R system) in the SWS and in some sites in the LVB improved yield. A combination of infield rainwater harvesting and slashing a fallow, for example, should be vital in raising soil water levels at sowing in the SWS. Findings suggest typical θ_i values of 0.21–0.27 m^3 m^{-3}, about 50% PAW, but, the difficult question to answer is, at what level of θ_i should farmers sow to optimise yield under low rainfall conditions? In other areas in the LAC, prolonged dry spells causing mid-season WS make it necessary to alter sowing dates.

The SWB-Sci model enabled the detection of some of the location-specific differences in Y_P in Uganda and gaps, albeit with a lack of reference yields under optimum conditions. It was not surprising that a realistic rice Y_P of about 10 t ha^{-1} exists for some locations. Kaizzi et al. (2014) reported rice yields at Kwera and Kiziranfumbi in the Hoima District, which are approximately 60–70% of the highest simulated Y_P in this study. It was unfortunately not possible to model rice yields for these sites (which are on-farm) primarily due to lack of appropriate weather records. The sites in the Hoima District in the LAC are not the only areas with a high yield potential. The NMF received higher annual rainfall (see Tables 6.1, 6.2 and 6.3) and between 500 to 700 mm during the actual growing season. Such high rainfall amounts on dominantly fine-textured soils (Kaizzi et al. 2014) with good water holding capacity (estimated field capacity of 0.33 m^3 m^{-3}), should be considered for intensive upland rice cropping systems. However, Y_P in the NMF may be limited by low incoming solar radiation (Rs) compared to other sites because the AEZ has a unimodal rainfall regime and many cloudy days are likely. Akuraju et al. (2017) reported that crop ET was not primarily constrained by limited soil water, but by atmospheric demand. Appropriate sowing dates are important in such conditions and may be advised for commercial rice production.

Farmers in the NMF have a yield merit in growing a medium-duration, high yielding variety, over those in the other AEZs, based on a high Y_w/Y_P ratio in both seasons. Double rice crops per annum of Nerica 4 are recommended for the NMF. Although most of the farmers prefer the second to the first growing season due to belief of WS risk (NEMA 2003), the study findings suggest that double crops of rice per annum is feasible in the ESM as well. In contrast, in some sites in the LVB, farmers may have a difficult choice of season to grow Nerica 4 because of the small mean Y_w/Y_p ratio values. A single rice crop per annum restricted to the second season seems appropriate for most sites in the LAC, some sites in the SWS and sites which are distant from the Lake Victoria in the LVB.

In areas of the ESAR, upland soils are predominantly sandy with a transition between SC and SCL (Kaizzi et al. 2014), and the water holding capacity is too low to exert acceptable crop yield from increased θ_i, as was illustrated in the scenario analysis results. Fallows should be practiced with caution in the ESAR, because from scenario simulations drainage was considerable during the cropping season with a F–R system. High drainage has implications on nutrient use efficiency and on the ground water quality. Farmers should achieve yields higher than the current Y_t and Y_w in the ESAR because rainfall data over the simulation period showed an even distribution and incidences of WS was common only at end of the season. Practices that reduce surface runoff and soil evaporation should be adopted in the ESAR.

Whereas yields of upland rice under irrigation and nutrient non-limiting conditions have not been measured or documented in African equatorial regions; studies in the tropical lowlands elsewhere indicated maximum achievable yield, always lower than Y_P, of 10 t ha^{-1} (Peng et al. 1999). A recent study by Kato et al. (2009) revealed that maximum yield (not Y_P) of Japonica rice in uplands under adequate water supply closely matched yields in flooded lowlands. Short dry spells, notably in the NMF and ESM, make it necessary to irrigate for commercial rice production. Modelled data across 17 cases from research sites (soil, field management and weather data are reliable) indicated that irrigation would account for between 14 and 55% (median = 30%) of seasonal water requirement to attain simulated Y_P, across varieties. Many breeding efforts to improve rice yields in Uganda, among others the studies Lamo et al. (2000) conducted evaluation trials under rainfed conditions. It is proposed that trials under non-limiting conditions should be introduced in future breeding activities to establish Y_P of released varieties or during screening. Establishing Y_P aids in decision making on the level of crop management for profitable and sustainable productivity.

Estimates of Y_P for Uganda are probably reasonably correct, as values were all below the theoretical Y_P (15.9 t ha^{-1}) of rice with irrigation in the tropics (Peng et al. 1999). Like Yoshida (1991), the present study derived amount of incident R_s during a season from diurnal temperature ranges, because of lack of measured R_s records. However, derivation of R_s in this way can lead to errors in estimated maximum Y_P (le Roux et al.2016). Actual experiments will therefore need to be done at some sites to demonstrate maximum achievable yields.

It was noted that the likely low Y_P for the short-duration variety could be because some agronomic practices (spacing specifically) were not optimised. Radiation use efficiency of 2.1 g MJ^{-1} of intercepted R_s with maximum light interception of about 60% and LAI of less than 2.0 m^2 m^{-2}, suggested that growth could have been improved by higher plant density. This is in contrast to reports of Nerica 4 grown under similar density (100 plants m^{-2}), in which canopy closure was almost achieved, with approximately 95% fractional interception of PAR and LAI of about 4.0. Investigations on optimising Y_P of upland rice based on planting density are thus required.

Simulated Y_w declined with WS during reproductive growth stages. Previous field studies showed that grain yield of rice was greatly reduced by WS occurring around panicle initiation or just before flowering (Hossain et al. 2002; Okada et al. 2002; Kato et al. 2006; Xangsayasane et al. 2014). Terminal drought was common in many sites, resulting in advanced crop maturity, even under F–R system in certain locations. Disruption of grain filling and lower mass of single grains by terminal drought in rice (Wopereis et al. 1996) may explain the low rice grain yields measured by researchers in the African equatorial region. This study recommends long-term simulations to advise on feasibility of varying sowing times to match seasonal crop ET requirement with rainfall distribution in AEZs of Uganda to close water-limited yield gaps.

6.4 Conclusions

This study investigated the application of a crop simulation model to explain growth and yield of upland rice, quantify yield gaps and evaluate adaptive cropping strategies under rainfed conditions along the equatorial tropics. The parameterised SWB-Sci model for well-watered, nutrient non-limiting conditions was able to simulate rice grain yield and phenology well under water limiting conditions in rainfed crop in this tropical region. Simulated potential yield (10 t ha^{-1}) of upland rice in Uganda is well above the highest yields of 4.5 t ha^{-1} measured under rainfed conditions. Yield gaps of rainfed crops with nutrients limiting are thus large, at least 40%. Water stress is the principal yield limitation accounting for large yield gaps in AEZs close to the equator. Yield gaps are dictated by rainfall regimes, being very variable in bimodal rainfall conditions close to the equator, rather than the seasonal rainfall patterns, which in contrast to the general perception. The water-limited to potential yield ratio for a medium-duration variety did not significantly differ between seasons in two AEZs with a bimodal rainfall pattern (the Lake Victoria Basin and the Eastern Savannah Moist Farming system). Conversely, in unimodal rainfall zones, simulated yield for the short-duration variety was not considerably affected by WS in either of the two planting seasons (14% and 25% yield gap).

CHAPTER 7

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Rice (*Oryza sativa* L.) can be grown on uplands, lowlands, saline and hydromorphic soils or environments. Genotypes and management practices differ across these systems. In equatorial African regions, rice production is a tale of several small-scale farmers who cultivate on rainfed uplands (non-flooded aerobic soils) with limited or no fertilisers, which is not sustainable. New Rice for Africa (NERICA) is the popular germplasm grown on uplands. Compared to lowland rice, upland rice can be rotated with most upland crops, thereby conserving soil fertility. Malaria (a leading killer disease in SSA, transmitted by *Anopheles* mosquitoes) is prevalent with lowland rice cultivation, and can be mitigated through upland rice production. Low crop yields undermine the significance of rice to food and income status. It is therefore important to quantify yield gaps and production targets, and identify the principal yield limitations at an agroecological scale, so as to advise producers on cropping strategies to improve system productivity.

To understand the impact of WS on growth, phenology, yield, WUE and sink-source relations, rice was grown in a rain-out shelter under different irrigation water regimes (well-watered or irrigation withheld during key phenological stages) for two seasons. Water stress during PI caused severe yield reduction (~70%) compared to stress during tillering, anthesis and grain filling (~25%), relative to the control. In addition to high yield loss, soil evaporation constituted a larger fraction of crop ET, due to considerable reduction in fraction of intercepted radiation by the canopy, with stress during PI. Aligning the cropping system to limit WS during critical stages of growth is recommended to reduce yield depression. Furthermore, findings suggest that excessive tillering should be controlled, or a medium-tillering variety be selected to cope with WS during early reproductive stages. Considerable water savings (14–22%) without substantial yield penalty are possible when water is withheld during some growth stages, which offers opportunities for designing water saving technologies.

There was a significant delay in the days to booting, first flowering and anthesis as a result of stress during PI, compared to the control. It is reported that WS during and before flowering stage speeds up development of most similar upland crops (C_3 grasses and tillering crops), for example wheat (*Triticum aestivum*), which is regarded less sensitive to water deficit than rice. Physiological studies are needed to explain the mechanisms to cope with reproductive WS. While development was delayed under stress during panicle initiation and tillering stages and growth was reduced, the recovery source size was greater than the well-watered control at the same development stage. In evaluating WS impacts on rice growth, the development stage should be considered, because it was noted that the source size can be equal between the different development stages.

Delaying of flowering and anthesis is not dependent on tiller abortion. This study revealed that there is no association between tillering ability during and after WS, and thermal time to reach reproductive stages. Thermal time response has a strong bearing on phenology and crop duration of upland rice in water-limited environments.

In another study, N- and water use efficiencies were investigated under water non-limiting conditions and varying N rates (0–160 kg N ha^{-1}) for two years on the same field. Variety Nerica 10 was grown in rotation with unfertilised winter wheat to mop up residual N from the soil. Grain yield was variable between seasons, even without N fertilisers, due to distinctly different rainfall distribution. Too much rainfall during early growth in one season and much water in late growth stages in the other affected crop performance differently. Nitrogen fertiliser had a positive effect on grain yield (yields more than doubled at the optimum N rate of 120 kg N ha^{-1}) and N had a mild effect on protein quality. Average grain N (1.82%) was, however, not significantly different between most N fertilised treatments. It is noted that grain yield for the short-duration variety was 5.5 t ha^{-1}, but a higher yield than this is achievable with optimisation of agronomic practices, especially planting density. A density of 100 plants m^{-2} resulted in maximum fractional interception of approximately 60%, which is low. Thus, mutual shading could not be blamed for the high tiller number without panicles in N fertilised treatments. To enhance grain yields, N fertiliser should be applied to promote reproductive growth, because while spikelets increased at high N rates, they were poorly filled.

Irrigation amount in both seasons increased with increasing N fertiliser rates, which was attributed to the effect thereof on rooting depth and biomass production. Nitrogen stress limited water consumption by reducing effective rooting depth and canopy growth. Nitrogen stress also delayed tiller development, resulting in a longer time to reach maximum tillering, and a considerable delay in flowering, especially for the zero N and 40 kg N ha^{-1} treatments.

High water levels (rainfall) during the early vegetative stage reduced grain yield, WUE and harvest index. Variable WUE between seasons, especially at the optimum N rate of 120 kg N ha^{-1} (5.91 and 9.26 kg ha^{-1} mm^{-1}), can be explained by different tiller development, canopy growth and yields. Results indicate that resource use efficiencies in upland rice declined with increasing N rates, a challenge to rice growers who strive to achieve higher NUE. The findings revealed that while upland rice luxuriously took up N (estimated apparent recovery of 56% and 44% in the two seasons), a mechanism that was beneficial in the early wet season, N was not efficiently utilised to produce grain. The highest crop N uptake was estimated to be between 120 and 130 kg N ha^{-1} and at these N uptake levels, grain yield increased at a diminishing rate in Y_1 and dropped by approximately 1.6 t ha^{-1} relative to the maximum yield in Y_2. These findings will help farmers, agronomists and breeders to better understand opportunities to improve rice yields under non-limiting conditions and traits which are stable over seasons.

