Soil and water conservation technologies in the West African Sudan Savanna: Cropping system options to address variability of crop yield and impacts of climate change

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Soil and water conservation technologies in the West African Sudan Savanna: Cropping system options to address variability of crop yield and impacts of climate change

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Bonn, den, 30 November, 2015

Isaac Danso

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Abstract

In the Sudan Savanna region of West Africa, smallholder agricultural production is almost entirely rain-fed. Some of the major constraints to crop production are low soil fertility and high intra- and inter-annual rainfall variability. The above constraints motivated us to investigate the impact of climate change and different soil and water conservation techniques, for both high and low intensity nitrogen fertilization on yield and yield stability of key crops namely, maize, cotton and sorghum in the Sudan Savanna of Ghana (Vea), Benin (Dassari) and Burkina Faso (Dano). In the empirical studies, we evaluated the effect of tillage practices (contour and reduced tillage), nitrogen fertilizer rates (no nitrogen-N0, recommended nitrogen-NREC and high nitrogen-N2REC) and residue management (improved and standard) on the yield of maize, sorghum and cotton, for two landscape positions (upslope and footslope) in an on-farm researcher managed experiment. The 3 locations each with 3 growing seasons (2012, 2013 and 2014) were analyzed as 9 contrasting or site-seasons. Over all site-seasons, crops planted at the footslope had 31% higher relative yields and 18% higher relative aboveground biomass than those planted at the upslope. Generally, the use of contour ridging in combination with improved residue management and recommended N fertilizer was justified regardless of site-seasons and landscape position. The experimental data from short season maize (Dorke SR) was used to parameterize and evaluate the cropping system model, Decision System for Agro technology Transfer (DSSAT V 4.6) CERES-Maize. The simulated effects of climate change and adaptation options to reduce negative effect of climate change on maize were assessed. Daily climatic data for the period 2040-2060 under the scenarios RCP 4.5 and 8.5 were obtained from the GCM GFDL-ESM-2M (Geophysical Fluid Dynamics Laboratory) downscaled by the Regional Climate Model version 4 (RegCM4). Both scenarios show an increase in mean temperature of 0.7, 1.5 and 1.7^{o}C for Dano, Vea and Dassari respectively as compared to baseline 1985-2004. Precipitation is projected to increase by 40, 44 and 47% in Dano, Vea and Dassari respectively by 2050 under the two scenarios. Assessment of climate impacts on maize grain yield suggest a reduction in yield of 72, 42 and 41% for Dano , Vea and Dassari for no N fertilizer and a reduction in yield of 53, 37 and 11% for Dano, Dassari and Vea respectively under recommended N fertilizer. Analysis of adaptation measures (recommended nitrogen fertilizer, contour ridges and improved residues management as adaptation N^{o} 1 (NREC) and high nitrogen, contour ridges and improved residue management as adaptation N^{o} 2 (N2REC) with both adaptations tested under single and split dose of nitrogen application) indicated substantial reduction of negative impacts of climate change on maize grain yield as compared to the current practice by farmers (without adaptation). N2REC and NREC were able to reduce the negative impact of climate change on current maize production in the Sudan Savanna by 75 and 45% respectively. On the two methods of N fertilizer application, model estimated 64% for split and 56% for single nitrogen fertilizer application in reducing negative impact of climate change across the three sites relative to the current farmers' practices. The biggest benefit of reducing the effect of climate change on maize in this study will be the replacement of short season Dorke SR with long duration high temperature tolerant maize cultivar with high thermal requirements. This cultivar will develop under more favorable thermal and rainfall conditions, increasing the duration of vegetative phase, which will lead to increased yield. Policy makers should therefore create the enabling environment for farmers to afford credits to change crop and agronomic strategies in response to negative impact of climate change. Additionally improving the knowledge and skills of the few extension agents in the Sudan Savanna region on climate change and adaptation strategies is crucial in successful adaptation program to combat climate change.

Zusammenfassung

In der Sudansavanne Westafrikas ist die kleinbäuerliche Agrarproduktion fast vollständig vom Niederschlag abhängig. Zu den wichtigsten Einschränkungen für das Pflanzenwachstum gehören die geringe Bodenfruchtbarkeit und die hohe intra- und interannuelle Niederschlagsvariabilität. Diese Einschränkungen motivierten uns, die Auswirkungen des Klimawandels und unterschiedlicher boden- und wasserkonservierender Maßnahmen sowohl für hohe als auch niedrige Stickstoffdüngungsniveaus auf den Ertrag und die Ertragsstabilität der bedeutendsten Nutzpflanzen in der Region nämlich Mais, Baumwolle und Sorghum in Ghana (Vea), Benin (Dassari) und Burkina Faso (Dano) zu untersuchen. In einem Feldexperiment untersuchten wir die Auswirkung der Bodenbearbeitung (Bodenbearbeitung und Anhäufeln von Dämmen entlang der Höhenlinien (Konturanbau) und reduzierte Bodenbearbeitung (reduziert)), des Stickstoffdüngungsniveaus (kein Stickstoff (N0), empfohlene Stickstoffmenge (NREC) und hohe Stickstoffmenge (N2REC)) und des Strohmanagements (Rückführung der Ernterückstände (Verbessert) oder traditionelle Abfuhr der Ernterückstände (Standard)) auf die Erträge von Mais, Sorghum und Baumwolle an zwei Landschaftspositionen (Oberhang und Unterhang) in einem On-farm Experiment. Die drei Standorte mit jeweils drei Vegetationsperioden (2012, 2013, 2014) wurden als neun Anbauperioden mit unterschiedlichen Witterungsbedingungen betrachtet. Über alle neun Anbauperioden waren der mittlere relative Ertrag der Feldfrüchte, die am Unterhang angebaut wurden um 31% höher und der relative Trockenmasseertrag um 18% höher als am Oberhang. Im Allgemeinen schnitt der Konturanbau in Kombination mit verbessertem Management der Ernterückstände und mit der empfohlenen Stickstoffmenge in allen neun Anbauperioden und in allen Landschaftspositionen am besten ab.

Die Daten aus den Feldversuchen mit der frühreifen Maissorte Dorke SR wurden zur Parametrisierung und Validierung das Pflanzenwachstumsmodel DSSAT (Decision Support System for Agro-technology Transfer, Version 4.6) verwendet. Mit dem Modell wurden die Auswirkungen des Klimawandels auf den Maisanbau abgeschätzt und Anpassungsmöglichkeiten getestet, um die negativen Effekte zu vermindern. Zeitreihen mit Tageswerten über die Periode 2040-2060 für die Klimaszenarien RCP4.5. und 8.5 wurden vom GCM GFDL-ESM-2M (Geophysical Fluid Dynamics Laboratory) geliefert, dessen Ausgabegrößen mit dem Regionalen Klimamodell RegCM4 (Version 4) disaggregiert worden waren. Die Klimaszenarien zeigten, gemittelt über RCP4.5 und 8.5, mittlere Temperaturerhöhungen von 0.7, 1.5 und 1.7°C für die Standorte Dano, Vea und Dassari im Vergleich zur Referenzperiode 1985-2004. Der Niederschlag stieg in den Klimaszenarien in Dano, Vea und Dassari im Mittel um 40, 44 und 47% in der Periode 2040-2060 an. Die Abschätzung der Auswirkungen auf den Maisertrag ergab eine Reduktion um 72, 42 und 41% für Dano, Vea und Dassari in den nicht mit Stickstoff gedüngten Parzellen während in den mit der empfohlenen Menge gedüngten Parzellen die Ertragsreduktion nur 53, 37 und 11% betrug. Eine Analyse zweier möglicher Anpassungsmaßnahmen (empfohlene Stickstoffmenge, Konturanbau und verbessertes Management der Ernterückstände als Anpassung 1 (NREC) und erhöhte Stickstoffmenge, Konturanbau und verbessertes Management der Ernterückstände als Anpassung 2 (N2REC) jeweils entweder mit einfacher oder geteilter Stickstoffgabe) ergab eine substanzielle Verminderung der Ertragsverluste im Vergleich zu der momentanen Anbaupraxis der Landwirte (ohne Anpassung). N2REC und NREC konnten die Ertragsverluste durch die Klimaszenarien aus der GDFL/RegCM4 Klimamodellkombination um 75% (N2REC) bzw. 45% (NREC) vermindern. Im Vergleich der zwei Stickstoffausbringungsmethoden, schnitt die Teilmengengabe mit 64% Verminderung der Ertragsverluste im Vergleich zu der aktuellen Anbaupraxis besser ab als die Einzelgabe (56% Verminderung der Ertragsverluste). Eine weitere Verringerung der Ertragsverluste könnte durch die Substitution der frühreifen Sorte DORKE SR mit einer mittel-oder spätreifen, hitzetoleranten Maissorte erzielt werden. Diese Sorte könnte unter den günstigeren Niederschlagsbedingungen und mit den höheren Wärmeansprüchen die Wachstumsperiode verlängern und damit das Ertragsniveau erhöhen. Politiker sollten deshalb die Voraussetzungen für die Landwirte schaffen, um an die benötigten Kredite zu kommen, die für die Anpassung der Anbaupraxis an den Klimawandel nötig sind. Zusätzlich müssen das Wissen und die Kapazitäten der landwirtschaftlichen Berater in der Sudansavanne im Bezug auf den Klimawandel und mögliche Anpassungsmaßnahmen verbessert werden. Dies ist entscheidend für ein erfolgreiches Anpassungsprogramm zur Bekämpfung der Folgen des Klimawandels.

Dedication

This thesis is dedicated to my Grandparents and my Mother-in-Law whom i lost during the course of my studies. I wish them perfect rest in peace (RIP).

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Chapter one

1.0. General introduction

1.1. Problem statement

Food insecurity and widespread poverty are severe challenges facing the West African Sudan Savanna. Agriculture is a critical element of the region's economy and the main livelihood strategy for many people. Farming systems are characterized by low external input, mixed crop-livestock systems with sorghum, millet, maize, groundnut and cowpea constituting the primary staple crops. Traditionally, shifting fallow cultivation was relied on to restore soil fertility (Vlek *et al.*, 1997; Smaling *et al.*, 1993). Farming is severely constrained by many factors including limited infrastructure (roads, storage facilities, input and sales markets), lack of access to information and extension services, and increasing pressure on land resources (Valbuena *et al.*, 2015), of which degraded soils and low productivity are the ultimate consequences (Samaké *et al.*, 2005). The above constraints to crop production are likely to be further exacerbated by climate change and climate variability. In West Africa, extremes of climate variability such as those that occurred in 1983 confirms the inability of majority of sub Saharan smallholder farmers to adapt to extremes of climate conditions (Cook et al., 2004; IPCC, 2007; Segele and Lamb, 2005;Washington *et al.*, 2006).With future climate projections suggesting that the continent will become hotter (Desanker, 2002; Hulme *et al.*, 2002) and extremes more frequent (IPCC, 2014), it is clear that climate change will cause more harm to poor countries because they are highly dependent on natural resources which are prone to destruction by floods and drought. This will affect the livelihoods of the poor and worsen their standard of living (Rethman and Hope, 2013).

1.2. Soil and water conservation technologies

In the Sudan Savanna region of West Africa, cropping systems include monocrops, permanent intercrops, mixed farming, and lands under temporary intercrops in rotation with fallows, largely on a small scale with the inclusion of exotic species determined by socio-economic and environmental settings (Gyasi and Uitto, 1997).

The cropping systems and their socio-economic environment are characterized by low yields and declining productivity, with high risk of climate and market uncertainties, labor constraints, low use of external inputs, weak extension services, poor transport and communication infrastructure, which eventually move towards strong orientation to subsistence production (Yilma *et al.*, 2008; Kpongor, 2007a; Ntare *et al.*, 2008). The agricultural problems associated with the cropping systems in the Sudan Savanna raise many questions. How will different tillage practices and residue management strategies, under different nitrogen fertilization levels increase and stabilize yields under the current highly variable climate conditions? What will be the impact of future climate change and variability on crop yields in the Sudan Savanna? How will the use of different tillage and residue management strategies under recommended nitrogen fertilization rates as adaptation strategies reduce the negative impact of future climate change?

The identification of crop management practices such as residue management strategies, tillage practices and fertilizer application needed to reverse the negative impact of climate variability and climate change in the Sudan Savanna requires a long term crop yield data set on contrasting sites covering the wide range of site conditions. A number of soil and water conservation strategies (stone bunds, moldboard ploughing, the ZAI etc) are practiced by some of these farmers in the region but making it more agromically effective to both planners and policy makers necessitate the inclusion of state of the art tools such as the crop simulation models. The use of robust crop growth models can be an effective way to analyze the complex relationship between agronomic management options and crop productivity but they need proper, multi-site testing and calibration. In recent years, crop simulation models have been increasingly used in West Africa. (Naab *et al.*, 2004) used CROPGRO-Peanut to quantify yield gaps in peanut production in the Guinea Savannah region of Ghana. APSIM was used to aid decision making in N fertilization in Pearl millet in the Sahelian region

(Akponikpe *et al.*, 2010). There has been an assessment of the impact of residue management practices on the yield of sorghum in semi-arid Ghana (MacCarthy *et al.*, 2009). (MacCarthy *et al.*, 2012), reported on evaluating DSSAT-CERES model to simulate the response of maize to N fertilization in the Sub-humid region of Ghana. The DSSAT is one of the most comprehensive decision support systems (Hoogenboom *et al.*, 2004) which have been proven to be a useful tool. It has been successfully applied globally in a broad range of conditions and for a variety of purposes as an aid to adapt crop management (Hunkár, 2002) under climate change (Iglesias *et al.*, 2000;Semenov *et al.*, 1996). With the use of crop simulation models to simulate crop yields, faster results and greater understanding can be obtained more quickly, thus reducing the risk of total crop loss through the impact of climate change.