Historically, rice yields in uplands have not matched those in lowland under best management practices in different regions of the world. This study reported that grain yield for Nerica 4 variety was high (up to 7.2 t ha^{-1}), which closely matches high yields in lowlands. Of practical relevance, water inputs (approx. 800 mm over four months) in the present study are lower, compared to levels used to achieve similar yields in lowlands.

A literature search on rice production systems in the equatorial region (the case of Uganda) revealed the following: Grain yields limited by water and nitrogen (Y_t) are variable (0.34–3.86

t ha^{-1}). In some seasons, high grain yield (4–5.2 t ha^{-1}) were measured with N fertilisers under rainfed conditions, but in other cases adequate fertilisers did not considerably improve yield. Low yields measured under adequate fertilisation in seasons with moderate rainfall suggests that several agronomic practices need to be optimised to raise yields. As secondary data was inadequate in terms of site-specific reference yields, improved reporting of results is needed in future agronomic studies.

This study is one of few that determined crop model parameters for upland rice. High radiation use efficiency (2.10 g aboveground dry matter MJ^{-1} intercepted solar radiation) and high contribution of pre-anthesis assimilates may explain the high yields of upland rice measured under irrigation.

The parameterised SWB-Sci model was useful in predicting water uptake, growth and yield of upland rice under WS at different phenological stages. However, when compared to measured trial data, the model underestimated leaf area index after recovery from stress imposed at PI. Accurate modelling of rice growth when WS is applied in the reproductive stages will require the introduction of an additional set of parameters to capture canopy regrowth from new tillers and extended canopy duration. Nevertheless, WS in this study may have been more severe than what is commonly experienced in field conditions, and this should not be a concern when estimating grain yield under similar scenarios.

The SWB-Sci model was robust enough to predict grain yield across research sites in Uganda, based on statistical similarity between paired observed and simulated data and good performance was generally observed (e.g. $R^2 > 0.6$, RMSE < 2.0 t ha^{-1} and MDE < 46%). The model simulated potential grain yields of about 10 t ha^{-1} for Nerica 4 and 7 t ha^{-1} for Nerica 10, which indicates that the residual yield gap is moderate.

With low input rice cultivation in Uganda, results suggest that farmers have to increase the current yields by about 70% of the water-limited yield to close the Y_a/Y_w gap. There is need to identify local practices to increase rainfall efficiency, especially in areas in the NMF and some pockets in the MWZ with relatively high yields under rainfed conditions.

The ratio of measured attainable (yield limited by N and water stresses) to simulated potential yield (yield with no growth limitations) was similar between varieties and the minimum yield gap is 40% of the Y_P. With respect to water limitations singly, the yield gaps were small in the unimodal rainfall zones over the simulation period. The average water-limited to potential yield ratio (0.12–0.86) across AEZs, was highest in the NMF and lowest in the SWS and ESAR.

To answer key agronomic questions on yield gaps and propose strategic practices, scenarios of management and cropping systems were analysed. Simulations were then performed for combinations of scenarios in other principal rice growing areas in Uganda, in addition to the research sites. Water-limited yield gaps differed between the first and the second season, rainfall regimes and AEZs. A large water-limited yield gap for the medium-duration variety (Nerica 4) is very likely in the Eastern Savannah Moist medium-altitude system, Lake Victoria Basin and Lake Albert Crescent, based on a low maximum Y_w/Y_P ratio of 0.4 over the 2008–2012 simulation period. The short-duration variety (Nerica 10) appears to be suitable for these three AEZs, because the Y_w/Y_P ratio was rarely below 0.52. Between seasons, the yield gap of Nerica 10 did not significantly differ in the Lake Albert Crescent zone and the Eastern Semi-Arid Mid altitude zone. Findings indicated that farmers in rice locations slightly above the equator (~2.28^o–3.28^o N) and very close to the equator (~0.68^o–1.53^o N) may not benefit with choice of seasons to grow the short-duration variety.

By practising a fallow period in the first season, a single rice crop per annum could be a feasible system to enhance rice production in the water-limited AEZs of the SWS and ESAR. Grain yields per annum for a long fallow scenario (fallow the entire first season-sow rice) was similar to that for a shortened fallow (fallow three to five weeks late-sow rice). Delayed sowing in the second season following a long fallow period resulted in better chances of high annual yields, compared to other possible combinations of a fallow period-sowing date scenario. Such a cropping system will be beneficial if farm labour is scarce at the onset of the season.

A wide array of soil water conservation measures can be adopted to aid farmers to achieve yields well-above current yields. However, soil type needs to be considered in the ESAR (because soils are predominantly sandy) if excessive drainage losses and its impacts are to be minimised in a fallow-rice system. This is a concern because water balance simulations showed that in some cases, drainage occurred during the crop growth period, meaning that a loss of fertiliser and water is likely.

Double rice crops per annum involving a medium-duration, high yielding variety is suitable in areas with a unimodal rainfall pattern in view of maximising yields per annum. In AEZs with a different rainfall pattern, modelled data supports the proposition of introducing a short-duration variety, as opposed to the medium-duration in the first season in low yielding AEZs.

This body of work identified the following opportunities for future research:

- Planting densities should be revised per rice variety, especially when optimising N fertiliser rates and under rainfed (water stress) conditions. Related to this, optimum N rates and applications at specific stages should be investigated for rice varieties of different durations.
- The significance of tillering ability to cope with WS early in the season was highlighted. Establishing the minimum number of tillers required to flower is key in enhancing grain yield under WS conditions.
- Detailed root studies in upland rice should be done to quantify root growth and development under WS as increased rooting depth was specific to WS during panicle initiation.
- There is a need to determine potential yields of upland rice in the tropics by conducting field experiments under non-limiting conditions in diverse environments.
- Long-term simulations are required to recommend best-suited adaptive practices to AEZs and this requires increasing availability of and access to long-term weather data.

- There is need for more widely distributed weather stations in the different AEZs. For cardinal weather parameters, at least rain gauges and thermometers should be installed in administrative units within agricultural extension service systems.

REFERENCES

Asch M, Dingkuhn M. 1999. Phenological responses of *Oryza sativa* L., *O. glaberrima* and inter-specific rice cultivars on a toposequence in West Africa. *Euphytica* 110: 109–126.

Addiscott TM, Wagenet RJ. 1985. A simple method for combing soil properties that show variability. *Soil Science Society of America journal* 49: 1365–1369.

Africa Rice Centre (ARC). 2005. Overview: Rice in Africa. Module 1. Africa Rice Centre Brief. Contonu, Benin. 9 p. Available at www.africanrice.orgpublications/nerica-com/module.Pdf (accessed 01 April 2013).

Africa Rice Centre (ARC). 2007. Africa Rice Trends: Overview of recent developments in the sub-Saharan African rice sector. Africa Rice Centre Brief. Contonu, Benin. 10 p. Available at www.africanrice.orgpublications.html (accessed 01 April 2013).

Agricultural Productivity Enhancement Program (APEP) 2005. "Commodities: Rice." Available at www.apepuganda.org/htm/commodities_rice (accessed 06 January 2012).

AgriLASA, 2004. Agri Laboratory Association of Southern Africa. Soil Handbook. pp 1–109.

Ahuja LR, Ma L, Howell TA. 2002. Agricultural system models. *Field Research and Technology Transfer*. CRC press. New York, USA.

Akinbile CO, Ebd El-Latif, Abdullah R, Yusoff MS. 2011. Rice production and water use efficiency for self-sufficiency in Malaysia. A review. *Trends in Applied Sciences Research* 6: 1127– 1140.

Alliance for a Green Revolution in Africa (AGRA). Growing Africa's Agriculture. Going Beyond demos to transform African Agriculture. Available at https://agra.org/wp-content/uploads/2016/09/Going-Beyond-Demos. 140 p. (accessed 12 July 2017).

Allen RG, Pereira LS, Raes D, Smith M. 1998. Food and Agriculture Organization of the United Nations (FAO). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Rome, Italy. 137 p.

Alou IN, Kakeeto R, Akio G. 2012. Effect of weeding regimes on yields of NERICA 4 rice in an acidic ferralsol in Lake Albertine Crescent. Proceedings of Minia International Conference for Agriculture and Irrigation in the Nile Basin Countries. El-Minia, Egypt 26th–29th March 2012. 1309–1313.

Amarasingha RPRK, Suriyagodab LDB, Marambe B, Gaydon DS, Galagedarab LW, Punyawardena R, Silva GLLP, Nidumolu U, Howden M. 2015. Simulation of crop and water productivity for rice (*Oryza sativa* L.) using APSIM under diverse agro-climatic conditions and water management techniques in Sri Lanka. *Agricultural Water Management* 160: 132–143.

Angus JF, Bowden JW, Keating BA. 1993. Modelling nutrient responses in the field. *Plant Soil* 155/156: 57–66.

Annandale JG, Benade N, Jovanovic N, Steyn J, Du Sautoy N. 1999. Facilitating irrigation scheduling by means of the Soil Water Balance Model. Water Research Commission Report. No. 753/1/99. Water Research Commission: Pretoria, South Africa.

Annandale JG, Jovanovic NZ. 2000. Crop growth model parameters of 19 summer vegetable varieties for use in mechanistic irrigation scheduling models. *Water South Africa* 26: 67–76.

Annandale JG, Campbell GS, Olivier FC. 2000. Predicting crop water uptake under full and deficit irrigation: an example using pea (*Pisum sativum* L. cv. Puget). *Irrigation Science* 19: 65–72.

Annandale JG, Stirzaker RJ, Singels A, van der Laan M, Laker MC. 2011. Irrigation scheduling research: South African experiences and future prospects. *Water SA* 37 (5): 751–763.

Arai-Sanoh Y, Takai T, Yoshinaga S, Nakano H, Mikiko K, Sakakibara H, Kondo M, Uga Y. 2014. Deep rooting conferred by *DEEPER ROOTING 1* enhances rice yield in paddy fields. Scientific reports. 4; 5563. DOI: 10.1038/srep05563.

Arora VK. 2006. Application of a rice growth and water balance model in an irrigated semi-arid subtropical environment. *Agricultural Water Management* 88: 51–57.

Asch F, Dingkuhn M, Sow A, Audebert A. 2005. Drought-induced changes in rooting patterns and assimilate partitioning between root and shoot in upland rice. *Field Crops Research* 93: 223–236.

AQUAEARTH, University of Pretoria, 2017. Aquifer testing of production boreholes 62, 66 and 67. Report No. AEC0434/01/03/2017/1.0. Available at https://www.aquaearth.co.za.

Basnayake J, Fukai S, Ouk M. 2006. Contribution of potential yield, drought tolerance and escape to adaptation of 15 rice varieties in rainfed lowlands in Cambodia. Proceedings of the Australian Agronomy Conference, Australian Society of Agronomy, Brisbane, Australia.

Bray, RH, Kurtz, LT 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59: 39–45.

Belder P, Bouman BAM, Spiertz JHJ, Peng S, Castaneda AR, Visperas RM. 2005. Crop performance, nitrogen and water use in flooded and aerobic rice. *Plant and Soil* 273: 167–182.

Blum B. 2009. Effective use of water (EWU) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research* 112: 119–123.

Boojung H, Fukai S. 1996. Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions. 2. Phenology, biomass production and yield. *Field Crops Research* 48: 47–55.

Boojung H. 2000. Climatic variability and rice production in rainfed rice in northeast Thailand: risk analysis and management applications. Available at http://www.earthscape.org/rmain/rsites/clch.html (accessed 10 May 2017).

Borga M,Vizzaccaro A. 1996. On the interpolation of hydrologic variables: Formal equivalence of multiquadratic surface fitting and kriging. *Hydrology Journal* 195: 160–171.

Boschetti M, Bocchi S, Stroppiana D, Brivio PA. 2006. Estimation of parameters describing morpho-physiological features of Mediterranean rice varieties for modelling purposes. *Italian Journal of Agrometeorology* 3: 40–49.

Bouman BAM, Wang H, Yang X, Zhao J, Wang C. 2002. Aerobic rice (Han Dao); A new way of growing rice in water-short areas. In: Proceedings of the 12th International Soil Conservation Organisation Conference, 26–31 May, 2002. Beijing, China. Tsinghua University Press, 175-181.Bouman BAM, Humphreys E, Tuong TP, Barker R. 2007. Rice and water. *Advances in Agronomy* 92: 187–237.

Bouman BAM, Kropff MJ, Tuong TP, Wopereis, MCS, ten Berge HFM, van Laar HH. 2001. ORYZA2000. Modelling lowland rice. Los Baños (Philippines): International Rice Research Institute, and Wageningen University, 235 p.

Bouman BAM, Peng S, Castaneda, AR, Vispera RM. 2005. Yield and water use of irrigated tropical aerobic rice systems. *Agricultural Water Management* 74: 87–105.

Bremner JM, Keeney DR. 1966. Determination of isotope-ratio analysis of different forms of nitrogen in soils: 3. Soil Science Society of American Proceedings 30: 577–582.

Campbell, CS, Heilman, JL, McInnes KJ, Wilson LT, Medley JC, Wu G, Cobos DR. 2001. Seasonal variation in radiation use efficiency of irrigated rice. *Agricultural and Forest Meteorology* 110: 45–54.

Cao W, Moss D. 1997. Modelling phasic development in wheat: a conceptual integration of physiological components. *Journal of Agricultural Science* 129: 163–172.

Cassman KG, Gines GC, Dizon MA, Samson MI, Alacantra JM. 1996. Nitrogen-use efficiency from indigenous and applied nitrogen. *Field Crops Research* 47: 1–12.

Caviglia OP, Sadras VO. 2001. Effect of nitrogen supply on crop conductance, water- and radiation-use efficiency of wheat. *Field Crops Research* 69: 259–266.

CGIAR Science Council. 2006. IRRI's upland rice research follow-up review to the 6th IRRI EPMR. Science Council Secretariat, Rome, Italy.

Chang T-T. 1976. Rice. In: Simmonds N W (ed), Evolution of crop plants. pp. 98-104. London: Longman Group Ltd.

Cissoko M, Boisnard A, Press MC, Scholes JD, Rodenburg J. 2011. New rice for Africa (NERICA) varieties exhibit difference levels of post-attachment resistance against the parasitic weeds *Striga hermonthica* and *Striga asiatica. New Phytologist* 192: 952–963.

Clerget B, Bueno C. 2013. The effect of aerobic soil conditions, soil volume and sowing date on the development of four tropical rice varieties grown in the greenhouse. *Functional Plant Biology* 40: 79–88.

Confalonieri R, Bocchi S. 2005. Evaluation of CropSyst for simulating the yield of flooded rice in northern Italy. *European Journal of Agronomy* 23: 315–326.

Cooper PJM, Gregory PJ, Tully D, Harris HC. 1987. Improving water use efficiency of annual crops in rainfed systems of west Asia and North Africa. *Experimental Agriculture* 23: 113–158.

Dasgupta P, Bhabani SD, Soumitra KS. 2015. Soil water potential and recoverable water stress in drought tolerant and susceptible rice varieties. *Agricultural Water Management* 152: 110–118.

Devatgar N, Neishabouri MR, Sepaskhah AR, Soltani A. 2009. Physiological and morphological responses of rice (*O. sativa* L.) to varying water stress management strategies. *International Journal of Plant Production* 3: 19–32.

DeWit CT. 1992. Resource use efficiency in agriculture. *Agricultural Systems* 40: 125–151.

DeWit CT, VanKeulen H. 1987. Modelling production of field crops and its requirements. *Geoderma* 40: 253–265.

Diagne A, Amovin-Assagba E, Futakuchi K, Wopereis MCS. 2013. Estimation of rice cultivated area, number of farming households and yield for major rice growing areas in Africa. In: Wopereis

MCS, Johnson DE, Ahmadi N, Tollens E, Jalloh A (eds.), Realising Africa's rice promise. CAB International, Wallingford, UK. 35–45.

Dingkuhn M, Le Gal. 1996. Effect of drainage date on yield and dry matter partitioning in irrigated rice. *Field Crops Research* 46: 117–176.

Dingkuhn M, De Datta SK, Dörffling, K, Javellana C. 1989. Varietal differences in leaf water potential, leaf net CO_2 assimilation, conductivity and water use efficiency in upland rice. *Australian Journal* of *Agricultural Research* 40: 1183–1192.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE. 1998. Management of phosphorus, potassium, and sulphur in intensive, irrigated lowland rice. *Field Crops Research* 56: 113–138.

Dobermann A, Fairhurst T. 2000. Economics of fertiliser use. In: Rice: Nutrient disorders and nutrient management (1st eds.), Potash and Phosphate Institute (PPI), Potash and Phosphate Institute of Canada (PPIC), and International Rice Research Institute (IRRI) 40-117.

Du W, T C-P, Jiang X-S, Chen GY. 2010. Balance and pollution potential of nitrogen in a typical rice-based agricultural watershed of Yangtze River delta region. [abstract]. *Journal of Ecology and Rural Environment* 26: 9–14

Ebaid RA, El-Refaee IS. 2007. Utilization of rice husk as an organic fertiliser to improve productivity and water use efficiency in rice fields. African Crop Science Conference proceedings. 8: 1923–1928.

Fageria NK, Virupax C, Baligar VC, Jones CA. 2010. *Growth and Mineral Nutrition of Field Crops* (3rd edn). USA: CRC Press. pp 257–311.

Fageria NK, de Morais OP, dos Santos AB. 2010. Nitrogen use efficiency in upland rice genotypes. *Journal of Plant Nutrition* 33: 1696–1711.

Fageria NK. 2007. Yield physiology of rice. *Journal of Plant Nutrition* 30: 843–879.

Fageria NK, Baligar VC. 2005. Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy* 88: 97–185.

Falconnier G, Corbeels M, Boote K, Adam M, Basso B, Ruane A, Affholder F, Ahuja LR, Alou IN, Amouzou KA, Chen Y, Deryng D, Elasayed ML, Faye B, Folorunso A, Gaiser T, Galdos M, Gayler S, Gerardeaux E, Giner M, Grant M, Hoogenboom G, Ibrahim ES, Jones CD, Justes E, Kamali B, Kersebaum KC, Kim SH, Kumar SN, van der Laan M, et al. 2019. Model intercomparison of maize response to climate change in low-input smallholder cropping systems. Poster presented at the 3rd Agriculture and Climate Change Conference Budapest, 24th to 26th March 2019.

Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. 2009. Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development*, Springer Verlag/EDP Sciences/INRA. 29: 185–212.

Fessehazion MK, Annandale JG, Everson CS, Stirzaker RJ, Tesfamariam EH. 2014. Evaluating soil water balance (SWB-Sci) model for water and nitrogen interactions in pasture: example using ryegrass. *Agricultural Water Management* 146: 238–248.

Food and Agricultural Organisation of the United Nations (FAO). 1970. Key to soil units for the soil map of the world. AGL: SI/70/2, WS/A7460, FAO, Rome, Italy, 16 pp.

Food and Agricultural Organisation of the United Nations (FAO/UNEP). 1992. Advisory services to Syria and Uganda on the formulation of the national soils policies. 48 p.

Food and Agricultural Organisation of the United Nations (FAO). 2004. FAO Soil and legacy Maps-Uganda. Available at http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/fao-soil-legacy-maps/en.

Food and Agricultural Organisation of the United Nations (FAO). 2012. The State of Food Insecurity in the World. FAO, Rome. Available at http://www.fao.org/publications (accessed 02 August 2017).

Food and Agricultural Organisation of the United Nations (FAO). 2014. Rice in the shadow of skyscrapers. Policy choices in a dynamic East and Southeast Asian setting. FAO, Rome. Available at http://www.fao.org/publications (accessed 02 February 2020).

Food and Agricultural Organisation of the United Nations (FAO). 2017. Rice market monitor. http://www.fao.org/publications (accessed 02 August 2017).

Food and Agricultural Organisation of the United Nations (FAO). 2013. Food Outlook: Biannual Report on Global Food Markets. June 2013, Rome. Available at http://www.fao.org/publications (accessed 02 August 2017).

Food and Agricultural Organisation of the United Nations (FAO). 2017. Rice market monitor. Production, international trade, rice utilisation and domestic prices. Available at http://www.fao.org/fileadmin/templates/est/comm_markets_monitoring/rice/Images/RMM/RMM-Jul17.pdf (accessed 02 August 2017).

Forum for Agricultural Research in Africa (FARA). 2009. Patterns of change in rice production in Africa: Implications for rice policy development. Forum for Agricultural Research in Africa, Accra, Ghana.
Available at http://www.faraafrica.org/media/uploads/library/docs/Ministerial_Policy_LR.pdf⟩ (accessed 02 April 2013).

Fukai S, Ouk M. 2012. Increased productivity of rainfed lowland rice cropping systems of the Mekong region. *Crop and Pasture Science* 63: 944–973.

Garrity DP, O'Toole JC. 1994. Screening rice for drought resistance at the reproductive phase. *Field Crops Research* 39: 99–10.

George T, Magbanua R, Garrity DP, Tubana BS, Quiton J. 2002. Yield decline of rice associated with successive cropping in aerobic soil. *Agronomy Journal* 94: 981–989.

Ghezehei SB, Annandale JG, Everson CS. 2015. Modelling radiation interception and water balance in agroforestry systems. In: Ong C, Blacl C, Wilson J (eds.), *Tree-crop interactions. Agroforestry in a changing climate*. Walling, Oxfordshire, United Kingdom: CAB International. pp 41–56. Available at http://www.cabi.org (accessed May 25 2017).

Gina K, Burlingame B, Nguyen VN. 2002. Nutritional contribution of rice: Impact of Biotechnology and biodiversity in rice consuming countries. International Rice Commission Article Number, IRC:02/10. Available at https://http://www.fao.org/3/Y6618E/Y6618E00.htm (accessed January 24 2019).

Glaszman JC, Benoit H, Arnaud M. 1984. Classification des riz cultivés (*Oryza sativa* L.). Utilisation de la variabilité isoenzymatique. *Tropical Agronomy* 39: 83–90.

Glaszmann JC. 1985. A varietal classification of Asian cultivated rice (*Oryza sativa* L.) based on isozyme polymorphism. In: Rice Genetics. International Rice Research Institute, Manila Philippines 83–90.

Glaszmann JC. 1987. Isozymes and classification of Asian rice varieties. *Theoretical Applied Genetics* 74: 21–30.

Glaszmann JC, Benoit H, Arnaud M. 1987. Classification dez riz cultivés (*Oryza sativa* L.). Utilization de la variabilité isoenzymatique. *Tropical Agronomy* 39: 83–90.

Global Rice Science Partnership (GRiSP) 2013. Source book for one of the most important economic activities on earth. Rice Almanac 4th edition. Los Baños. International Rice Research Institute, Metro Manila, Philippines.

Goto A, Nishimaki R, Suzuki S, Watanabe F, Takahashi S. 2012. Terrace development applied as a water harvesting technology for stable NERICA Production in Uganda. *Journal of Arid Land Studies* 22: 243–246.

Heinemann AB, Stone LF, Fageria NK. 2011. Transpiration rate response to water deficit during vegetative and reproductive phases of upland rice varieties. *Scientia Agricola* (Piracicaba, Braz.) 68: 24–30.

Hsiao TC, Xu LK. 2000. Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport. *Journal of Experimental Botany* 51: 1595–1616.