1.3. Study area characterizing climate and soils

The experiments were conducted as researcher managed on-farm trials in the Sudan Savanna of Ghana, Benin and Burkina Faso. The villages selected for the studies were Anabisi, (Vea watershed), Ghana, Tambiri (Dano watershed), Burkina Faso and Ouriyouri (Dassari watershed) Republic of Benin. Anabisi (10 º 50´N, 0º 54´W) is in the Bongo district of the Upper Eastern region of Ghana (Fig.1.1). The soils are predominantly Plinthosols (upslope) and Luvisols (downslope). Tambiri (11º10´N, 2º 38´W) is in the Ioba Province of Burkina Faso. The soils are predominantly Lixic Plinthosols except in the valley floors (Deckers *et al.*, 2001). Ouyirouri (10º 49´N,1º 04´E) is in the Atakora Province of Republic of Benin. The soils are dominated by Haplic Lixisols (Igué, 2014). The region has a monomodal rainfall regime of 3 to 5 humid months from May to October, with mean annual rainfall between 900 and 1000mm; the remaining seven months are dry (Kpongor, 2007b; Sandwidi, 2007). Temperatures oscillate strongly, from 15^{o}C during the night to more than 40^{o}C during the day (Sandwidi, 2007) with low amplitude in the rainy season. Farming systems are characterized as extensive, low external input, mixed crop and livestock systems of a subsistence nature (Callo-Concha *et al.*, 2013).

Figure 1.1: Geographical location of study areas

1.4. Research objectives

This thesis investigates the impact of climate change and different soil and water conservation techniques, for both high and low intensity nitrogen fertilization on yield and yield stability of key crops (maize, cotton and sorghum) in the Sudan Savanna of Ghana (Vea), Benin (Dassari) and Burkina Faso (Dano).

The specific objectives are to:

1. Determine the effect of three levels of nitrogen fertilization (no nitrogen, recommended nitrogen and high nitrogen), tillage practice (contour ridges and reduced tillage) and residue management (improved residue management and standard residue management) on crop productivity (maize, sorghum and cotton) for different landscape positions in the Sudan Savanna.
2. Evaluate the ability of different tillage practices and residue management strategies, for two levels of nitrogen fertilization intensity, to stabilize yields over a wide range of weather conditions.
3. Evaluate the impact of climate change to 2040 and 2060 on maize productivity for both high and low nitrogen fertilization intensity systems.
4. Evaluate the use of contour ridges and improved residue management combined with two N fertilization rates as adaptation strategies to reduce the negative impact of climate change to 2040 and 2060.

1.5. Hypotheses

We hypothesized that: 1) soil water conservation measures such as residue retention and contour ridges under recommended nitrogen fertilizer rates can increase average yields and stabilize yields in years with drought conditions and that the effect is related to slope positions; 2) the average yield of maize will decrease with increase in temperature and changes in rainfall pattern for the future period 2040 to 2060 compared with average yields of the baseline climate; 3) use of contour ridges and improved residue management combined with two nitrogen application rates as adaptation strategies will reduce the negative impact of climate change to 2040 and 2060. The overall hypothesis of this study was that rain-fed agriculture in the Sudan Savanna is negatively affected by climate change and variability, but adaptation strategies exist to reduce the negative impacts of climate change and stabilize yields under dry and humid conditions.

1.6. Outline of thesis

The thesis is structured into six main chapters. The first chapter gives a general introduction into soil and water conservation strategies in the West African Sudan Savanna and options to address variability of crop yields and impacts of climate change and states the objectives and hypothesis of the study. Following the Chapter 1, is Chapter 2 to 4 which contains the main findings of this study, and will be published in international peer reviewed journals. Chapter 2 evaluates crop management adaptations to improve current yield in Sudan Savanna of West Africa in the face of current climate variability with the results of field experimentation. Chapter 3 presents an evaluation of the impact of climate change on maize for the period of 2040 to 2060 under two climate scenarios. Chapter 4 provides information on the potential of crop management adaptation strategies to reduce the negative impact of climate change. Chapter 5 is general discussion while Chapter 6 summarizes the main findings of the study, the contribution to knowledge and recommendation for further study.

Chapter two

2.0. Crop management options to improve crop yields in the Sudan Savanna of West Africa and their interaction with topography and climate variability

2.1. Introduction

Agriculture is the main source of livelihood for the majority of West Africans. It employs approximately 60% of the active labor force and contributes 35% of gross domestic product (GDP). Most production is rainfed and from small holder farms, where it is primarily for subsistence and participation in local markets. Together with poor market infrastructure and limited investment capacity of farmers, low soil fertility (Pieri, 1995; Bationo and Buerkert, 2001; Giller *et al.*, 2011; Vanlauwe *et al.*, 2011) is a major constraint to improving agricultural productivity. Current climate variability and future climate change pose additional challenges to increasing yields in the region. Studies stemming from the global change studies in the Volta Basin (Glowa Volta Project) confirm climate change effects in the region and warn of related risks, in connection with extreme climatic events (Kunstmann and Jung, 2005). Current cropping systems are highly influenced by the seasonal patterns of rainfall, which vary strongly between years (Sultan and Janicot, 2003; Sultan *et al.*, 2005). Seasonal rainfall amount, intra-seasonal rainfall distribution and dates of onset/cessation of the rains influence crop yields and determine the agricultural calendar (Sivakumar, 1988; Maracchi *et al.*, 1993). Climate change will cause increasing mean temperatures in the region (Christensen *et al.*, 2007) and observational evidence has already detected a rise in the average temperature of 1^{o}C between 1960 and 1990 (Sandwidi, 2007). High temperatures occurring in combination with drought are expected to lead to increased crop water stress, heat stress and strongly reduce crop yields (Mackill *et al.*, 1982; Zheng and Mackill, 1982; Fisher *et al.*, 2010). Though it is difficult to generalize across crop modelling impact studies for the region (Webber *et al.*, 2014) in a review of 16 impact studies across West Africa, Roudier *et al.*, (2011) determined median yield losses of 15% with increased temperature alone. Uncertainty in the projections results from the uncertain effects on CO_2 concentration and how precipitation will change, as well as the different methodologies used in the studies (Webber *et al.*, 2014).

In this context, the identification of soil and crop management options to improve soil fertility and increase yield levels while maintaining adequate yield levels in years with drought is needed. There are a number of studies on performance of various management options (e.g. tillage practice, residue management, fertilization intensity) with regards to improve yields for cropping systems of the Sudan Savanna. However, there is much less experimental evidence from West Africa on the performance of these options under varying soil and climate conditions when all other factors are equal. This type of information is critical to calibrate and test cropping systems models such that management options can be investigated as adaptations to climate change. Our aim in this chapter was to assess the potential of residue retention, tillage practices and nitrogen fertilization to (1) increase average yields and (2) stabilize yields in years with drought conditions. The adaptation options were evaluated for three major crops (maize, sorghum, and cotton) at two slope positions for three locations of the Sudan Savanna of West Africa over three contrasting growing seasons. The precipitation amount and distribution together with information on soil characteristics were used to rank the nine site-season combinations in terms of level of drought stress by the crops. Interactions between management options and season-site combinations were analyzed to determine which practices had the greatest potential to stabilize yields under the driest conditions. It is assumed that the three seasons at three contrasting locations constitute a wide range of weather conditions representative for the inter-annual variability of the Sudan Savanna.

2.2. Materials and methods

2.2.1. Study area description

The experiments were conducted in the Sudan Savanna of Ghana, Benin and Burkina Faso in the year 2012, 2013 and 2014. The villages selected for the studies were Anabisi, (Vea watershed), Ghana, Tambiri (Dano watershed), Burkina Faso and Ouriyouri (Dassari watershed) Republic of Benin. Anabisi (10 º 50´N, 0º 54´W) is in the Bongo district of the Upper Eastern region of Ghana. Tambiri (11º10´N, 2º 38´W) is in the Ioba Province of Burkina Faso. Ouyirouri (10º 49´N,1º 04´E) is in the Atakora Province of Republic of Benin.

2.2.2. Field experiment

A strip-split plot design was used at each of the three sites with a combination of three experimental factors: 1) tillage: contour ridges (CR) and reduced tillage (RT) as the main plots. 2) nitrogen fertilizer level: no nitrogen (N0), recommended (NREC) and high nitrogen (N2REC) and 3) residue management: improved residue management (IRM) (residue retention with cowpea as a relay crop) and standard residue management (SRM) (no residues retained and no cowpea relay) constituting the sub-plot factors. The landscape position was treated as experimental strips as shown in the field layout in Fig. 2.1 with upslope and footslope as the two levels considered. The amount of residue returned to the plots with improved residue management was based on the amount of biomass produced in that plot from previous season. Generally it averaged at about 5 t ha^{-1} for both 2nd and 3rd cropping season, though varied with treatment levels. Treatments were laid out with four replications at each slope position for a total of 96 subplots.

The main plot size measured 30m x 10m with subplots measuring 10 m x 5 m. The fertilizers used were urea (46% N), triple super phosphate (46% P_2O_5) and muriate of potash (60% K_2O). The nutrient levels applied to each crop type are summarized in Table 2.1.

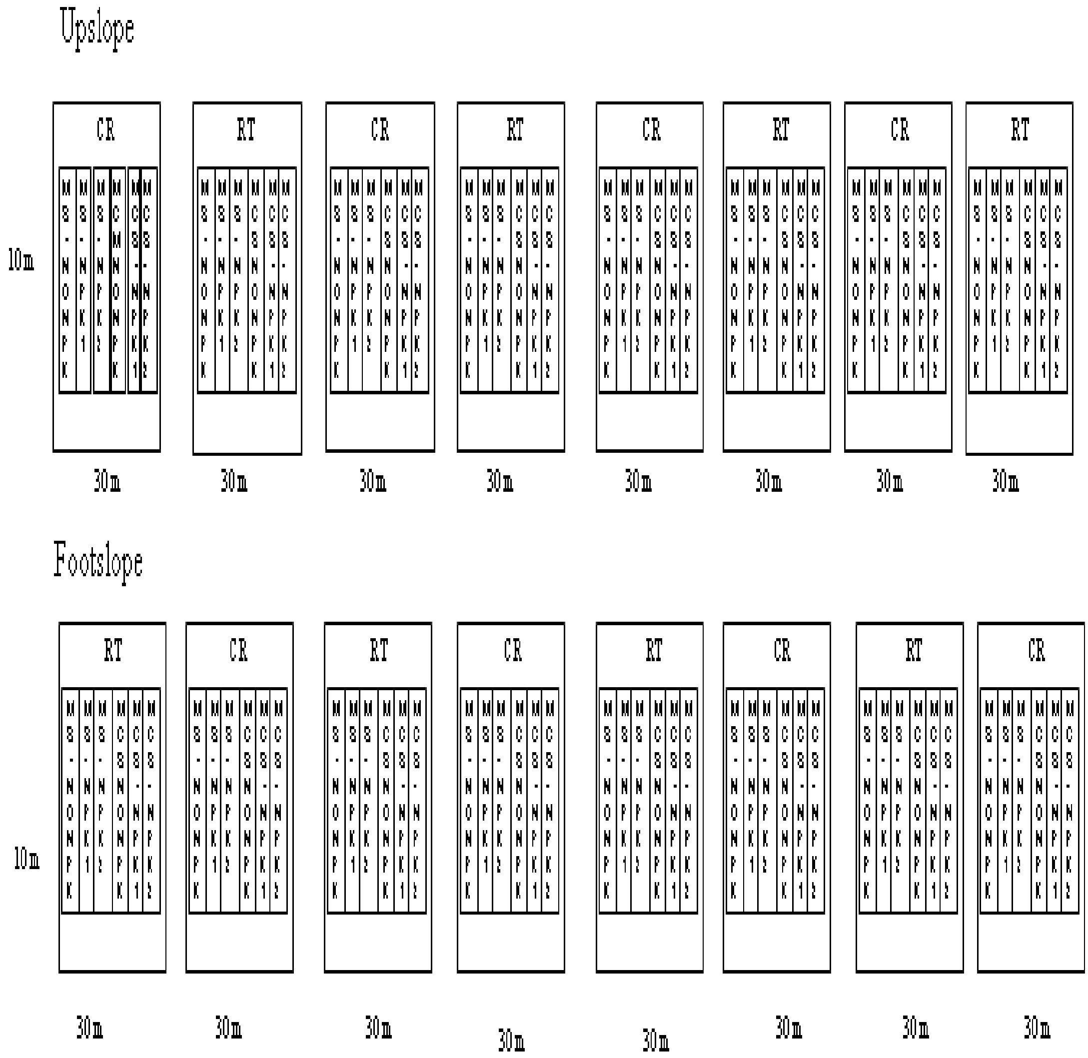


Figure 2.1: Field layout showing upslope (first strip) and footslope (second strip) landscape positions of main treatment tillage practices with subplots (N fertilizer levels and residue management, not depicted as randomized in this figure). Where RT=reduced tillage and CR=contour ridges

Table 2.1: Nitrogen fertilizer treatment levels

Crop	Levels of mineral fertilizer applied (kg ha^{-1})			Treatment code
	N	P_2O_5	K_2O	
Maize	0	60	60	N0
	60	60	60	NREC
	120	60	60	N2REC
Sorghum	0	60	40	N0
	40	60	40	NREC
	80	60	40	N2REC
Cotton	0	60	60	N0
	45	60	60	NREC
	90	60	60	N2REC

N0=zero nitrogen level, NREC=recommended nitrogen level, N2REC=high nitrogen level

The fertilizers were broadcasted in plots and worked into the soil immediately to avoid nitrogen volatilization. An optimum of P and K with 50% N was applied 25 days after planting (DAP) and the remaining 50% N was applied 45 DAP for all plots as practiced by farmers. Early maturing (90 days) maize variety Dorke SR, Padi Tuya (cowpea variety), Kadaga (sorghum variety) and non-transgenic FK 37 cotton variety were the cultivars used for the experiment. The maize, cowpea and sorghum were obtained from Council for Scientific and Industrial Research-Savana Agricultural Research Institute (CSIR-SARI) at

Nyanpkala, near Tamele in Ghana, while the cotton variety was obtained from SOFITEX in Burkina Faso.