Humphreys E, Timsina J. (eds.). 2002. Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting. Proceedings of a workshop held at CSIRO Land and Water, Griffith on 25–28 February 2002. CSIRO Land and Water, Griffith, NSW 2680, Australia. 118 p.

Imanywoha JB. 2001. Rice. In: Mukiibi JK (ed.), *Agriculture in Uganda* (Vol. 2). Crops. Fountain Publishers/CTA/NARO. 70 p.

Imanywoha J, Kibwika P, Walusimbi M, Bigirwa G, Lamo J. 2004. Adaptability of 16 upland rice varieties to two moisture regimes. In: Poland D, Sawkins M, Ribaut JM, Hoisington (eds.), *Resilient crops for water limited environments*. Proceedings of workshop held in Cuenavarca Mexico, 24–28 May 2008. pp 4–5.

International Rice Research Institute (IRRI) 2002. Rice Today. International Rice Congress, Beijing, China. 16–20 September 2002. Published by IRRI, Philippines. 1: 31 p.

International Rice Research Institute (IRRI). 2009. Natural resource management for poverty reduction and environmental sustainability in fragile rice-based systems. IRRI limited proceedings, Metro Manila, Philippines. Available at http://www.irri.org (accessed on 20 July 2015).

International Rice Research Institute (IRRI) 2012. Revising Setgen – IRRI Rice knowledge Bank. Available at http://www.knowledgebank.irri.org/ricebreedingcourse (accessed on 17 February 2020).

Isabirye M, Mwesige D, Ssali H, Magunda M, Lwasa J. 2004. Soil resources information and linkages to agricultural production. *Uganda Journal of Agricultural Sciences* 9: 215–221.

James J, Tas J. 1984. *Histochemical protein staining methods*. Microscopy handbooks 04. Royal Oxford University Press, Microscopy Society, New York, USA. 591 p.

Jensen CR, Mogensen VO, Poulsen HH, Henson IE, Aagot S, Hansen E, Ali M, Wollenweber B. 1998. Soil water matric potential rather than water content determines drought responses in field-grown lupin (*Lupinus angustifolius*). *Australian Journal of Plant Physiology* 25: 253–363.

Jones MP, Dingkuhn M, Aluko GK, Semon M. 1997. Interspecific *O. sativa* L. x *O. glaberrima* Steud. Progenies in upland rice improvement. *Euphytica* 92: 237–246.

Kaizzi CK, Ssali H, Vlek PLG. 2004. The potential of Velvet bean (*Mucuna pruriens*) and N fertilizers in maize production on contrasting soils and agroecological zones of East Uganda. *Nutrient Cycling in Agroecosystems* 68: 59–72.

Kaizzi CK. 2013. Application of the GYGA approach to Uganda. Details from collected literature for Uganda to be used for crop modelling. Available at http://.www.yieldgap.org/gygamaps (accessed 22 August 2016).

Kaizzi KC, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nasamba A, Odama E, Wortmann CS. 2014. Upland rice response to nutrient application in Uganda. *African Journal of Plant Science* 89: 416–425.

Kaizzi KC, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Musinguzi P, Ebanyat P, Hyuha T, Wortmann CS. 2012. Sorghum response to fertilizer and nitrogen use efficiency in Uganda. *Agronomy Journal* 104: 83–90.

Kaizzi KC, Byalebeka J, Wortmann CS, Mamo M. 2007. Low input approaches for soil fertility management in semiarid eastern Uganda. *Agronomy Journal* 99: 847–853.

Kamara AY, Ekeleme F, Omoigui LO, Oikeh SO, Chikoye D, Tegbaru A. 2010. Response of upland rice varieties to nitrogen fertiliser in the savannas of Nigeria. *Agronomy Journal* 102: 333–339.

Kapoor N, Arya A, Siddiqui MA, Kumar H, Amir A. 2011. Physiological and biochemical changes during seed deterioration in aged seeds of rice (*Oryza sativa* L.). *American Journal of Plant Physiology* 69 (1): 28–35.

Karam F, Kabalan R, Breidi J, Rouphael Y, Oweis T. 2009. Yield and water production functions of two durum wheat varieties grown under different irrigation and nitrogen regimes. *Agricultural Water Management* 96: 603–615.

Kato S, Kosaka H, Hara S. 1928. On the affinity of rice varieties as shown by the fertility of rice plants. Centre for Agricultural Institute Kyushu Imperial University 2: 76–241.

Kato Y, Katsura K. 2014. Rice Adaptation to Aerobic Soils: Physiological considerations and implications for agronomy. *Plant Production Science* 17: 1–12.

Kato Y, Okami M, Katsura K. 2009. Yield potential and water use efficiency of aerobic rice (*Oryza sativa* L.) in Japan. *Fields Crop Research* 113: 328–334.

Kato Y, Kamoshita A, Yamagishi J, Abe J. 2006a. Growth of three rice (*Oryza sativa* L.) varieties under upland conditions with different levels of water supply. 1. Nitrogen content and dry matter production. *Plant Production Science* 9: 422–434.

Kato Y, Kamoshita A, Yamgishi J. 2006b. Growth of three varieties (*Oryza sativa* L.) under upland conditions with different levels of water supply.2. Grain yield. *Plant Production Science* 9: 435–445.

Kato Y, Kamoshita A, Yamgishi J. 2008. Preflowering abortion reduces spikelet number in upland rice (*Oryza sativa* L.) under water stress. *Crop Science* 48: 2389–2395.

Kato Y, Katsura K. 2014. Adapting to aerobic soils: Physiological considerations and implications for agronomy. *Plant Production Science* 17: 1–12.

Kato Y, Okami M. 2010. Root growth dynamics growth and stomatal behaviour of rice (*Oryza sativa* L.) grown under aerobic and anaerobic flooded conditions in Japan. *Fields Crops Research* 117: 9–17.

Kato Y, Okami M, Katsura K. 2009. Yield potential and water use efficiency of aerobic rice (*Oryza sativa* L.) in Japan. *Field Crops Research* 113: 328–334.

Keeney DR, Nelson, DW. 1982. Nitrogen-inorganic forms. In: Page AL (ed.), *Methods of soil analysis. Part 2*. American Society of Agronomy. Madison Wis. Soil Science Society of America 1997. Glossary of soil science terms by the committee of terminology. Madison, Wis. Technicon: Soil Science Society of America.

Kijima Y, Otsuka K, Sserunkuuma D. 2008. Assessment of a NERICA on income and poverty in Central and Western Uganda. FASID Discussion Paper Series on International Development Strategies. No. 2007-10-001. 46 p.

Kijoji AA, Nchimbi-Msolla S, Kanyeka ZL, Serraj R, Henry A. 2014. Linking root traits and grain yield for rainfed rice in sub-Saharan Africa: Response of *Oryza sativa* x *Oryza glaberrima* introgression lines under drought. *Field Crops Research* 165: 25–35.

Koné B, Amadji GL, Aliou S, Diatta S, Akakpo C. 2011. Nutrient constraint and yield potential of rice on upland soil in the south of the Dahoumey gap of West Africa. *Archives of Agronomy and Soil Science* 57: 763–774.

Koné B, Fofana M, Sorho F, Diatta S, Ogunbayo A, Sie M. 2014. Nutrient constraint of rainfed rice production in foot slope soil of Guinea Forest in Côte d’Ivoire. *Archives of Agronomy and Soil Science* 60: 735–746.

Kondo M, Murty VRM, Aragones DV. 2000. Characteristics of root growth and water uptake from soil in upland rice and maize under water stress. *Soil Science and Plant Nutrition* 46: 721–732.

Kondo M, Pablico PP, Aragones DV, Agbisit R, Abe J, Morita S, Courtois B. 2003. Genotypic and environmental variations in root morphology in rice genotypes under upland field conditions. *Plant and Soil* 255: 189–200.

Kondo M, Singh V, Agbisit R, Murty MVR. 2005. Yield response to urea and controlled-release urea as affected by water supply in tropical upland rice. *Journal of Plant Nutrition* 28: 201–219.

Kropff MJ, van Laar HH, Matthews RB. 1994. ORYZA1: An ecophysiological model for irrigated rice production. SARP Research Proceedings, ABDLO, Wageningen, The Netherlands.

Kumar R, Sarawgi AK, Ramos C, Amarante ST, Ismail AM, Wade WJ. 2006. Partitioning of dry matter during drought stress in rainfed lowland rice. *Field Crops Research* 96: 455– 465.

Kuo S-F, Ho S-S, Liu C-W. 2006. Estimation irrigation water requirements with derived crop coefficients for upland and paddy crops in ChiaNan Irrigation Association, Taiwan. *Agricultural Water Management* 82: 433–451.

Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B. 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research* 81: 159–180.

Lafitte HR, Yongsheng G, Yan S, Li1 ZK. 2007. Whole plant responses, key processes, and adaptation to drought stress: the case of rice. *Journal of Experimental Botany* 58: 169–175.

Lamo J, Bigirwa G, Walusimbi M, Kyetere D, Kikafunda J, Kalule T. 2010. First NERICA rice released in Uganda tops farmers' rankings. Genetic resources. International Rice Research Institute Notes 2010, 0117–4185.

Lampayan RM, Bouman BAM, de Dios JL, Espiritu AJ, Soriana JB, Lactaoen AT, Faronilo JE, Thant KM. 2010. Yield of aerobic rice in rainfed lowlands of the Philippines as affected by nitrogen management and row spacing. *Field Crops Research* 116: 165–174.

Latiffe HR, Courtois B, Arrandeau M. 2002. Genetic improvement of rice in aerobic systems: Progress from yield to genes. *Field Crops Research* 75: 171–190.

Legates DR, McCabe G.J. 1999. Evaluating the use of 'goodness-of-fit' measures in hydrologic and hydroclimatic model validation. *Water Resources Research* 35: 233–241.

Lenka S, Singh AK, Lenka NK. 2013. Soil water and nitrogen interaction effect on residual soil nitrate and crop nitrogen recovery under maize-wheat cropping system in the semi-arid region of northern India. *Agriculture Ecosystems and Environment* 179: 108–115.

le Roux B, van der Laan M, Vahrmeijer T, Annandale JG, Bristow KL. 2016. Estimating water foot prints of vegetable crops: Influence of growing season, solar radiation data and functional unit. *Water* 8: 473.

Liebig J. 1841. Organic chemistry in its applications to agriculture and physiology. Cambridge, J. Owen.

Lilley JM, Fukai S. 1994. Effect of timing and severity of water deficit on four diverse rice varieties. III. Phenolological development, crop growth and yield. *Field Crops Research* 37: 225 –234.

Lodin JB, Jirström M, Mugenyi M. 2005. New seeds and women's welfare: A revolution revisited — The case of NERICA upland rice and gendered labour dynamics in Hoima District, Uganda. Second Africa Rice Congress, Bamako, Mali, 22–26 March 2000: Innovation and Partnerships to realize Africa's rice potential 4. Available at www.africarice.org/workshop/arc.

Lopes SM, Reynolds MP. 2010. Partitioning of assimilates is associated with cooler canopies and increased yield under drought in wheat. *Functional Plant Biology* 37: 147– 156.

Lutz JF, 1965. Glossary of Soil Science Terms. *Soil Science Society of America Proceedings* 29: 330–351.

MacVicar CN, De Villiers JM, Loxton RF, Verster E, Lamprecht UN, Merry weather FR, Le Roux, Van Rooyen TH, Harmse HJ, Von M. 1977. Soil classification: A binomial system for South Africa. Sci. Bull. 390. Department of Agriculture: Pretoria.

Maji AT, Gana A S, Ukwungwu MN. 2011. Responses of *Oryza glaberrima* Steud accessions to rice stresses and their morphological characteristics. *African Journal of Agricultural Research* 6: 732–737.

Mall RK, Aggarwal PK. 2002. Climate change and rice yields in diverse agro-environments of India. I. Evaluation of impact assessment model. *Climate change* 52: 315–330.

Manjaliwa JGM, Tenywa MM, Bamanya D, Majugu W, Isabirye P, Nandozi C, Nampijja J, Musinguzi P, Nimusiima A, Luswata KC, Rao KPC, Bonabana J, Bagamba F, Sebuliba E, Azanga E, Sridher G. 2015. Characterisation of historical seasonal and annual rainfall and temperature trends in selected climatological homogenous rainfall zones of Uganda. *Global Journal of Science Frontier Research* 15 (4): 21–39.

Mathews RB, Wassmann R, Arah J. 2000. Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. I. Model development. *Nutrient Cycling in Agroecosystems* 58: 141–159.

Mathobo R, Marais D, Steyn JM. 2018. Calibration and validation of the SWB model for dry beans (*Phaseolus vulgaris* L.) at different drought stress levels. *Agricultural Water Management* 2002: 113–121.

Matsunami M, Matsunami T, Kokubun M. 2009. Growth and yield of New Rice for Africa (NERICAs) under different ecosystems and nitrogen Levels. *Plant Production Science* 12: 381–389.

Matsuo, N . 1952. Genecological studies on cultivated rice (in Japanese). Bulletin Natural Institute of Agricultural Science in Japan D 3: 1–111.

Matsuo N, Ozawa K, Mochizuki T. 2010. Physiological and morphological traits related to water use by three rice (*Oryza sativa* L.) genotypes grown under aerobic rice systems. *Plant and Soil* 335: 349–361.

Matsumoto S, Tsuboi T, Asea G, Maruyama A, Kikuchi M, Takagaki M. 2014. Water response of upland rice varieties adopted in sub-Saharan Africa: A water application. *Journal of Rice Research* 2: 121.

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF). 2010. The Agricultural Sector Development Strategy and Investment Plan 2010/2011 -2014/15.

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF). 2012. Uganda National Rice Development Strategy, 2008–2018. Available at https://riceforafrica.net/images/stories/PDF/nrds_uganda_en.pdf (accessed 17 August 2017).

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF). 2009. Uganda National Rice Development Strategy (UNRDS) second draft. Available at https://www.jica.go.jp (accessed 15 February 2013).

Minyamoto K, Marutyama A, Haneishi Y, Matsumoto S, Tsuboi T, Asea G, Okello S, Tkagaki M, Kikuchi M. 2012. NERICA cultivation and its yield determinants: The Case of upland rice Farmers in Namulonge, Central Uganda. *Journal of Agricultural Science* 4: 120–135.

Monteith J.L. 1977. Climate and efficiency of crop production in Britain.

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers* 50 (3): 885–900.

Mubiru DN, Komutunga E, Agona A, Apok A, Ngara N. 2012. Characterising agrometeorological climate risks and uncertainties: Crop production in Uganda. *South African Journal of Science* 108 (3/4): Article #470.

Murata Y, Iyama J, Himeda M, Izumi S, Kawabe A, Kanzaki Y. 1966. Studies on the deep-plowing, dense-planting cultivation of rice plants from the point of view of photosynthesis and production of dry matter. Bull. National lnstiute of Agricultural Sciences, Japan, Ser. D, 15:1–53.

Monteith JL 1977. Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London*. Series B: 281: 277–294.

New Vision 2019. As it happened: Museveni’s New Year address. The President’s new year address to the nation on 31 December 2018. Available at https://www.newvision.co.ug/new_vision/news/1491957/live-museveni-delivers-message (accessed 01 January 2019).

Nanfumba D, Tenywa MM, Okui O, Majaliwa MJG, Wasige JE, Lufafa A, Musiime O.2011. Characterisation of Anopheles Mosquitoes breeding habitats in lowland rice fields in Uganda. *Nature and Science* 9: 44–57.

National Crop Resources Research Institute (NaCRRI). 2010. Rice cultivation handbook. NaCRRI and JICA, Kampala, Uganda.

National Environment Management Authority (NEMA). 2008. National implementation plan of the Stockholm convention on persistent organic pollutants in Uganda. National Environment Management Authority (NEMA), Kampala. Available at http://www.nemaug.org/disrictProfiles/HOIMA.pdf (accessed 10 July 2018).

National Environment Management Authority (NEMA). 2003. Hoima District Environment Report. Last modified on July 17 2003. Available at http://www.nemaug.org/disrictProfiles/HOIMA.pdf (accessed 06 January 2012).

Ndjiondjop MN, Semagn K, Cissoko M, Jones MP, McCouch S. 1998. Molecular characteristics of NERICA lines. Unit 1 molecular profiling of NERICA lines. Available at http://www.africarice.org/publications/nerica-comp/Nerica%20Compedium/(accessed 25.05.14).

Nsubuga FWN, Botai OJ, Olwoch JM, deW Rautenbach CJ, Bevis Y, Adetunji AO. 2014. The nature of rainfall in the main drainage sub-basins of Uganda. *Hydrological Sciences Journal* 59: 278–299.

Ogallo LA. 1989. The spatial and temporal patterns of the East African seasonal rainfall derived from principle component analysis. *International Journal of Climatology* 9: 145–167.

Ogbazghi ZM, Tesfamariam EH, Annandale, JG. 2016. Modelling N mineralisation from sludge-amended soils across agro-ecological zones: A case study from South Africa. *Ecological modelling* 322: 19 –30.

Oikeh SO, Nwilene F, Diatta S, Osiname S, Touré O, Okeleye KA. 2008. Responses of upland NERICA rice to nitrogen and phosphorus in forest agroecosystem. *Agronomy Journal* 100: 735–741.

Oikeh SO, Touré A, Sidibé B, Nianga A, Semon M, Sokei Y, Mariko M. 2009. Responses of upland NERICA® rice varieties to nitrogen and plant density. *Archives of Agronomy and Soil Science* 55: 301–314.

Oka HI, Chang WT. 1959. The impact of cultivation on populations of wild rice, *Oryza sativa* f. *spontanea*. *Phyton* 13: 105–117.

Okada K, Kondo M, Ando H, Kakuda K. 2002. Water uptake under water stress at panicle initiation stage in upland rice as affected by previous soil water regimes. *Soil Science and Plant Nutrition* 48: 151–158.

Okonya JS, Brigitte L, Maass L. 2014. Potential of cowpea variety mixtures to increase yield stability in subsistence agriculture: Preliminary results. *International Journal of Agronomy* Article ID 515629. http://dx.doi.org/10.1155/2014/515629.

Onaga G, Asea G, Lamo J, Kikafunda J, Bigirwa G. 2012. Comparison of response to nitrogen between Upland NERICAs and ITA (*Oryza sativa*) rice Varieties. *Journal of Agricultural Science* 4: 197–205.

Oonyu J. 2011. Upland rice growing: A potential solution to declining crop yields and the degradation of the Doho wetlands, Butaleja district-Uganda. *African Journal of Agricultural Research* 6: 2774–2783.

Otim GA, Mubiru DN, Lwasa J, Namakula J, Nanyeenya W, Okello R, Elem J. 2015. Evaluating permanent planting basin for optimum plant populations of maize and beans. *Journal of Environmental and Agricultural Sciences* 2: 2313–8629.

O'Toole JC. 1982. Adapatation of rice to drought-prone environments. Drought resistance in crops with emphasis on rice. International Rice Research Institute, Manila, Philippines 195–213.

Parent B, Suard B, Seraraj R, Tardieu F. 2010. Rice leaf growth and water potential are resilient to evaporative demand once the effects of root system are neutralized. *Plant*, *Cell and Environment* 33: 1256–1267.

Passioura JB, Angus JF. 2010. Improving Productivity of Crops in Water-Limited Environments. In: Donald LS (eds.), *Advances in Agronomy* 106: 37–75.

Peng S, Khush GS, Cassman KG. 1994. Evolution of the new plant ideotype for increased yield potential. Plant type and rice yield potential in retrospect. In: Cassman KG (ed.), Breaking the yield barrier. Proceedings of a workshop on rice yield potential in favorable environments. International Rice Research Institute, 29 November - 4 December 1993.

Peng S, Garcia SV, Laza RC, Sanico AL, Visperas RM, Cassman KG. 1999. Increased N-use efficiency using a chlorophyll meter on high yielding irrigated rice. *Field Crops Research* 47: 243–252.

Peng S, Huang J, Zhong X, Yang J, Wang G, Zou Y, et al. 2002. Research strategy in improving fertilizer-nitrogen use efficiency of irrigated rice in China. *Scientia Agricola Sinica* 35: 1095–1103.

Philips J, McIntyre B. 2000. ENSO and interannual rainfall variability in Uganda: Implications for agricultural management. *International Journal of Climatology* 20: 171–182.

Plan for Modernisation of Agriculture (PMA). 2009. Rice value chains in the Acholi and Lango sub-regions. Kampala: Plan for the Modernisation of Agriculture Secretariat.

Power JF. 1983. Soil management for efficient water use: Soil fertility. In: Taylor HM, Jordan WR, Sinclair TR (eds.), *Limitation to efficient water use in crop production*. Madison, Wisconsin: American Society of Agronomy, Crop Society of America, Soil Science Society of America. pp 461–470.

Prasertsak A, Fukai S. 1997. Nitrogen availability and water stress interaction on rice growth and yield. *Field Crops Research* 52: 249 –260.

Price AH, Steele KA, Gorham J, Bridges JM, Moore BJ, Evans JL, Richardson P, Jones RGW. 2002. Upland rice grown in soil-filled chambers and exposed to contrasting water deficits regimes root distribution, water use and plant water status. *Field Crops Research* 76: 11–24.

Rebolledo MC, Luquet D, Courtois B, Henry A, Soulié JC, Rouan L, Dingkuhn M. 2013. Can early vigour occur in combination with drought tolerance and efficient water use in rice genotypes? *Functional Plant Biology* 40: 582–594.

RICE (CGIAR Research Program on Rice Agrifood Systems) 2017. RICE Annual Report 2017. Los Baños (Philippines): International Rice Research Institute. Available at https://storage.googleapis.com/cgiarorg/2018/08/RICE-2017-Annual-Report.pdf (accessed on 17 February 2020).

Richards M, van Ittersum M, Mamo T, Stirling C, Vanlauwe B, Zougmoré R. 2016. Fertilisers and low emission development in sub-Saharan Africa. Climate Change and Agriculture and Food Security (CCAFS) policy brief no. 11. Copenhagen, Denmark: CGIAR Research Program on CCAFS. Available at: www.ccafs.cgiar.org (accessed 23 February 2017).

Ritchie JT. 1990. Specifications of the ideal model for predicting crop yields. In: Muchow RC, Bellamy JA. (eds.), *Climatic Risk in Crop Production*: *Models and management for the Semiarid tropics and subtropics*. CAB International, Wallingford, UK. pp 97–121.

Ritchie JT. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* 8: 1204–1213.

Sadras VO, Hall AJ, Connor DJ. 1993. Light-associated nitrogen distribution profile in flowering canopies of sunflower (*Helianthus annuus* L.). *Oecologia* 95: 488–494.

Sadras VO, Rodriguez D. 2010. Modelling nitrogen-driven trade-off between nitrogen utilization efficiency and water used efficiency of wheat in eastern Australia. *Field Crops Research* 118: 297–305.

Sadras VO, Hayman PT, Rodriguez D, Monjardino M, Bielich M, Unkovich M, Mudge B, Wang E. 2016. Interactions between water and nitrogen in Australian cropping systems: physiological, agronomic, economic, breeding and modelling perspectives- review. *Crop and Pasture Science* 67: 1019–1053.

Saito K, Linquist B, Atlin BN, Phathaboon K, Shiraiwa T, Horie T. 2005. Response of traditional and improved upland rice varieties to N and P fertilizers in northern Laos. *Field Crops Research* 96: 261–223.

Saito K, Dieng I, Toure AA, Somado E, Wopereis MCS. 2015. Rice yield growth analysis for 24 African countries over 1960–2012. *Global Food Security* 5: 62–69.