2.2.3. Climate data

Daily weather data (rainfall, solar radiation, relative humidity, wind speed and minimum and maximum air temperature) were collected from meteorological stations situated at both upslope and downslope positions at the 3 research locations.

The three locations each with three growing seasons (2012, 2013 and 2014) were considered as nine contrasting climate conditions so called site-seasons. The site-seasons are depicted in Fig. 2.2.

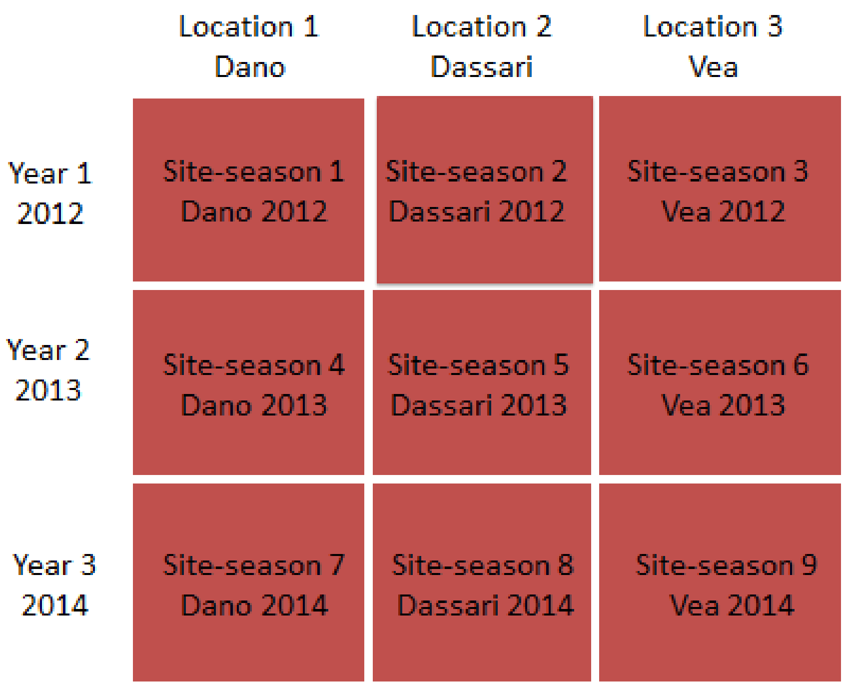


Figure 2.2: Diagrammatic representation of nine site-seasons as combination of locations and contrasting annual weather conditions

2.2.4. Precipitation regime from planting to harvest across nine site-seasons

The various seasonal water availability for each of the nine site-seasons was characterized for each site based on the following quantities: total amount of rainfall during the growing period, total number of rainy days with rainfall events >2mm, length of the longest period without precipitation, days after seeding on which the longest dry spell started, the days to physiological maturity and crop type are found in Table 2. Across site-seasons, the total amount of rainfall received during the growing season ranged from 448mm (Vea 2013) to 683mm (Dano 2014). The longest dry spell during the growing cycle of 26 days was recorded in Dassari 2013 while the shortest of 6 days was recorded in Vea 2012. Generally in 7 out of 9 site-season combinations longest dry spell of the season fell in September/October.

Table 2.2: Precipitation regime from planting to harvest in the nine site-seasons

Site-season	TAR (mm)	Rainy days	Longest dry spell (days)	Month of longest dry spell	DAS dry spell started	PM	**Crop**
Dano 2012	653	31	11	Sept./Oct.	92	102	Maize
Dano 2013	659	46	17	August	118	150	Cotton
Dano 2014	683	44	9	Oct.	100	107	Maize
Dassari 2012	516	32	13	Sept./Oct	66	95	maize
Dassari 2013	647	39	26	Oct.	117	142	cotton
Dassari 2014	637	39	13	July	11	108	maize
Vea 2012	514	39	6	Sept.	67	101	maize
Vea 2013	448	31	21	Sept./Oct.	106	137	sorghum
Vea 2014	509	28	18	October	2	98	maize

DAS=days after sowing, PM=physiological maturity and TAR=total amount of rainfal

Precipitation amount and distribution, together with soil depth and % gravel content main determinants of soil water storage capacity) (Table 4 and 5) were used to semi quantitatively rank the 9 site-season combinations (Fig. 2.3) in terms of the level of drought stress experienced by crops. The Dano 2014 site-season was ranked highest in terms of wetness, having the highest amount of rainfall which was evenly distributed during the growing season. As a result, none of the critical developmental stages (seedling emergence, floral initiation, silking etc) of the crop experienced any drought stress. Dassari 2014 site-season followed in terms of wetness ranking with a relatively high amount of rainfall; though not as evenly distributed as in Dano 2014 site-season it had deeper soils with lower gravel content. Based on the characteristics of precipitation and soil properties, the remaining site-seasons followed in order of wettest to driest as, Dano 2012, Dano 2013, Dassari 2014, Dassari 2012, Vea 2012, Vea 2014 and Vea 2013. The extremely low amount of rainfall with frequent occurance of lengthy dry spells during the growing cycle of the crop (sorghum) which coincided with critical developmental stages characterized the Vea 2013 site-season as the driest among the 9 site-seasons studied, particularly when considering its low soil water capacity arising from the high gravel content in the soils.

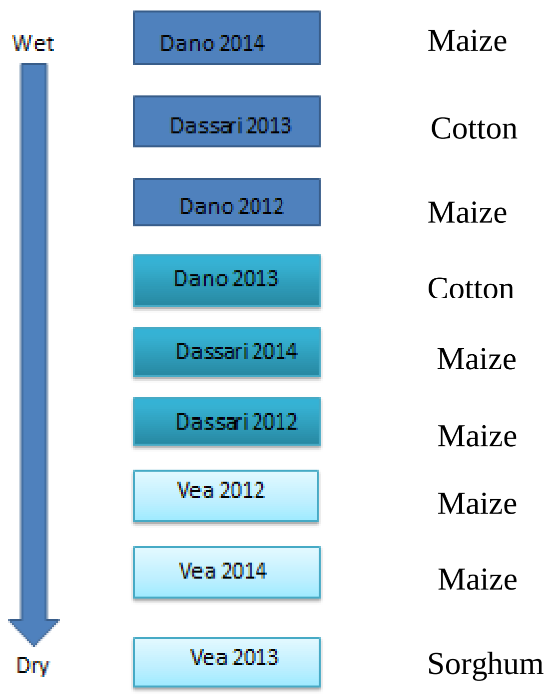


Figure 2.3: Ranking of the nine site-season conditions

2.2.5. Crop management

Prior to ploughing, sites were sprayed with glyphosate at 2.1 l ha^{-1} to clear the land of weeds. When the soil was sufficiently moist, animal drawn mould board ploughs were used to make contour ridges at Dano and Dassari whereas hand hoeing was used to make contour ridges at Vea following local customs. Planting density for maize and sorghum were fixed at 62,500 plants ha^{-1} with 0.8m between rows and with two plants per hole at a spacing of 0.4m distance. The planting density for cotton was 83,333 plants ha^{-1}. The inter-row distance for cotton was 0.8m with a within row plant distance of 0.3m. All crops were thinned (2 plants /hole) at 15 days after planting to achieve the target densities. All treatments were weeded with hand hoe 5-6 times each season to minimize weed pressure. Weeding on reduced tillage plots was shallow to avoid soil disturbances as much as possible. Cotton bolls were protected against pests, mainly *Helicoverpa armigera,* with the standard recommendations of 5-6 sprayings with Super Lambda, ie once every two weeks starting at 45 days after planting. Precautions were taken to minimize birds, pigs, donkeys and ruminants damage to the plots during the period of the study by hiring two guards on the field. The planting and harvesting schedule is summarized in Table 2. 3.

Table 2.3: Planting and harvesting schedule of crops during the seasons

Site	**Date of planting**			**Date of harvesting**		
	2012	**2013**	**2014**	**2012**	**2013**	**2014**
Dano	25/6/12	14/6/13	26/6/14	01/10/12	10/10/13	15/10/14
Vea	30/6/12	25/6/13	01/7/14	17/10/12	02/11/13	29/10/14
Dassari	25/6/12	26/6/13	24/6/14	06/10/12	15/11/13	14/10/14

Crops: Maize planted in 2012 and 2014 in all sites; cotton planted in Dano and Dassari in 2013; sorghum planted in Vea in 2013

2.2.6. Field measurements and laboratory analysis

Long periods without rain shortly after seeding had a large negative impact on the germination of seeds particularly in reduced tillage plots at the upslope position at Vea. As a result, re-seeding was done twice and in some cases three times during the experimental seasons at Vea. At Dano and Dassari, emergence was better requiring limited re-seeding. All crops were harvested at physiological maturity. Crop yields were estimated from a net area of 9 m^2 (4 rows of 3 metres length) in the center of each plot to minimize border effects. For maize, a sub-sample (10) of cobs per plot was shelled and oven dried at 70^0C for 2 days to determine grain yield at 12.0 % moisture. Cotton was harvested twice to estimate for lint mass. Sorghum grains were removed from the head and oven-dried at the same temperature for yield estimation. Aboveground biomass at harvest for all crops was determined from an area of 2 m^2. The samples were oven-dried at 70 ^{o}C for 2 days.

Before sowing, soil sampling was carried out in each of the 96 subplots at each location. Composite samples were made from six sub-samples at two depths: 0 – 20 cm and 20 - 40 cm. Percent gravel content (Table 2.4) was determined after air drying samples for about 4 weeks. After weighing, soil was passed through a 2mm sieve mesh and soil minus gravel was weighed. Percent gravel content was determined as:

$$\%\ \text{gravel content} = \frac{\text{Sample weight} - \text{Weight passing through 2mm sieve mesh}}{\text{Sample weight}}\ x\ 100 \quad \text{(Eq. 1)}$$

The sieved samples were then subject to chemical and physical analysis. Soil pH was measured with 1:2.5 soil: water suspension using a HI 9017 microprocessor pH meter. The Walkley and Black procedure as modified by (Nelson and Sommers, 1982) was used to assess the organic C content in the soils. Total N was determined by Kjeldahl digestion method (Bremner and Mulvaney, 1982). The available P and K was extracted by a method as described by (Bray and Kurtz, 1945) and P determined colorimetrically using the molybdenum blue at the wavelength of 636nm. Avaialable K was determined using a Gallenkamp flame analyzer (Black, 1986). Soil particle size (texture) was determined by using the hydrometer method (Bouyoucos, 1962) only for main plots.

2.2.7. Soil properties in the three study areas (Vea, Dano and Dassari) before planting

The results of soil physical and chemical analysis at the experimental locations are presented in Table 4. The soil pH across study areas was generally slightly acidic (ranging from 6.1 to 6.6) at both soil depths. The soils were generally very low, but availble in available P and K. Total soil mineral N is rated as low to medium (0.06 – 0.18%) according to (Stoop, 1987). The low levels of available P in the study area is consistent with results from other studies carried out in the Savannah Zone of Ghana (Abekoe and Tiessen, 1998). Soil organic matter contents of the soils were low, resulting in poor soil structure. Soils in the sub-region have been described as inherently poor in nutrient and soil organic carbon stocks (Kpongor, 2007b). This is consistent with the results of the present study where values of important nutrient such as total soil mineral N, available P, and soil organic carbon ranged from 0.01 – 0.02%, 0.18 - 8.32 mg/kg and 0.40 - 1.03% respectively. For the two soil depths considered, soil fertility values decreased with increasing depth. The slight variations of soil parameters between the three sites may be attributed to differences in management practices, soil physical properties and cropping history. Dassari had the lowest amount of gravel, compared to the amounts 1.9 times higher in Vea and 2.3 times higher in Dano. Soils at Vea were classified as sandy loam in both soil depths. At Dassari the soil at footslope was classified as sandy loam or loam while that of the upslope was classified as sandy loam and silt loam. Dano soils are sandy clay loam upslope and sandy loam or loam at the footslope. Soil depths are given in Table 2.5. A rod was driven into the soil until a hardpan was encountered. The soils at the footslope position were, on average, deeper than soils at the upslope position. Generally, the increasing order of average soil depth was Dano < Vea < Dassari.