Sanchez PA. 2002. *Soil fertility and hunger in Africa*. Science 295: 2019–2020.

Seck PA, Touré AA, Coulibaly J, Diagne A, Wopereis MCS. 2013. Africa's rice economy before and after the 2008 crisis. In: Wopereis MCS, Johnson DE, Ahmadi N, Tollens E, Jalloh A (eds.), Realising Africa's rice promise. CAB International, Wallington, UK, pp. 24–34.

Shangguan Z, Shao M, Dyckmans J. 2000. Effects of nitrogen nutrition and water deficit on net photosynthetic rate and chlorophyll fluorescence in winter wheat. *Australian Journal of Plant Physiology* 156: 46 –51.

Shatar TM, McBratney AB. 2004. Boundary-line analysis of field-scale yield response to soil properties. *The Journal of Agricultural Science* 142: 553–560.

Shiratsuchi H, Yamagishi T, Ishii R. 2006. Leaf nitrogen distribution to maximize the canopy photosynthesis in rice. *Field Crops Research* 65: 291–304.

Shrestha S, Asch F, Dingkuhn M, Becker M. 2011. Cropping calendar options for rice-wheat production systems at high-altitudes. *Field Crops Research* 121: 158–167.

Shrestha S, Asch F, Brueck H, Giese M, Dusserre C, Ramanantsoanirina A. 2013. Phenological responses of upland rice grown along an altitudinal gradient. *Environmental and Experimental Botany* 89: 1–10.

Stirzaker R, Mbakwe I, Mziray RN. 2017. A soil water and solute learning system for small-scale irrigators in Africa. *International Journal of Water Resources and Environment* 33: 788–803.

Song XZ, Zhao CX, Wang XL, Li J. 2009. Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. *Comptes Rendus Biologies* 332: 385–392.

Stöckle CO, Donatelli M, Nelson R. 2003. CropSyst, a cropping systems simulation model. *European Journal of Agronomy* 18: 289–307. Second special issue 2nd International Symposium on modelling cropping systems, Florence, Italy.

Tanner CB, Sinclair TR. 1983. Efficient water use in crop production: research or re-search? In: Taylor, HM, Jordan WR, Sinclair TR (eds.), *Limitations to efficient water use in crop production*. Madison, Wiscosin: American Society of Agronomy. pp 1-27.

Tesfamariam EH. 2009. Sustainable use of sewage sludge as a source of nitrogen and phosphorus in cropping systems. University of Pretoria, South Africa (Ph.D. Thesis).

Tesfamariam EH, Annandale JG, Steyn JM, Stirzaker RJ, Mbakwe I. 2015. Use of the SWB-Sci model for nitrogen management in sludge-amended land. *Agricultural Water Management* 152: 262–276.

Timsina J, Humphreys E. 2003. Performance and application of CERES and SWAGMAN® Destiny models for rice-wheat cropping systems in Asia and Australia: a review. CSIRO Land and Water Technical Report 16/03.

Tittonnell P, Giller KE. 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research* 143: 76–90.

Tuong TP, Bouman BAM, Mortimer M. 2004. More rice, less water -integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Proceedings of the 4th International Crop Science Congress. Brisbane, Australia, 26 September–1 October 2004. Available at http// www.cropscience.org.au (accessed 01 December 2012).

Uganda Bureau of Statistics (UBOS). 2012. Statistical abstract. Uganda Bureau of Statistics. Kampala.

United States Department of Agriculture (USDA). 2013. Production, supply and distribution (PSD) online [data base]. Foreign Agricultural Service, United States Department of Agriculture. Available at https://www.fas.usda.gov/psdonline (accessed 20 December 2018).

United Nations, D.o.E.a.S.A., Population Division, 2011. World Population Prospects: The 2010 Revision, Highlights and Advance Tables. ESA/P/WP.220. Available at http://esa.un.org/wpp/Documentation/pdf/WPP2010 Highlights.pdf (accessed 23 June 2017).

Uphoff N. 2013. Rethinking the concept of 'yield ceiling' for rice: implications of the System of Rice Intensification (SRI) for agricultural science and practice. *Journal of Crop and Weed* 9: 1–19.

Vadez V. 2014. The forgotten side of roots in drought adaptation. *Field Crops Research* 165: 15–24.

Van der Laan M. 2010. Development, testing and application of a crop nitrogen and phosphorus model to investigate leaching losses at the local scale. University of Pretoria, South Africa (Ph.D. Thesis).

Van Genuchten M, Th Leij FJ, Yates SR. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils (Computer Product PB92-501329). U.S. Environ. Prot. Agency., U.S. Department of Agriculture, Agricultural Research and Services, Washington, USA. 100 p.

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. 2013. Yield gap analysis with local to global relevance – a review. *Field Crop Research* 143: 4–17.

van Oort PAJ, Saito K, Tanaka A, Amovin-Assagba E, Van Bussel LGJ, van Wrt J, de Groot H, van Ittersum MK, Cassman KG, Wopereis MCS. 2015. Assessment of self-sufficiency in 2025 in eight African countries. *Global Food Security* 5: 39–49.

van Wart J, Kersebaumb KC, Peng S, Milner M, Cassman KG. 2013. Estimating crop yield potential at regional to national scales. *Field Crops Research* 143: 34–43.

Walkley A, Black IA. 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29–37.

Watson DJ. 1952. The physiological basis of variation of variation in yield. *Advances in Agronomy* 4: 101–145.

Wilfred OR. 2006. Final survey report on the status of rice production, processing and marketing in Uganda. Available at https://www.mofa.go.jp/mofaj/gaiko/oda/bunya/agriculture/pdf/uganda_report.pdf (accessed 10 July 2017).

Willmott CJ. 1981. On the validation of models. *Physical Geography* 2: 184–194.

Wopereis MCS, Bouman BAM, Tuong TP, ten Berge HFM, Kropff MJ. 1996. ORYZA_W: Rice growth model for irrigated and rainfed environments. SARP Research Proceedings, Wageningen, p. 160.

World Bank. 2008. Agriculture for Development. World Development Report. The World Bank, Washington, DC.

World Health Organisation (WHO). 2018. World health report. 50 Facts: Global health situation and trends 1955–2025. Available at www.who.int/whr (accessed 18 April 2018).

World Health Organisation (WHO). 2003. The African Malaria Report. Available at https://www.who.int/malaria/publications (accessed 18 April 2018).

Wright RJ, Stuczynski T. 1996. Atomic absorption and flame emission spectrometry. In: Sparks DL, (ed.), *Methods of soil analysis: Chemical methods* (Part 3). Madison, Wisconsin. Soil Science Society of America. pp. 65–90.www.yieldgap.org. Global yield gap atlas (accessed 23 April 2018).

Xangsayasanea P, Jongdee B, Pantuwanb G, Fukai S, Mitchell JH, Inthapanya P, Jothiyangkoon D. 2014. Genotypic performance under intermittent and terminal drought screening in rainfed lowland rice. *Field Crops Research* 156: 281–292.

Xu K, Guofang S. 2003. Promoting Chinese rice production through innovative science and technology, In: Mew TW, et al. (eds.), Proceedings of the International Rice Research Conference. Beijing, China, 16–19 September 2002. pp 11–18.

Yang H, Li J, Yang J, Wang H, Zou J. et al. 2014. Effects of nitrogen application rate and leaf age on the distribution pattern of leaf SPAD readings in the rice canopy. *Plos One* 9: e92509.

Yoshida S, Cock JH, Parao FT. 1972. Physiological aspects of high yields. In: *Rice breeding*. International Rice Research Institute, Los Baños, Philippines. pp 455–469.

Yoshida S, Forno DA, Cock JH, Gomez KA. 1976. Laboratory manual for physiological studies of rice. International Rice Research Institute, Los Baños, Philippines.

Yoshida S. 1981. *Fundamentals of Rice Crop Science*. Los Baños, Philippines: International Rice Research Institute.

Yoyoongwech S, Chaum S, Supabulwatana K. 2013. Water relation and aquaporin genes (*PIP1;2* and *PIP2;1*) expression at reproductive stage of rice (*O. sativa* L. spp. *indica*) mutant subjected to water deficit. *Plant Omics Journal* 6: 79–85.

Zadoks JC, Chang TT, Konzak CF. 1974. A decimal code for the growth stages of cereals. *Weed Research* 14: 415–421.

Zhang X, Meinke H, DeVoil P, van Laar G, Bouman BAM, Abawi Y. 2004. Simulating growth and development of lowland rice in APSIM. 12th Australian Agronomy Conference. Brisbane, Australia 26th September–1st October 2004. Available at http://www.cropscience.org.au (accessed 26 November 2015).

Zeigler RS, Puckridge DW. 1995. Improving sustainable productivity in rice based rainfed lowland systems of South and Southeast Asia. *The Geographical Journal* 35: 307–324

APPENDICES: SUPPLEMENTARY MATERIALS

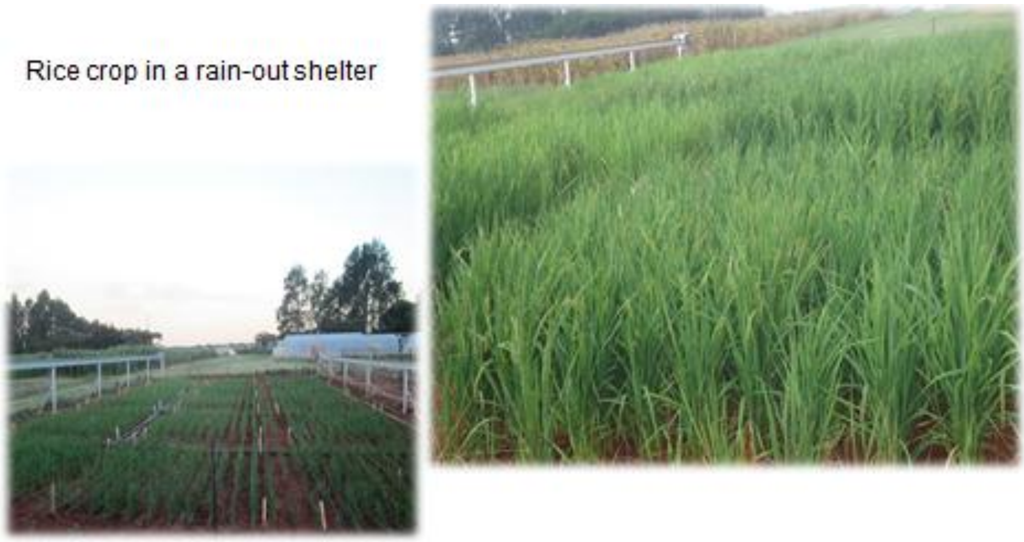
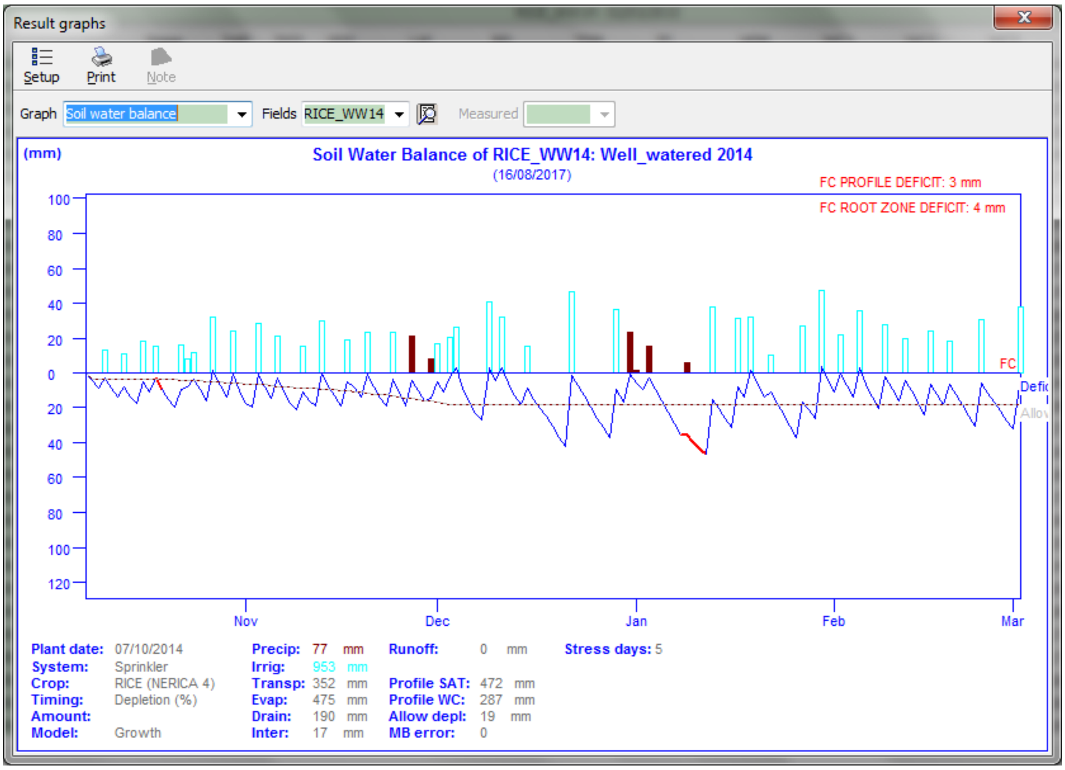


Figure A3.1 Lay out of plots in 2013/2014 (left) and crop canopies after water treatments at different sizes but around same development stages (right) of the picture.