Table 2.4: Mean chemical and physical properties of soil at Vea, Dano and Dassari before planting at two soil depths (cm) under two slope positions

Soil Property	Footslope		Upslope	
	0-20	20-40	0-20	20-40
Vea				
pH (1:2.5 H_2O)	6.45	6.55	6.1	6.17
Organic carbon (%)	0.72	0.56	0.46	0.40
Total nitrogen (%)	0.02	0.01	0.02	0.01
Aval. Bray P (mg/kg)	5.48	3.01	4.9	3.11
Avail. Bray K (mg/kg)	32.15	46.64	24.28	37.97
Sand (%)	68.4	58.4	67.4	66.2
Silt (%)	29.5	36.2	30.6	32.4
Clay (%)	2.1	5.4	2.0	1.4
Texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Gravel content (%)	32	38	44	43
Dano				
pH (1:2.5 H_2O)	6.5	6.5	6.5	6.58
Organic carbon (%)	0.80	0.40	1.03	0.43
Total nitrogen (%)	0.08	0.06	0.01	0.01
P	2.31	0.88	2.87	2.34
K	36.41	21.65	33.37	25.4
Sand (%)	52.9	45.5	32.8	28.3
Silt (%)	43.1	49.6	17.1	26.3
Clay (%)	3.0	6.0	50.0	45.4
Texture	Sandy loam	loam	Sandy clay loam	Sandy clay loam
Gravel content (%)	47	63	26	51
Dassari				
pH (1:2.5 H_2O)	6.16	6.21	6.58	6.60
Organic carbon (%)	0.68	0.58	0.84	0.65
Total nitrogen (%)	0.02	0.01	0.02	0.01
P	5.95	3.50	7.56	8.32
K	56.87	72.43	36.57	34.37
Sand (%)	66.4	46.5	56.9	41.5
Silt (%)	32.5	51.6	40.1	53.8
Cla	1.1	3.0	2.0	4.7
Texture	Sandy loam	loam	Sandy loam	silt loam
Gravel content (%)	19	17	21	22

Table 2.5: Average soil depth (cm) of the 3 locations under two slope positions

Location	Slope	Average soil depth	Maximum soil depth
Dano	UP	60	65
	FS	61	75
Vea	UP	60	75
	FS	64	80
Dassari	UP	60	75
	FS	74	90

UP=upslope, FS=footslope

2.2.7. Statistical Analysis

Data was analyzed using SAS (version 9.4). PROC mixed procedure using the Restricted Maximum Likelihood method was performed for ANOVA. Treatment least square means were compared by least significant differences (LSD) at $p < 0.05$.

To account for the different final yield and aboveground biomass at harvest levels across locations and crops, the plot yields in each site-season combination were normalized by calculating the relative yield (RY) (equation 2) and relative aboveground biomass (RAGB) (equation 3) for each crop and site-season as:

$$RY = \frac{Ya}{Yma} \quad \text{(Eq. 2)}$$

$$RAGB = \frac{Yb}{Ymb} \quad \text{(Eq. 3)}$$

where: RY=relative plot yield, Y_a=absolute plot yield, Y_{ma}=mean yield across plots for each site-season, RAGB=relative aboveground biomass, Y_b=absolute aboveground biomass and Y_{mb}=mean absolute aboveground biomass across plots for each site-season.

Mean absolute yield and mean absolute aboveground biomass for each site-season was used to normalize yields by calculating the relative yield and relative aboveground biomass (Table2. 6).

Table 2.6: Mean absolute yields (kg ha^{-1}) and mean absolute aboveground biomass (kg ha^{-1}) for each site-season

	2012		Crop	2013		Crop	2014		Crop
	Y_{ma}	Y_{mb}		Y_{ma}	Y_{mb}		Y_{ma}	Y_{mb}	
Dano	2500	5700	Maize	730	4900	Cotton	2090	4000	Maize
Dassari	4360	7500	Maize	1110	8700	Cotton	3320	5900	Maize
Vea	1360	4100	Maize	270	3100	Sorghum	1290	3300	Maize

Y_{ma}=mean yield across plots for each site-season and Y_{mb}=mean absolute aboveground biomass across plots for each site-season

2.3. Results

2.3.1. Main treatment effects

Analysis of the results of relative yield (RY) and relative aboveground ground biomass (RAGB) was conducted across the 9 site-season combinations to assess what effects the various climate management options have on average yields of maize, cotton and sorghum across site-seasons. The overall ANOVA results for main treatment effects and interactions are summarized in Table 2.7a. Across site-seasons (St) residue retention (R), tillage practice (T) and nitrogen fertilizer (N) and slope positions (S) had a significant effect ($p < 0.05$) on RY but not in all treatments on RAGB. Table 7a points to significant interactions between management options like tillage (T) and nitrogen application (N) with the 9 site-seasons (St).

Additional interactions were observed between the slope position and tillage practices (SxT) and a triple interaction between site, slope and tillage practices (StxS xT).

Table 2.7: Overall ANOVA results showing main treatment effects and interactions on relative yield (RY) and relative aboveground biomass (RAGB) for maize, cotton and sorghum (Proc. mixed model, limit of significance at $p < 0.05$). (S=Slope, T=Tillage, R=Residues, St=Site-season and N=nitrogen

Treatment	D.F	Relative yield	Relative aboveground biomass
S	1	<0.0001	<0.0001
T	1	<0.0001	0.0024
R	1	0.0125	ns
N	2	<0.0001	<0.0001
St	8	ns	ns
SxT	1	0.0014	ns
SxR	1	ns	ns
SxN	2	ns	ns
StxS	8	<0.0001	<0.0001
TxR	1	ns	ns
TxN	2	ns	ns
StxT	8	<0.0001	0.05
RxN	2	ns	ns
StxR	8	ns	ns
StxN	16	<0.0001	0.0014
SxTxR	1	ns	ns
SxTxN	2	ns	ns
SxRxN	2	ns	ns
StxSxT	8	<0.0001	0.0405
TxRxN	2	ns	ns
StxTxR	8	ns	ns
SxTxRxN	2	ns	ns

As shown in Table 2.8, crops planted at the footslope position had a significantly higher RY and averaged 31% more than those planted at the upslope. The RAGB followed a similar pattern in which crops at the footslope position had 8 % higher RAGB than crops planted upslop. The effect of tillage practices was also significant. CR led to significantly higher RY than the RT across site-seasons. The RY IR plots was significantly ($p < 0.05$) higher when compared to standard residue management (SR). Nitrogen application resulted in a significant difference ($p < 0.05$) between NREC and N0 on both RY and RAGB (Table 2.8). The average increase over the 9 site-seasons was about 37% and 25% for RY and RAGB respectively. Neither RY nor RAGB did increase when N2REC was applied relative to NREC.

Table 2.8: Main effects of slope position, tillage practice, nitrogen level, and residue management of maize, cotton and sorghum

Treatment	Relative yield	Relative aboveground biomass
Slope position		
FS	1.14a	1.13a
UP	0.83b	0.95b
Tillage practice		
CR	1.09 a	1.04a
RT	0.89b	0.95a
Nitrogen		
N0	0.72a	0.82a
NREC	1.09b	1.07b
N2REC	1.14b	1.09b
Residue management		
IR	1.03a	0.98a
SR	0.93b	1.00a

FS=footslope, UP=upslope, CR=contour ridges, RT=reduce tillage, N0=zero nitrogen, NREC=recommended nitrogen, N2REC=high nitrogen, IR=improved residue management, SR=standard residue. Numbers followed by the same letter in a column were not statistically different at $p < 0.05$

2.3.2. Interaction between tillage practice and slope position

The data pertaining to the interaction between T and S is illustrated in Fig. 2.4. Statistical analysis of the data revealed that interaction between T and S significantly affected RY all crops. Contour ridges lead to significantly higher RY than reduced tillage under footslope position with approximately 30 % higher. RY compared to reduced tillage at the foot slope position. At the upslope position, T was not significant. The interaction between T and S were all significant ($p<0.05$) for both variables.

(A) (B)

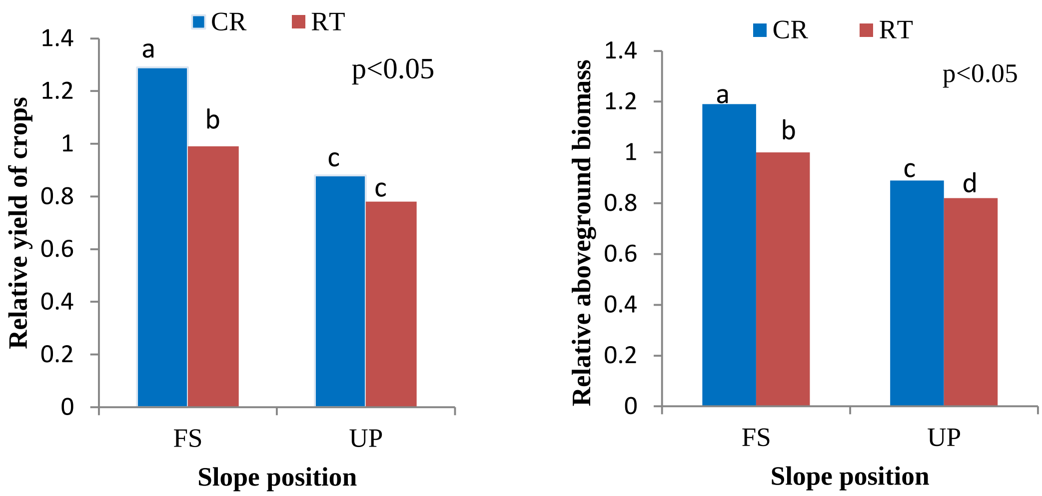


Figure 2.4: Interaction between two tillage practices (CR=contour ridges and RT=reduced tillage) and slope position (FS=footslope and UP=upslope) on (A) relative yield and (B) relative aboveground biomass of maize cotton and sorghum

2.3.3. Interaction between site-season and slope

The interaction between site-season and slope position is shown in Fig. 2.5. Over the period of the study, the ANOVA results showed significantly higher RY at the site-season footslope than the site-season upslope positions (Fig. 2.5). Except Dano 2013 and Dano 2014 site-season where cotton and maize were cultivated respectively at the upslope outperformed the footslope with a significant % increase of 20 % and 33 % respectively in 2013 and 2014. The RAGB (Fig. 2.6) followed a similar trend of higher gains at the footslope for all the three crops than the upslope position at Dano and Vea but the differences were only significant in 3 out of 9 site-seasons. The differences between the upslope and footslope could only translate into significant difference at Dassari 2013, Vea 2013 and Vea 2014 site-season where maize, sorghum and maize were cultivated respectively.

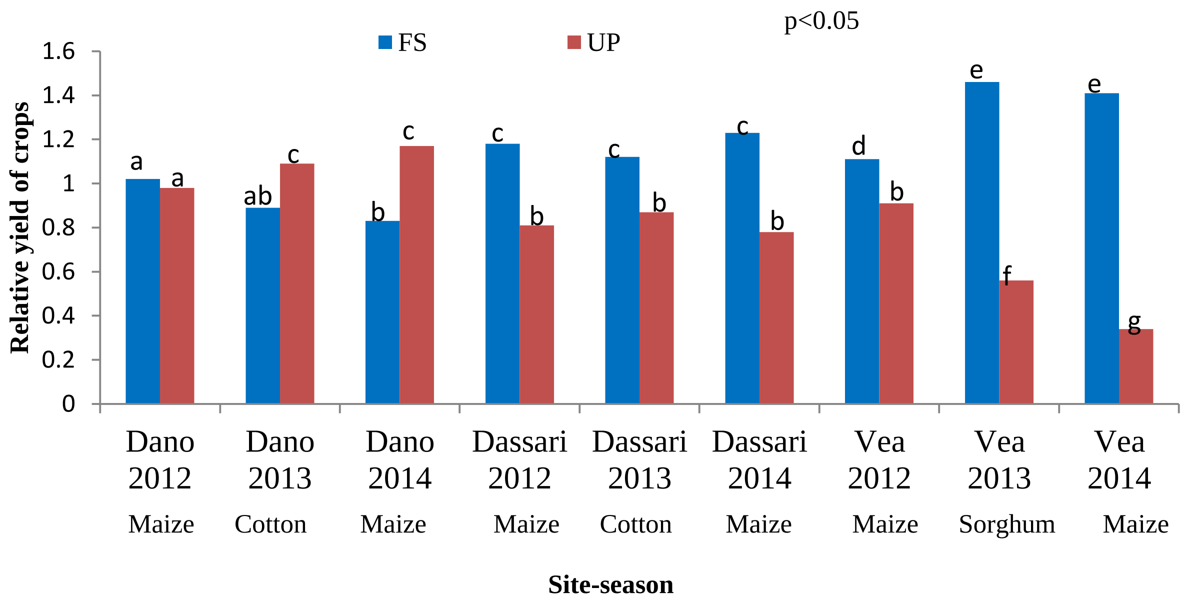


Figure 2.5: Interaction between site-season (St) and slope position (FS=footslope and UP=upslope) on relative yield of crops