Figure A3.2 Rice plot with no much ground cover after a week of withholding water during tillering (foreground) compared with well-watered plot (background 2013/2014).



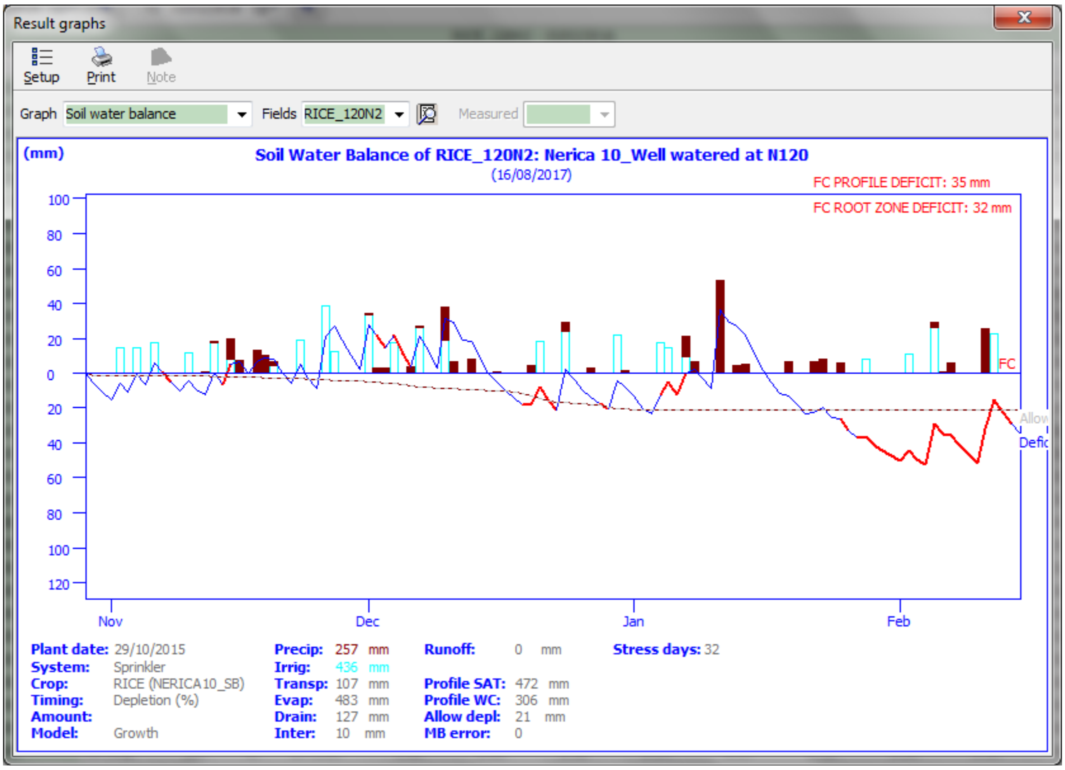


Figure A3.3 Print screen of SWB-Sci model simulation for Nerica 4 in a rain-out shelter (top) and Nerica 10 in open field (bottom) under adequate fertilisation, well-watered conditions during 2014/2015 showing components of the water balance. Transpiration and not evaporation is higher for Nerica 4 than Nerica 10 due to differences in crop duration.

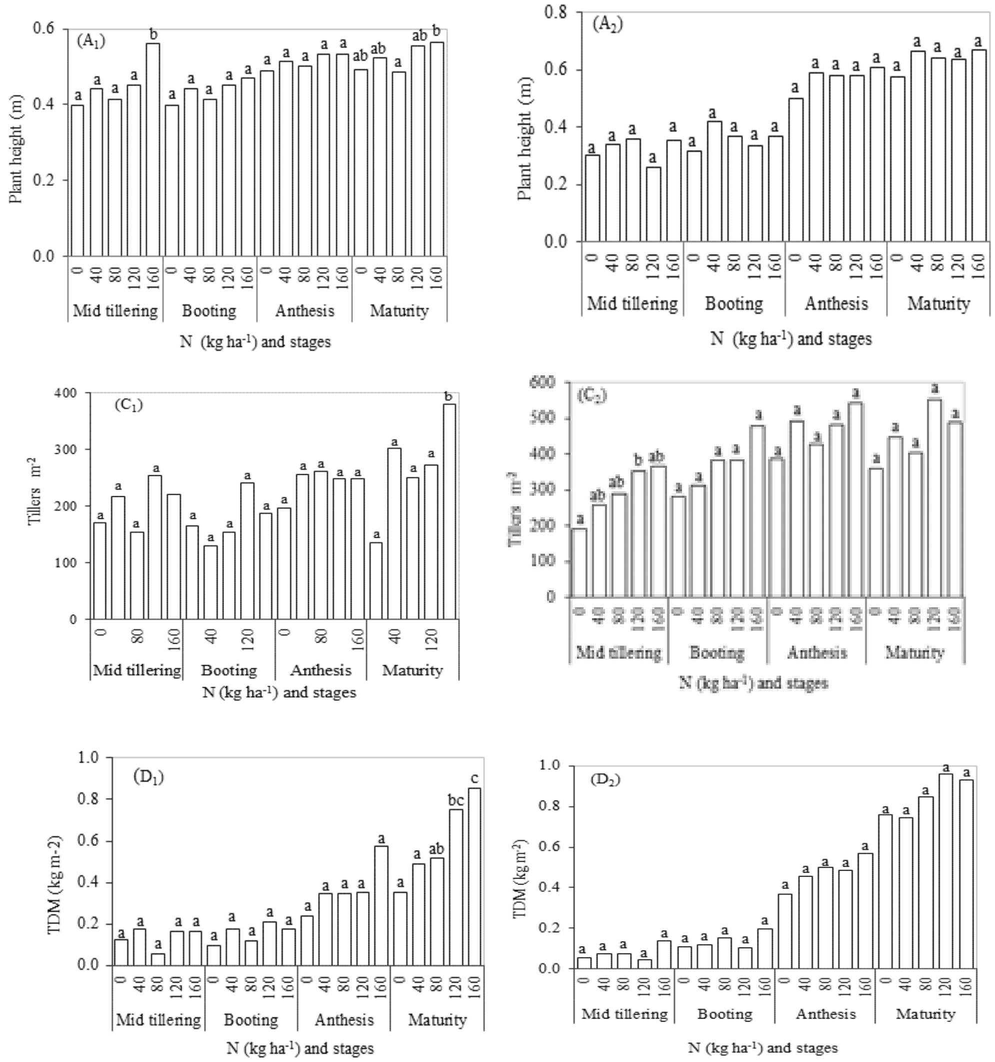
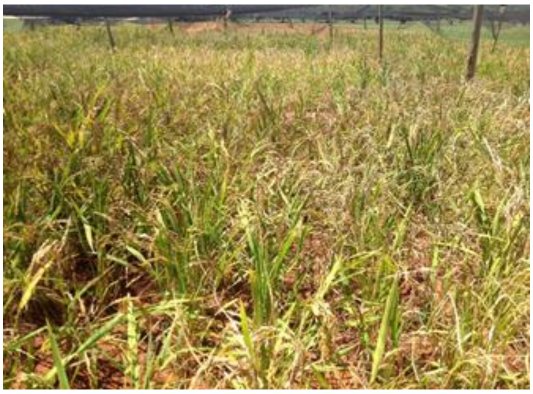


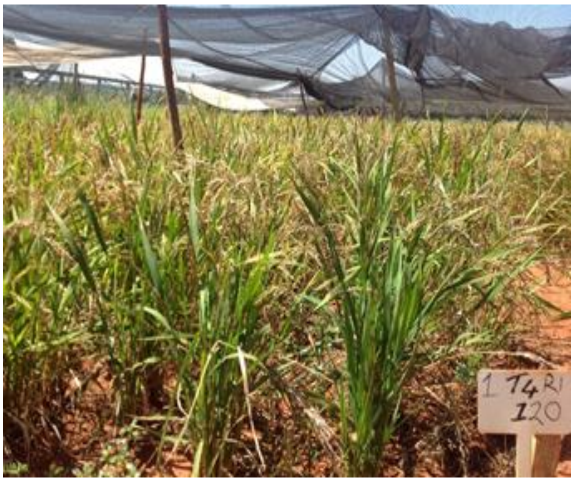
Figure A4.1 Plant height (A), number of tillers (C) and top dry matter (D) response of Nerica 10 around each key development stage to N fertiliser rates in two years. Subscripts ($_1$) and ($_2$) below the capital letters stand for 2014/2015 and 2015/2016, respectively. Means followed with the same letter for each development stage are not significantly ($p > 0.05$) different by Tukey's post hoc test.

A



B

C



D

Figure A4.2 Differences in plant stand, leaf senescence and canopy greeness for Nerica 10 at harvest in 2015/2016 for selected treatments, 0 kg N ha^{-1} (A), 40 kg N ha^{-1} (B) and 120 kg N ha^{-1} (C). Regenerated tillers in previously sampled areas at only high N rates at harvest (D), is shown to indicate excessive tillering at 160 kg N ha^{-1}.