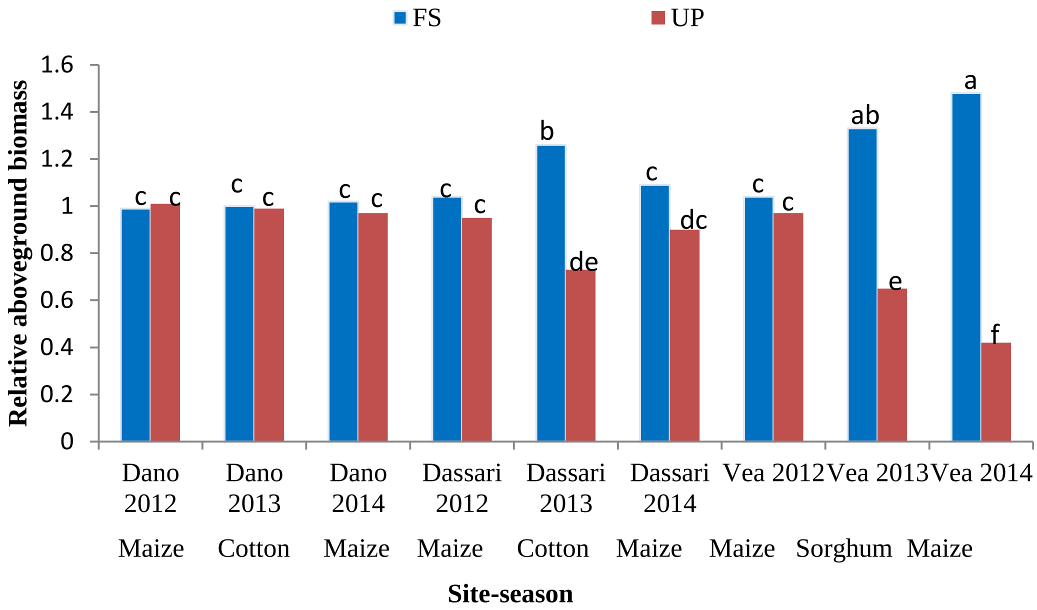


Figure 2.6: Interaction between site-season (St) and slope position (FS=footslope and UP=upslope) on relative aboveground biomass

2.3.4. Interaction between site-season and tillage practice

The interaction between site-season and tillage practice is summarized in Fig. 2.7. Averaged across site-seasons, RY were higher under CR than RT for all the crops. However, Vea 2013 and Vea 2014 cultivated to sorghum and maize respectively, had significantly higher RY under CR with RT.

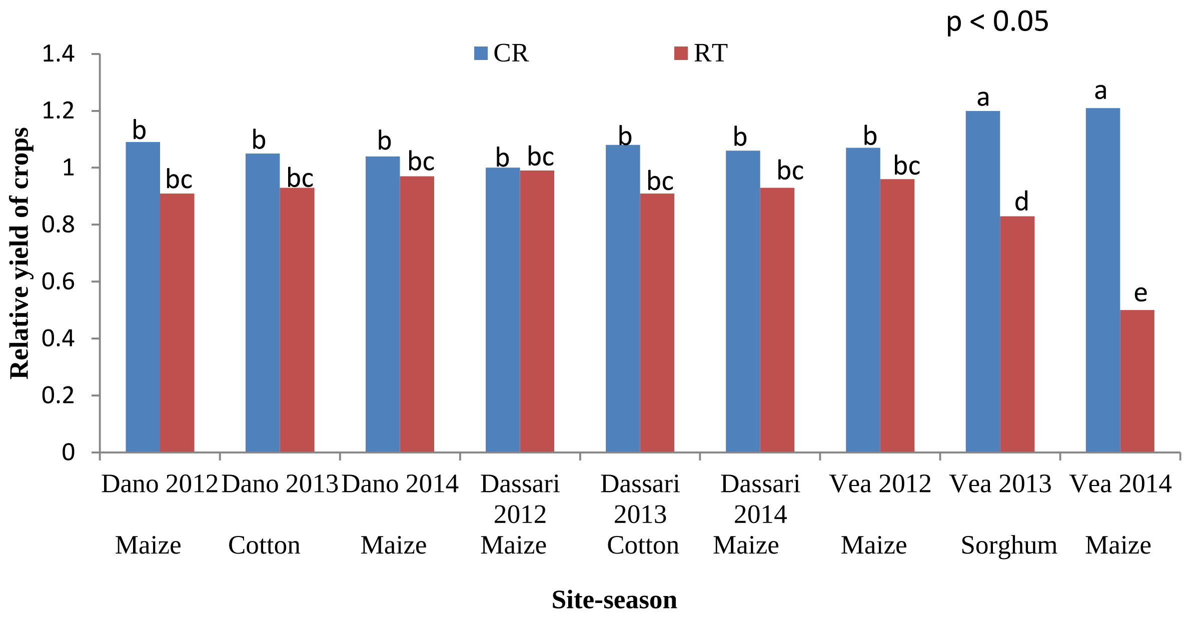


Figure 2.7: Interaction effects between site-season (St) and tillage practices (CR=contour ridges, RT=reduced tillage) on relative yield of crops

2.3.5. Interaction between site-season and nitrogen fertilizer

The interaction between nitrogen and site-season on relative yield is shown in Fig.2. 8. As expected RY and RAGB of cotton, maize and sorghum increased with N application across site-seasons. Generally, crops that received the recommended fertilizer (NREC) had the highest RY except at Dano 2012, Dano 2014 and Dassari 2012 site-seasons which were all cultivated to maize, increasing NREC to N2REC lead to significantly higher yields ($p<0.05$). Recommended N applied in Vea 2013 where sorghum was cultivated produced higher RY than N2REC. There was no difference in RY between N0 and N2REC at Vea 2013.

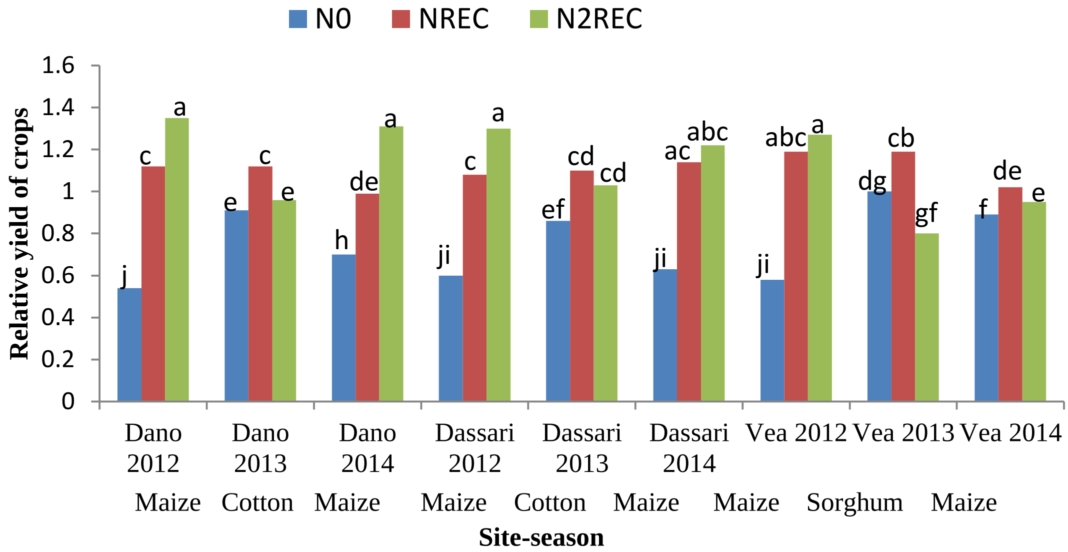


Figure 2.8: Interaction effects between site-seasons (St) and nitrogen fertilizer level (N0=zero nitrogen, NREC=recommended nitrogen, N2REC=high nitrogen) on relative yield of crops

2.3.6 Three way interaction between site-seasons, tillage and slope position

The three way interaction of site-season tillage and slope positions is shown in Fig. 2.9. For all the 3 seasons the Dano site in the footslope position, CR caused significantly higher RY than reduced tillage. However, for the upslope, only Dano 2012 cultivated to maize had significantly higher RY with CR compared to RT. Contrarily, at the Dassari site, there was no difference between CR and RT on the footslope whereas upslope CR had higher RY than RT in 2013 and 2014. In Vea, contour tillage had greatly pronounced higher RY than RT on the footslope whereas in 2013 and 2014, the driest site-season. There was no significant difference on the upslope. In Vea 2013 cultivated to sorghum, contour ridges led to slightly higher (5%) RY at the upslope.

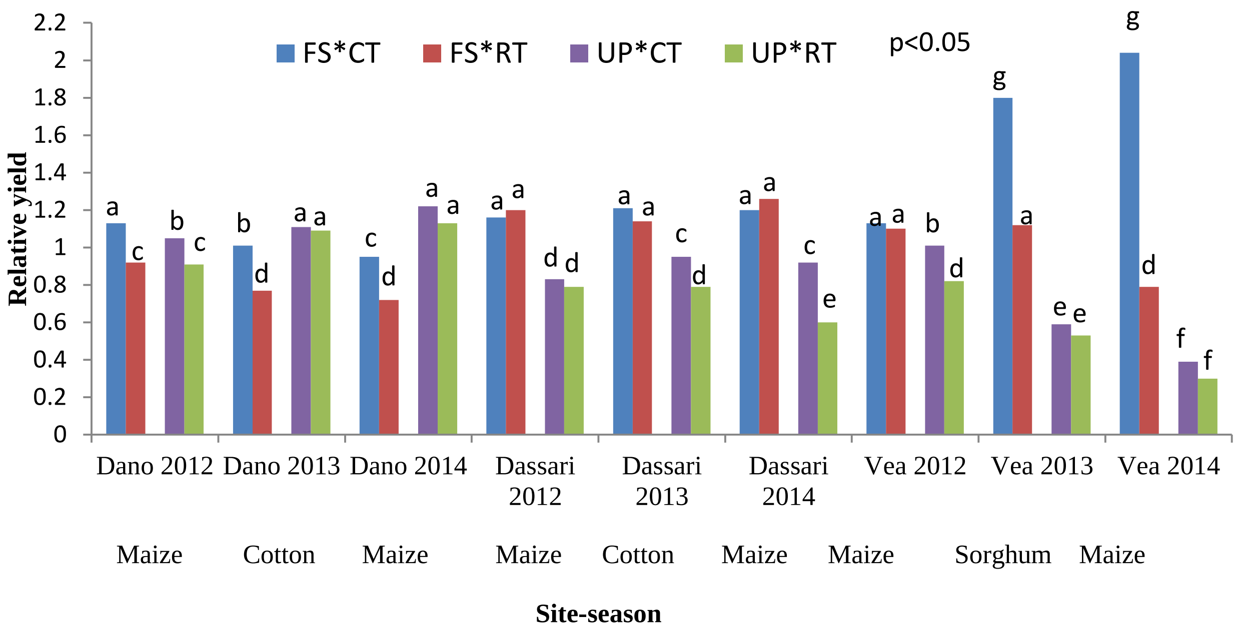


Figure 2. 9: Interaction effects between site-season, tillage practice and slope position on relative yields of crops

2.4. Discussion

2.4.1. Effect of residue management

The fact that the positive residue retention effects on RY were not influenced by other factors (Table 2.7) implies that this effect can be generalized across the soil and weather conditions studied here as a management practice that increases yields of maize, cotton and sorghum in the Sudan Savanna (+ 10% on average) (Table 2.8).

Our results suggest that plots that received residues from the previous harvest and included legume relays (improved residue management) had higher RY and higher RAGB compared to plots where residues were not retained (standard residue management). The site-seasons studied often suffered mid-season dry spells (Table 2.2) thus retention of residues with additional benefits of relayed cowpea, likely had an important role in moisture conservation and additional nitrogen input to the soil with subsequent yield benefits compared to standard residue management. Contrary to other reports, addition of residues did not lead to lower yield through immobilization by decomposing residues (Giller *et al.*, 2009). A number of authors have reported mulch retention as very important for soil moisture conservation and for nutrient recycling in semi-arid and sub-humid environments despite the challenge to find enough biomass for residue retention (Lal, 1997; Humphreys *et al.*, 2006; Mupangwa *et al.*, 2007; Wall, 2007; Thierfelder and Wall, 2009).

2.4.2. Effect of nitrogen fertilizer

Averaged across site-seasons, the addition of N fertilizer (NREC and N2REC) increased RY and RAGB. These increases were significant as compared to plots that received no nitrogen fertilizer (N0). This is in agreement with work by Boling et al. (2010) who found that, N deficiency in unfertilized plots was responsible for 35-63% of yield gaps on farmer's fields in Java. There was no significant difference between NREC and N2REC on RY and RAGB (Table 2.8).This finding fully supports the fact that it is not worth for farmers to double their nitrogen fertilizer rates. As expected and indicated in Fig. 2.8, plots with no nitrogen added recorded significantly lower RY than NREC regardless of the site-season. On the one hand, this is expected as nitrogen plays a pivotal role in several physiological processes in the plant. However it also indicates the low soil nitrogen levels and the fact that in all site-seasons nitrogen was more limiting than water. Generally across site-seasons, crops that received the recommended fertilizer (NREC) performed best except at Dano 2012, Dano 2014 and Dassari 2012 site-seasons cultivated to maize where doubling N lead to significant additional increase in RY differences ($p < 0.05$). This may be due to relatively high amount of rainfall in Dano 2012 and Dano 2014 which was evenly distributed at these site-seasons during the growing season (Table 2.2). This is in line with (Srivastava *et al.*, 2012), who reported an overall increase of about 52 % in yam total biomass production under relatively high nitrogen application with high rainfall amounts. While sufficient rainfall enhances the uptake of nutrients by crops from the soil, without adequate water, crop growth is likely water limited and additional nitrogen application cannot translate into increased yield. The crop response to applied nutrients also depends on the nutrient status of the soil. At the Dano site, with relatively low soil mineral N (Table 2.4) as compared to the two other sites (Dassarai and Vea), Dano 2012 and Dano 2014 site-seasons responded strongly to N application resulting in significantly higher RY by N2REC. This is corroborated by the cotton experiment by (Devkota-Wasti, 2011) who observed a strong response to N under low soil mineral N. The RY penalty of using double N at Vea 2013 and Dano 2013 site-seasons may be attributed to early drought conditions (Table 2.2) experienced at Vea 2013 and Dano 2013 site-seasons led to scorching of sorghum and cotton at the early stages. This suggests that there is a penalty for relatively high application of N during periods when drought conditions occur in semi-arid regions. The findings from our results thus, support our hypothesis that recommended nitrogen fertilization increases and stabilizes yields independent of soil and climate conditions. Any benefit of adding higher N rates in wet years may be offset in very dry years, and of other management practices. However our results indicating no benefit of fertilizer in the driest conditions suggest that if droughts become more common with higher temperatures under climate change, farmers will face higher risk of not realizing a return on their fertilizer investments more frequently (Rötter and Van Keulen, 1997).

2.4.3. Effect of tillage practice

For both RY and RAGB, higher yields were obtained with contour ridges compared to reduced tillage (Table 2.8), though varying with slope position (Fig. 2.4). These results are in agreement with those of Videnović *et al.*,(2011) who observed higher maize yield in conventional tillage plots in comparison with that of the no tillage plots on the chernozem soil type in Zemun Polje, Serbia. Ishaq *et al.*, (2002) reported higher wheat grain yield under conventional tillage as compared with that under minimum tillage on sandy clay loam soil in semi-arid region of Pakistan. The increase of RY of 20 % with contour ridging may be attributed to better soil and water availability with contour ridges than reduced tillage. This is in line with the observation by many researchers that moisture conservation is greatly improved by contouring to increase water infiltration and increase crop yields (Stewart *et al.*, 1975; Patil and Sheelavantar, 2004). These results indicate that contour ridges improve the physical condition of the soil through pulverization, which not only loosens the soil, but also supplies free oxygen, soil moisture and essential nutrients to plants. The results are similar to a three years maize trial in the semi-arid region of Mali where contour ridges increased maize yield by 35-38% (McGriff and Toliver, 2015). The evidence further support the hypothesis that contour ridges can potentially improve yields. Despite being significant as a main treatment factor, contour ridges did not have higher yields at most of the site-seasons studied. However, very critically, in the driest conditions, experienced at Vea 2013 and Vea 2014 (Fig. 2.7) yields were higher when CR was practiced. When rainfall is sufficient and evenly distributed, according to Cassel *et al.*, (1995) the effect of tillage method on plant growth, root distribution, and crop yield is often minimal. The implication of these results in the semi-arid regions is that contour ridge can stabilize yield under drought conditions. Its advantage is the greater accumulation of rainwater within the furrows due to the retention of potential runoff (Njihia, 1979) to increase yield of crops.

A significant interaction of tillage was observed (Fig. 2.9) with either footslope or upslope increased RY as compared to reduced tillage. Whereas yields under contour ridges were approximately 31% higher than reduced tillage at the foot slope position, contour ridges at the upslope produced relatively lower increased RY by about 10 % compared to reduced tillage. Additionally, there was a significant increase in RY under contour ridges at footslope portion in 5 out of 9 site-seasons as compared to reduced tillage. The positive effects of contour ridges at the footslope were mainly observed in Dano and Vea but never in Dassari.

This may be due to the fact that soils at footslope were deepest in Dassari and thus water supply was not limiting there. However, on shallower footslope soils with higher gravel contents in Vea and Dano, the effort to establish contour ridges seems to be justified at the footslope position.

2.4.4. Effect of slope position

The present results show that on average maize, cotton and sorghum planted at the footslope position have higher RY and RAGB than crops at the upslope position (Table 2.8) Dano, where it was the opposite in 2013 and 2014 for both maize and cotton (Fig. 2.5). Generally, the higher RY at the footslope may be attributed to the relatively deeper soils (Table 2.5) which have lower gravel content (except in Dano) thus a higher capacity to store water compared to the shallower soils of upslope with higher coarse fraction content. This is similar to findings of Whitmore and Whalley, (2009) and He *et al.*, (2011), who found deeper roots contributed to improving yield in water stress conditions. Furthermore, slope position is associated with fertility: reductions in soil fertility are often related to erosion of soils on the upper slopes during heavy rainfall events with subsequent sedimentation on the footslopes. Soil organic C, N and available P values in Table 2.4 indicate that greater erosion likely occurred on the upslopes as these quantities are associated with the selective transport of fine aggregates during erosion events which are chemically richer than the coarser ones (Wan and El-Swaify, 1997). The reasons behind significantly higher RY at the footslope compared to the upslope at Dassari and Vea may be due to the relatively high soil volumes of the deeper soils at the footslope (Table 2.5) which served as a reservoir of water and nutrients. This is in agreement with Hu *et al.*, (2009), who determined that more roots at greater depths contributes to improving yield under water stress conditions. However in Dano, RY though not RAGB was higher at the upslope position compared to the footslope in 2 out of 3 years. This may be attributed to the higher organic carbon content, which indicates better N supply, higher available P and the higher water retention capacity and lower gravel content at the upslope soil in Dano. As shown by overriding effect of N mineral application (Fig 2.8) nitrogen was the most limiting factor in all site-seasons, thus better N supply through higher soil organic matter is clearly increasing crop yield at the upslope in Dano, except in years with irregular rainfall as in 2012 in Dano which was cultivated to maize (Table 2.2). Then the effect of better N supply and higher availability of P at the upslope disappears.

Chapter three

3.0. Climate change impacts on the cropping system of the Sudan Savanna region of West Africa -variability across sites

3.1. Introduction

Maize (*Zea mays* L.) is one of the main staple cereals in West Africa, and Sub-saharan Africa more generally, accounting for 30% of the 27 million hectares (FAO, 2014). Despite the importance of maize in West Africa, yield remains low (Cooper *et al.*, 2008). While maize yields in the top five maize producing countries in the world (USA, China, Brazil, Mexico and Indonesia) have increased by a factor of three since 1961 from 1800 kg ha^{-1} to 6100 kg ha^{-1}, maize production in West Africa have stagnated at less than 1500 kg ha^{-1}. Low yield in this region could be attributed to low soil fertility, uncontrolled weeds, pest and diseases, dependence on highly variable rainfall and low input availability and use. Climate change is expected to present further challenges to increasing yield with higher temperatures and changes in precipitation patterns together leading to more droughts, heat waves, floods and bush fires (IPCC, 2013) .West Africa is considered particularly vulnerable to climate change, due to a combination of naturally high levels of climate variability, high reliance on climate sensitive activities, such as rainfed agriculture, and limited economic and institutional capacity to cope with, and adapt to, climate variability and change. Furthermore, under its current climate, West Africa is already facing recurrent food crises and water scarcity which are exacerbated by rapid population growth: climate change will thus, act as an additional stress in the future of African economies and livelihoods (von Braun *et al.,* 2014 ; Wheeler *et al.,* 2014). In Sub-Saharan West Africa, the (Wheeler and Beatley, 2014) observed decrease in rainfall (Dai *et al.*, 2004; Nicholson, 2001) and associated increase in temperatures since the 1970s has led to a decline in crop production (Barrios *et al.*, 2010); Traoré *et al.*, 2015) though there has been a recovery at the end of the 20^{th} Century (Niang *et al.*, 2014). Impact studies for SSA show a diverse range of expected yield changes ranging from -50% to +90% under various climate change scenarios and reported changes in crop yield are mostly negative (Roudier *et al.*, 2011). The reason for the disparity is attributed to differences in climate scenarios, timeframe and type of crop model as discussed in (Webber *et al.*, 2014).

In this study the Maize CERES-model (DSSAT V 4.6) was used to study climate change impacts on maize on three sites in the Sudan Savanna of West Africa. This model has been successfully applied globally under a broad range of conditions and for a variety of purposes: as an aid to crop management (Hunkár, 2002; Ruiz-Nogueria et al., 2001); to determine optimal fertilizer N management (Gabrielle and Kengni, 1996); to assess climate change impacts (Iglesias *et al.*, 2000; Semenov and Stratonovitch, 2010)) and to forecast yields (Landau *et al.*, 1998; Carter *et al.*, 2000). The objectives of the study was to (1) assess the potential impact of climate change on maize in 2050 for three locations in the Sudan Savanna of West Africa and (2) to determine if the magnitude of climate change impacts depends on nitrogen fertilizer use intensity.

3.2. Materials and methods

3.2.1. Study area

The study area description of the three sites, Anabisi (Vea watershed) in Ghana, Tambiri (Dano watershed) in Burkina Faso and Ouriyouri (Dassari watershed) in Republic of Benin is the same as that described in details in chapter 2.

3.2.2. Description of the DSSAT Model

The Decision Support System for Agrotechnology Transfer (DSSAT) was initially developed by an international team of scientists cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (Jones *et al.*, 1998) to facilitate the application of crop models in a systems approach for agronomic research. The CERES-Maize model is a deterministic stimulation model in DSSAT V 4.6 was used in this study. The CERES-Maize model simulates phenological development of the crop; growth of grains, leaves, stems, and roots; biomass accumulation based on light interception and environmental stresses; soil water balance; and soil N transformations and uptake by the crop. The primary variable influencing phasic development rate is temperature. The thermal time for each phase is modified by coefficients that characterize the response of different genotypes. The timing of crop phenological stages can be calibrated by modifying the coefficients that characterize vernalization (P1V), photoperiod response (P1D), duration of grain filling (P5) and phillochron interval (PHINT) of a particular variety.

The model predicts daily photosynthesis using the radiation-use efficiency approach as a function of daily irradiance for a full canopy, which is then multiplied by factors ranging from 0 to 1 for light interception, temperature, leaf N status, and water deficit. The "N stress" which is simulated in the model during the growing cycle of the plant is treated as index ranging from 0 to 1. It is interpreted as 1 when nitrogen stress is at maximum and 0 when there is no N stress. The soil water balance model computes the daily changes in soil water content of various soil layers as a result of infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration, and root water uptake (Ritchie and Godwin, 2000). The model uses an overflow or ''cascading bucket'' approach for computing soil water drainage when a soil layer's water content is above the drained upper limit. Input requirement for CERES-Maize model include weather and soil conditions, plant characteristics, and crop management (White *et al.*, 2005).

3.2.3. Experiment for model calibration and evaluation

Experimental data used for the evaluation and calibration of CERES-Maize were generated from experiments carried out in 2012 and 2014, respectively on all sites (Vea, Dassari and Dano) as described in detail in chapter 2. An early maturing (90 days) drought tolerant maize cultivar Dorke SR was used. The Dorke SR maize cultivar was obtained from Council for Scientific and Industrial Research-Savana Agricultural Research Institute (CSIR-SARI) at

Nyanpkala, near Tamele, Ghana. A strip-split plot design was used with varying nitrogen fertilizer levels: no nitrogen (N0) and recommended nitrogen (NREC) constituting the sub-plot factors each for upslope and footslope landscape positions as the experimental strips. Treatments were laid out with four replications at each slope position for a total of 96 subplots. The subplots measured 10m x 5m. Datasets from 2014 were used for model calibration and from 2012 for evaluation. Planting of seeds at 3 seed per pocket was on June 24, 2014 in Dassari, June 26, 2014 in Dano and July 1, 2014 in Vea. In 2012, planting was done on June 25, 2012 in Dassari, June 25, 2012 in Dano and June 30, 2012 for Vea. Planting density was fixed at 62,500 plants ha^{-1} with 0.8 m between rows, 0.4 m distance within rows. Maize was thinned (2 plants / hole) at 15 days after planting and reseeded as necessary to achieve the above density. Pest and weeds were controlled to minimize stress. The fertilizers applied were urea (46% N), triple super phosphate (46% P_2O_5) and muriate of potash (60% K_2O). The Mineral N was applied at 60 Kg ha^{-1}, P applied at 60 Kg ha^{-1}(P_2O_5) and K at 60 Kg ha^{-1} (K_2O). Fertilizers were broadcast and incorporated into soil to avoid volatilization. Maize phenological development was monitored for date of emergence, date of anthesis/flowering and date of physiological maturity. The phenological stages were noted when 50% of plant population attained that stage. Maize was harvested at physiological maturity and grain yield determined in t ha^{-1} after oven drying to required grain moisture content of 12%. TAGB was taken during the growing season at 2 weeks intervals. Soil samples were taken at different horizons (0-20, 20-40, 40-60 and 60 cm+) for both physical and chemical analysis. Table 3.1 to Table 3.3 summarize the soil data set physical, chemical and morphological properties in the different soil layers used as input for the DSSAT model.