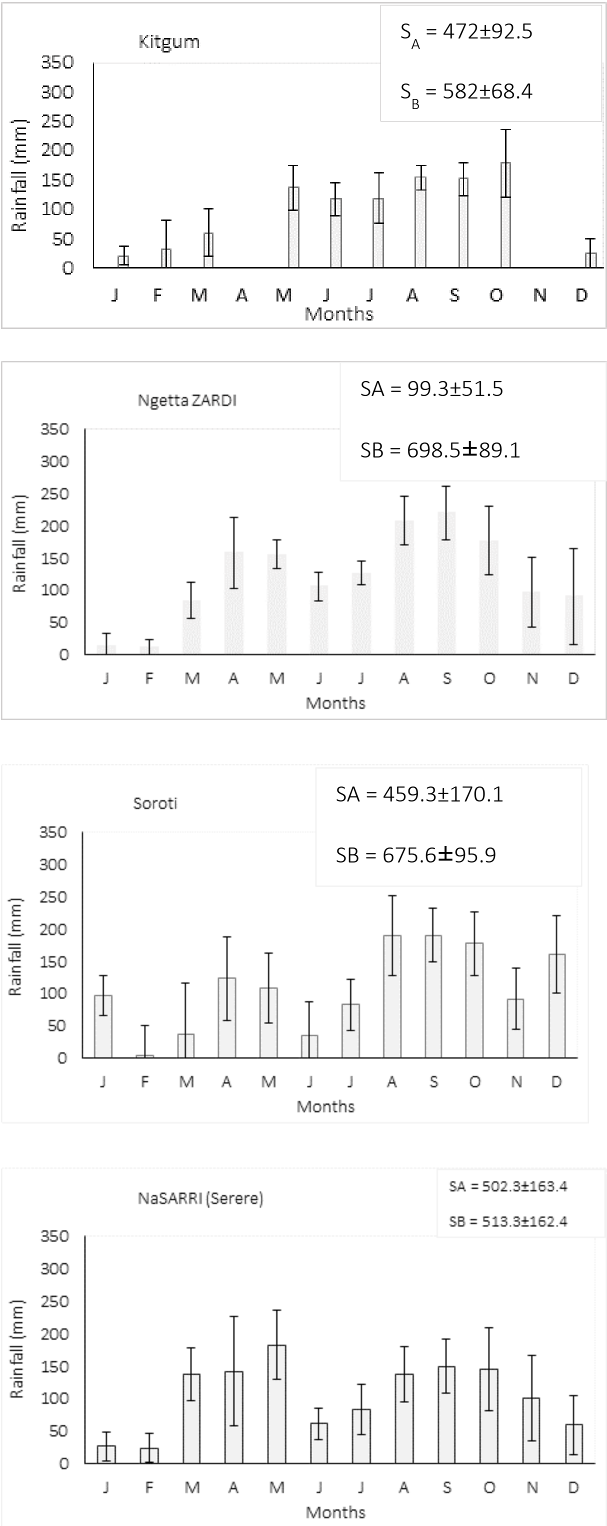


Figure A6.1. Average monthly rainfall from 2008 to 2012 showing a unimodal rainfall pattern in Kitgum and Ngetta ZARDI and a bimodal pattern in Soroti and NaSARRI (Serere). Standard deviation bars are for number of years (n = 5).

Table A 6.2a Water holding characteristics and levels of initial soil water content of the first 11 simulation sites used in modelling water-limited yield.

Site	Years	Soil Type	FC	PWP	PAW (mm m-1)	Plant available water at three %			Initial θ (mm) for respective PAW		
						25	50	75	25	50	75
Abi ZARDI	2008	SCL	0.391	0.276	0.115	0.029	0.058	0.086	0.305	0.334	0.362
	2009	SL	0.367	0.250	0.117	0.029	0.059	0.088	0.279	0.309	0.338
Bulindi ZARDI	2008	C	0.397	0.281	0.116	0.029	0.058	0.087	0.310	0.339	0.368
	2009A1	CL	0.379	0.263	0.116	0.029	0.058	0.087	0.292	0.321	0.350
	2009B	C	0.452	0.339	0.113	0.028	0.057	0.085	0.367	0.396	0.424
	2010A/2012A/B	C	0.388	0.272	0.116	0.029	0.058	0.087	0.301	0.330	0.359
	2010B, 2011A/B	C	0.447	0.333	0.114	0.029	0.057	0.086	0.362	0.390	0.419
Bushenyi	all years	SC	0.302	0.182	0.120	0.030	0.060	0.090	0.212	0.242	0.272
Entebbe	all years	CL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Gulu	all years	L	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Iganga	all years	SCL	0.280	0.159	0.121	0.030	0.061	0.091	0.189	0.220	0.250
Ikulwe Satelite	2013	CL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Jinja	all years	CL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
MUARIK	all years	SCL	0.362	0.245	0.117	0.029	0.059	0.088	0.274	0.304	0.333
Kalagala	all years	SCL	0.309	0.19	0.119	0.030	0.060	0.089	0.220	0.250	0.279
Kasese	all years	CL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330

Table A 6.2b Water holding characteristics and levels of initial soil water content of the last 13 simulation sites used in modelling water-limited yield.

Site	Years	Soil Type	FC	PWP	PAW (mm m-1)	Plant available water at three %			Initial θ (mm) for respective PAW		
						25	50	75	25	50	75
Kitgum	all years	SL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Kiige	all years	CL	0.380	0.263	0.117	0.029	0.059	0.088	0.292	0.322	0.351
Kituza (CORI)	all years	SCL	0.335	0.217	0.118	0.030	0.059	0.089	0.247	0.276	0.306
Lira	all years	SC	0.258	0.137	0.121	0.030	0.061	0.091	0.167	0.198	0.228
Makerere	all years	CL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Mbarara	all years	SCL	0.302	0.182	0.12	0.030	0.060	0.090	0.212	0.242	0.272
Mubende	all years	L	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
NaCRRI	all years	SCL	0.302	0.182	0.12	0.030	0.060	0.090	0.212	0.242	0.272
Ntusi	all years	SCL	0.302	0.182	0.12	0.030	0.060	0.090	0.212	0.242	0.272
Pakanyi	all years	SCL	0.317	0.198	0.119	0.030	0.060	0.089	0.228	0.258	0.287
Serere	all years	SCL	0.335	0.217	0.118	0.030	0.059	0.089	0.247	0.276	0.306
Soroti	all years	SL	0.359	0.242	0.117	0.029	0.059	0.088	0.271	0.301	0.330
Tororo	all years	SL	0.228	0.105	0.123	0.031	0.062	0.092	0.136	0.167	0.197

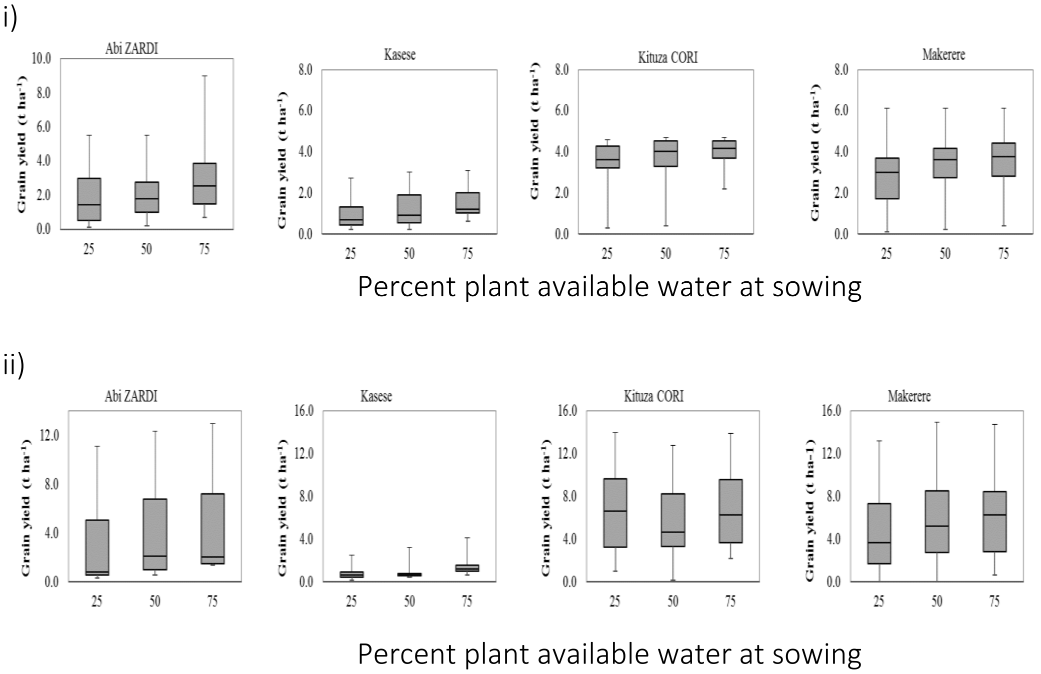
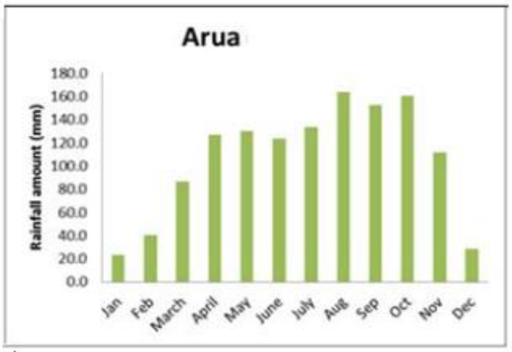
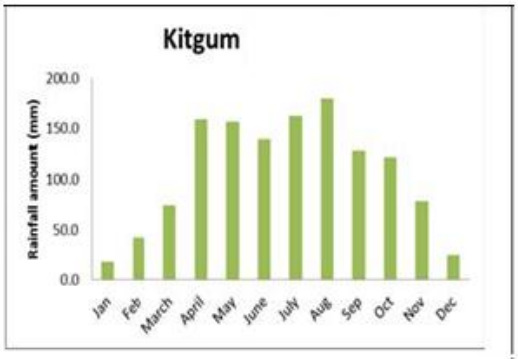


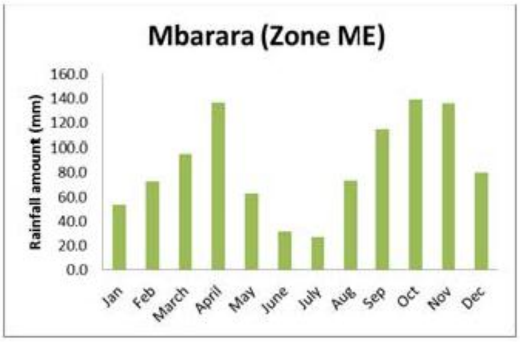
Figure 6.12 Range and distribution of simulated water-limited yields of Nerica 10 (i) and Nerica 4 (ii) disaggregated for initial soil water content for sites not considered in GLM procedure in SAS or in comparison across zones. Box plots indicate the 25th and 75th percentiles and dark line through the box is the median value.

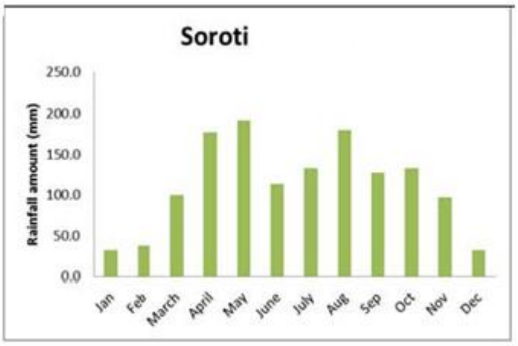
a) Unimodal



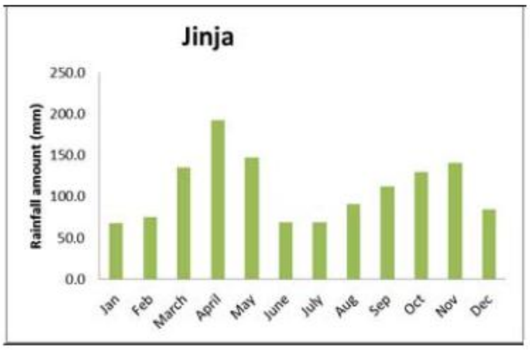


b) Bimodal





c) Bimodal



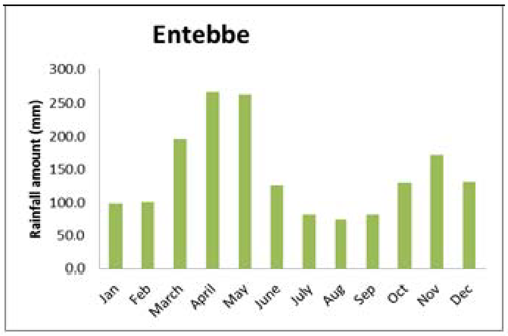


Figure A6.9 Monthly rainfall distribution (1970–2000) in selected sites in Uganda showing a unimodal rainfall regime in the Northern Moist Farming System (a) and a bimodal in the Southwest Semi-Arid for Mbarara and Eastern Semi-Arid for Soroti and the Lake Victoria Basin (b) [Manjaliwa et al. 2015]