*values were corrected for gravel content using DSSATs pedotransfer functions

3.2.4. Model calibration and evaluation

Calibration and evaluation were conducted for both recommended N fertilizer and no N fertilizer application at both footslope and upslope landscape positions. Four plots of each treatment were selected from upslope and footslope for calibration (2014 experiment) and evaluation (2012 experiment), making a total of eight plots selected in each of the three locations used for the experiment.

The properties that are required in each soil horizon such as permanent wilting point or lower limit of plant extractable water (LL, $cm^3\ cm^{-3}$), field capacity or drained upper limit (DUL, $cm^3\ cm^{-3}$), saturated water content (SAT, $cm^3\ cm^{-3}$), saturated hydraulic conductivity (KSAT, $cm\ h^{-1}$) and soil root growth factor (SRGF) were estimated (Hoogenboom *et al.*, 2004) for the calibration process (Table 3.1 to Table 3.3). The initial soil mineral nitrogen used for calibration and evaluation of sites is summarized in Table 3.4.

Table 3.1: Soil properties at Dano used as input to DSSAT for scenario analysis

Soil Property	Soil depth (cm)			
	20	40	60	> 60
DUL* ($cm^3\ cm^3$)	0.20	0.20	0.10	0.10
LL* ($cm^3\ cm^3$)	0.10	0.11	0.08	0.08
SAT ($cm^3\ cm^3$)	0.29	0.28	0.29	0.29
Root growth factor	1.00	0.55	0.36	0.27
Bulk density ($g\ cm^{-3}$)	1.35	1.42	1.39	1.39
Organic carbon (%)	0.91	0.37	0.36	0.36
pH (1:2.5 H_2O)	6.9	6.6	6.8	6.8
Total N (%)	0.09	0.04	0.04	0.04
Silt (%)	38.1	34.9	41.3	41.3
Clay (%)	21.5	27.6	18.1	18.1
Stone (%)	35	36	35	35

DUL=Drained Upper Limit, SAT=Volumetric water content at saturation, LL=Lower Limit

* values were corrected for gravel content using DSSATs pedotransfer functions

Table 3.2: Soil properties at Vea used as input to DSSAT for scenario analysis

Soil Property	Soil depth (cm)			
	20	40	60	> 60
DUL* (cm^3 cm^3)	0.15	0.18	0.18	0.18
LL* (cm^3 cm^3)	0.04	0.08	0.08	0.11
SAT (cm^3 cm^3)	0.43	0.39	0.39	0.31
Root growth factor	1.00	0.54	0.36	0.25
Bulk density (g cm^{-3})	1.28	1.34	1.34	1.57
Organic carbon (%)	0.75	1.04	1.04	0.29
pH (1:2.5 H_2O)	6.30	6.30	6.30	7.40
Total N (%)	0.08	0.10	0.10	0.03
Silt (%)	34.00	30.50	30.50	14.40
Clay (%)	1.40	8.50	8.50	21.10
Stone (%)	10	14	14	18

DUL=Drained Upper Limit, SAT=Volumetric water content at saturation, LL=Lower Limit

***** values were corrected for gravel content using DSSATs pedotransfer functions

Table 3.3: Soil properties at Dassari used as input to DSSAT scenario analysis

Soil Property	Soil depth (cm)			
	20	40	60	> 60
DUL* (cm^3 cm^3)	0.14	0.16	0.23	0.23
LL* (cm^3 cm^3)	0.04	0.04	0.10	0.10
SAT (cm^3 cm^3)	0.44	0.47	0.45	0.45
Root growth factor	1.0	0.54	0.36	0.25
Bulk density (g cm^{-3})	1.33	1.29	1.36	1.36
Organic carbon (%)	0.58	0.49	0.40	0.40
pH (1:2.5 H_2O)	6.1	6.3	5.9	5.9
Total N (%)	0.05	0.04	0.04	0.04
Silt (%)	30.8	36.8	42.9	42.9
Clay (%)	1.10	1.20	14	14
Stone (%)	6	2	2	2

DUL=Drained Upper Limit, SAT=Volumetric water content at saturation, LL=Lower Limit

***** values were corrected for gravel content using DSSATs pedotransfer functions

Table 3.4: Initial soil mineral nitrogen content (ppm) of the soil used in scenario analysis

Soil Property	Soil depth (cm)			
	20	40	60	> 60
Footslope				
Vea	9	1	1	1
Dano	9	1	1	1
Dassari	9	1	1	1
Upslope				
Vea	9	1	1	1
Dano	9	1	1	1
Dassari	11	1	1	1

Cultivar coefficients of Dorke SR (P1, P2, P5, G1, G2, G3 and PHINT) as found in Table 3.5 were obtained during calibration using 2014 maize planting season information. The genetic coefficients were calibrated until there was an agreement between measured and observed for days to anthesis and maturity, biomass and LAI dynamics and final biomass grain yield for the three sites in Dano, Dassari and Vea. The soil fertility factor (SLPF) was varied between the three locations studied. Climate data from WASCAL meteorological stations collected from various project catchments during the period of experiment were used in calibration and evaluation. This included daily solar radiation (MJ m^{-2}), daily maximum and minimum air temperature (°C) and daily precipitation (mm).

Table 3.5: CERES-maize genetic coefficients for Dorke SR

Cultivar specific parameters	Definition/name	Value
P1	Thermal time from emergence to end of juvenile phase	325
P2	Photoperiod sensitivity coefficient (0-1.0)	0.5
P5	Thermal time from silking to physiological maturity	650
G2	Potential kernel number	620.0
G3	Potential kernel growth rate	7.5
PHINT	Phyllochrom interval	45

P1: Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days, ^{o}C day, above a base temperature of 8 ^{o}C) during which the plant is not responsive to changes in photoperiod.

P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5h).

P5: Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C).

G2: Maximum possible number of kernels per plant.

G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg d^{-1}).

PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances (Hoogenboom et al., 1999).

Various statistical methods were used for assessing the performance of the crop simulation model in comparison with the observed/field measured data. The closeness of the relationships between observed and simulated was estimated using:

1. The coefficient of determination (R^2) which can be interpreted as the proportion of the variance in the observed data that is attributable to the variance in the simulated data.

2. Root mean square error (RMSE) by Willmott (1984):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}}$$

(3) Index of agreement (d) statistics by Willmott (1981):

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{M}\right| + \left|M_i - \bar{M}\right|\right)^2}$$

Where S_i is the simulated value, M_i is the measured value, n is the number of values, and M is the average of the measured values.

3.2.5. Climate change scenarios

The climate change scenarios used in this study are taken from the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4, RegCM4 (Giorgi *et al.*, 2012). RegCM4 dynamically downscales at 25 km horizontal grid resolution, the GFDL-ESM-2M (Geophysical Fluid Dynamics Laboratory Earth System Model version 2M; Dunne *et al.*, 2013) and contributed to the Coupled Model Intercomparison Project, Phase 5 (CMIP5; Taylor *et al.*, 2012). For this, three 20-year downscaling experiments are completed for the West African domain: baseline (1985-2004), and two future (2040-2060) under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways RCP4.5 and RCP8.5. RCP4.5 is a mid-level forcing scenario, while RCP8.5 represents a high forcing scenario (Moss *et al.*, 2010).

3.3. Results

3.3.1. Model calibration

3.3.1.1. Model calibration with no nitrogen fertilizer additions

The model overestimated days to physiological maturity (MDAT) in both Vea and Dano by 2 and 6 days with index of agreement of 0.4 and 0.2 respectively for no nitrogen addition during calibration. Dassari was however, underestimated by 8 days with an index of agreement of 0.5. Dassari recorded relatively high RMSE values indicate low accuracy in simulation for MDAT at this site (Table 3.6).

The model was able to simulate total aboveground biomass (TAGB) in good agreement with observations during calibration with (R^2) of 0.7 for all the three sites. The index of agreement for Vea, Dano and Dassari of 0.9, 0.8 and 0.84 respectively indicated good model performance (Table 3.6). The model performance in simulating grain yield was good at both Vea and Dano with R^2 of 0.7. However, the simulation in Dassari was underestimated by a value of -36%.

Table 3.6: Comparison of observed and simulated results during model calibration under no nitrogen application (N0) at the three sites in 2014

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
		Vea	112	114		0.4	2.8	8
Maturity	day	Dano	107	113		0.2	6.3	8
		Dassari	112	104		0.5	10.4	8
		Vea	1344	1542	0.7	0.9	659.4	8
Mat Yield	Kg ha $^{-1}$	Dano	1644	1164	0.7	0.6	749.9	8
		Dassari	2327	1473	0.1	0.5	1147.1	8
		Vea	3054	3579	0.7	0.9	1165	8
TAGB	Kg ha $^{-1}$	Dano	3989	4291	0.7	0.8	692	8
		Dassari	6099	5944	0.7	0.8	588	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N= Number of subplots

3.3.1.2. Model calibration with recommended nitrogen fertilization

Results for the model calibration under recommended nitrogen fertilization are shown in Table 3.7. MDAT at Dassari was underestimated by 3 days with index of agreement value of 0.4 and RMSE value of 3.6. MDAT at both Vea and Dano were overestimated by 12 and 5 days respectively. The model simulated TAGB well for all the three locations (R^2) values of 0.9, 0.9 and 0.7 for Vea, Dano and Dassari respectively. Index of agreement values ranging from 0.6 to 0.9 shows good performance of the model. Under recommended N application rates, the model overestimated TAGB in the Vea site but in Dano and Dassari mean simulated matched onserved TAGB. There was a close fit between observed and simulated results of grain yield at the three locations during calibration R^2 vary from 0.7 to 0.9.

Table 3.7: Comparison of observed and simulated results during model calibration for recommended nitrogen rates in 2014

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
		Vea	102	114		0.2	13.8	8
Maturity	day	Dano	107	112		0.3	5.7	8
		Dassari	107	104		0.4	3.6	8
		Vea	1522	1718	0.9	0.9	507	8
Mat Yield	kg ha $^{-1}$	Dano	2119	2253	0.7	0.6	924	8
		Dassari	3987	3878	0.7	0.5	431	8
		Vea	2991	3644	0.9	0.9	1241	8
TAGB	kg ha $^{-1}$	Dano	4853	4896	0.9	0.9	382	8
		Dassari	10714	10772	0.7	0.6	1209	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N= Number of subplots

3.3.2. Model evaluation

3.3.2.1. Model evaluation under no nitrogen at the three sites

The ability of the model to simulate MDAT is shown in Table 3.8. The model overestimated MDAT in Vea and Dano, but not in Dassari under no N fertilizer application. The best model performance between observed and simulated values was achieved at Dassari. There was a good agreement between observed and simulated values of TAGB at the three locations (Table 3.8). In both Dano and Dassari TAGB was slightly overestimated whereas at Vea simulation of TAGB was underestimated by a mean error value of -11%. The R^2 values as reported in Table 7 indicate a close fit between the observed and simulated TAGB values during evaluation. Grain yield values was slightly overestimated in Dano and Vea whereas at Dassari grain yield was underestimated with a mean error of -31% (Table 3.8). Generally, the model showed a fairly good performance in simulating grain yield under no N application as shown by d-stat values ranging from 0.58 to 0.7. For MDAT in Dassari, both simulated and observed were the same (104 days) with overestimation in both Vea and Dano.

Table 3.8: Comparison of observed and simulated results during model evaluation under no nitrogen treatments (current practice) at the three sites in 2012

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
		Vea	102	112		0.1	12.3	8
Maturity	day	Dano	106	113		0.1	6.5	8
		Dassari	104	104		0.4	1.4	8
		Vea	649	687	0.4	0.6	756	8
Mat Yield	kg ha $^{-1}$	Dano	1492	1664	0.5	0.7	534	8
		Dassari	2139	1473	0.8	0.7	524	8
		Vea	2675	2360	0.5	0.6	1144	8
TAGB	kg ha $^{-1}$	Dano	3829	4291	0.5	0.7	861	8
		Dassari	5014	5944	0.61	0.6	1555	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N=Number of subplots

3.3.2.2. Model evaluation under recommended N rates, at the three sites

In general the model overestimated MDAT in all the three locations studied (Table 3.9) with less index of agreement values of 0.2, 0.2 and 0.2 for Vea, Dano and Dassari respectively. The RMSE values which indicate less accuracy in all sites ranged from 6.2 to 16.3.

Generally, TAGB was underestimated at Dassari and Dano whereas Vea was overestimated with a mean error of 23%. There was a good agreement between observed and simulated values with an index of agreement values ranging from 0.63 to 0.9 and coefficient of model accuracy R^2 ranging from 0.5 to 0.6 (Table 3.9). Grain yield showed a fairly good agreement between observed and simulated grain yield values for NREC during evaluation Grain yield was overestimated at Vea and Dassari with good index of agreement values of 0.8 and 0.8 respectively. At Dano grain yield was underestimated with a mean error of -24%. The coefficient of model accuracy R^2 were Vea > Dassari > Dano in a decreasing order (Table 3.9).

Table 3.9: Comparison of observed and simulated results during model evaluation for recommended N rates treatment at the three sites in 2012

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
Maturity	day	Vea	101	112		0.21	11.5	8
		Dano	106	112		0.15	6.2	8
		Dassari	101	117		0.2	16.3	8
Mat Yield	kg ha $^{-1}$	Vea	1645	2214	0.59	0.8	818	8
		Dano	2978	2253	0.55	0.6	1202	8
		Dassari	4303	4645	0.57	0.8	564	8
TAGB	kg ha $^{-1}$	Vea	4669	5760	0.63	0.6	2248	8
		Dano	6096	4896	0.63	0.7	1672	8
		Dassari	10397	10309	0.56	0.9	1098	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N= Number of subplots

3.3.3. Climate change impacts

3.3.3.1. Simulated changes in temperature during growing cycle of maize

The changes in daily maximum temperature (T_{max}) and daily minimum temperature (T_{min}) during the maize growing seasons for the two climate scenario RCP 4.5 and RCP 8.5 to 2050 are summarized in Table 3.10. T_{max} is expected to increase at Dano, Dassari and Vea by 0.6°C, 1.50 °C, and 1.3°C respectively under RCP 4.5 (Table 3.10). An increase of T_{max} of 1.2°C, 2.1°C and 1.7°C is expected at Dano, Dassari and Vea respectively under RCP 8.5. With respect to the T_{min}. Both climate scenarios indicate T_{min} will increase but to a lesser extent than T_{max}.

Table 3.10: Average changes of Tmax and Tmin during the current maize growing season between 2040-2060 compared to 1985-2004 at Dano, Vea and Dassari under RCP 4.8 and RCP 4.5 climate scenario

Location	Temp. (°C)	Baseline (°C)	Scenario temperature (°C)			
			RCP 4.5		RCP 8.5	
			Temp. (°C)	Change (°C)	Temp. (°C)	Change (°C)
Dano	Tmax	30.7	31.3	0.6	31.9	1.2
	Tmin	23.6	23.8	0.2	24.5	0.9
	Mean	27.15	27.6	0.4	28.2	1.0
Dassari	Tmax	30.3	31.8	1.5	32.4	2.1
	Tmin	23.1	24.6	1.5	25.0	1.9
	Mean	26.7	28.2	1.5	28.7	2.0
Vea	Tmax	30.2	31.5	1.3	31.9	1.7
	Tmin	23.0	24.2	1.3	24.7	1.7
	Mean	26.6	27.9	1.3	28.3	1.7

Projected daily T_{max} during the maize growing season for the three locations for the baseline and the climate scenarios under the current growing season, is shown from Fig. 3.1 to Fig.3.3.

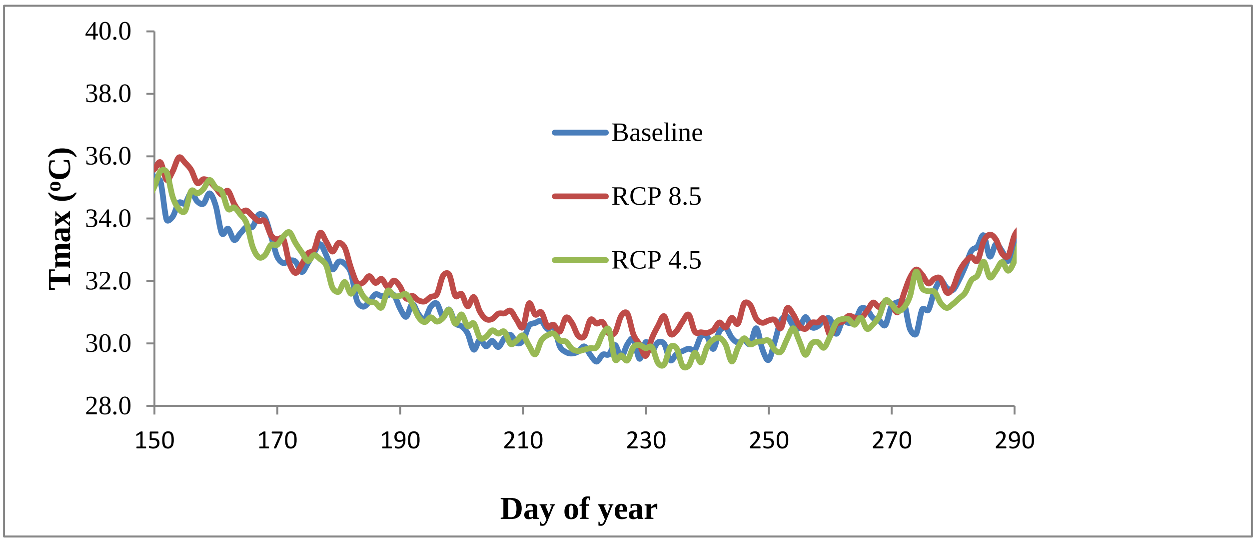


Figure 3.1: Growing season daily average Tmax at Dano for baseline and RCP 4.5 and RCP 8.5 in 2050

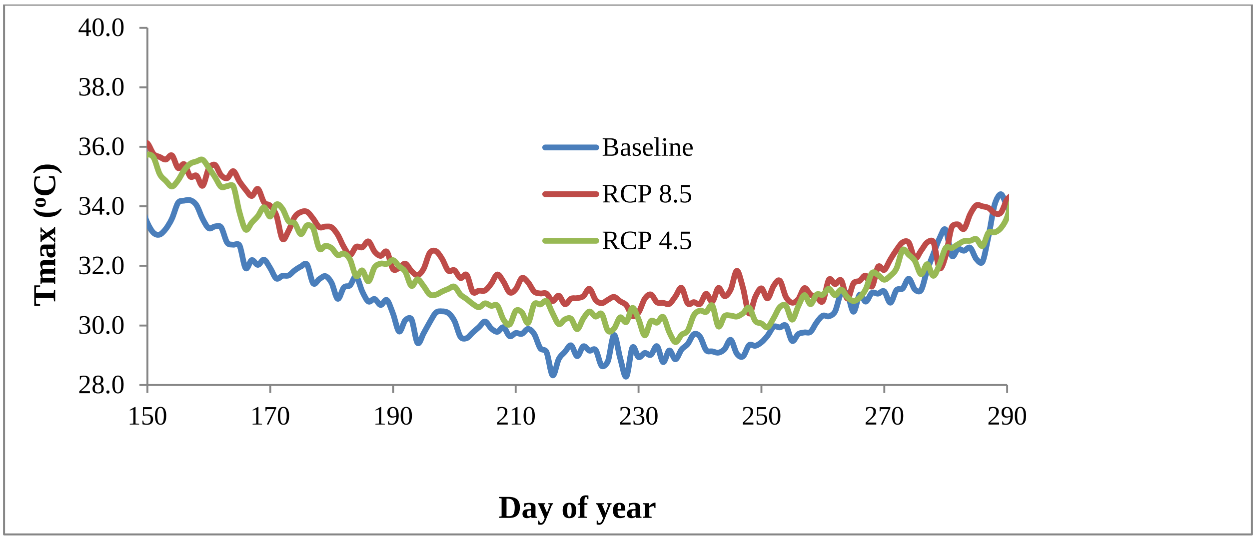


Figure 3.2: Growing season daily average Tmax at Dassari for baseline and RCP 4.5 and RCP 8.5 in 2050

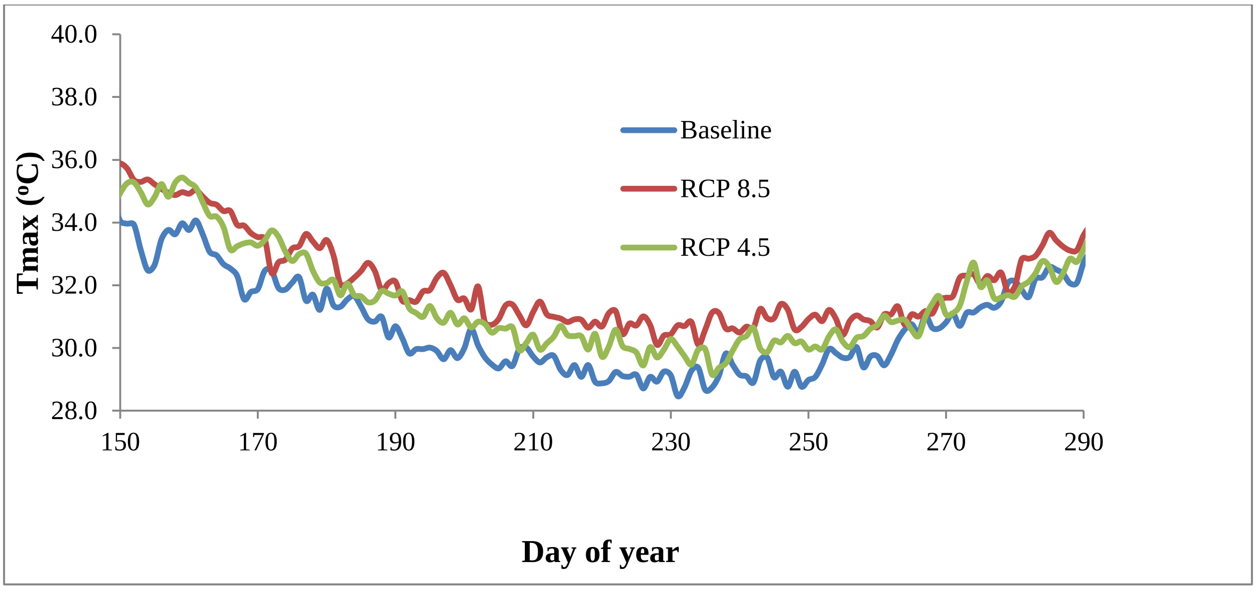


Figure 3.3: Growing season daily average Tmax at Vea baseline and RCP 4.5 and RCP 8.5 in 2050

3.3.3.2. Simulated changes in precipitation during growing cycle of maize

An increasing trend for precipitation is observed in the period centered on 2050 for all the locations under both climate scenarios relative to the baseline precipitation (Table 3.11). Precipitation is projected to increase by 48, 53 and 49% for Dano, Dassari and Vea respectively under RCP 4.5. For RCP 8.5 precipitation is expected to increase by 32, 36 and 46% for Dano, Dassari and Vea respectively.

Table 3.11: Simulated average changes of precipitation during the growing season of maize for Dano, Vea and Dassari under RCP 4.8 and RCP 4.5 climate scenarios

Location	Baseline (mm)	Scenario precipitation (mm)			
		RCP 4.5		RCP 8.5	
		Prec. (mm)	Change (%)	Prec. (mm)	Change (%)
Dano	717	1066	48	949	32
Dassari	563	863	53	766	36
Vea	611	911	49	895	42

3.3.3.3. Simulated nitrogen stress

3.3.3.3.1. No nitrogen fertilizer application

Projected nitrogen stress for baseline and the two climate scenarios are shown in Fig. 3.4 to Fig. 3.6 for the three sites when no nitrogen fertilizer is applied. Nitrogen stress is given as index ranging from 0 to 1. 0 indicating no nitrogen stress on maize crop and 1 indicating maximum nitrogen stress. There is virtually no nitrogen stress during the early growth stages of maize crop for Dano, Dassari and Vea. Nitrogen stress is expected to increase in all the three sites under both climate scenarios during projected years. The daily highest nitrogen stress of 0.4 is projected at Dano under RCP 4.5 with the lowest of 0.2 under RCP 4.5 at Vea. Growing cycle daily mean nitrogen stress is expected to increase by 72%, 140% and 26% for Vea, Dano and Dassari respectively relative to the baseline of the three locations under RCP 4.5. The anticipated daily mean change in nitrogen stress during the growing season for RCP 8.5 relative to the respective baseline for Vea, Dano and Dassari will be 100%, 100%, and 32% respectively.

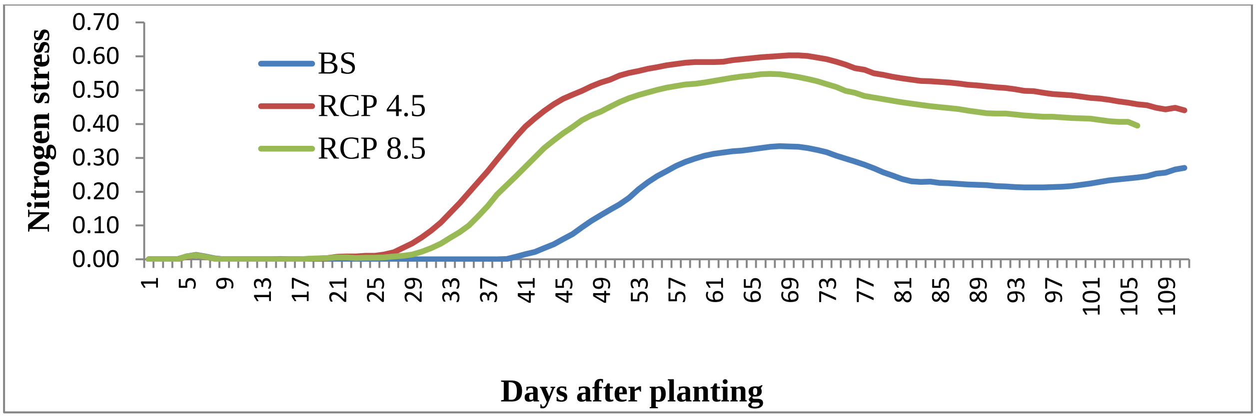


Figure 3.4: Simulated daily nitrogen stress during growing season of maize in Dano for N0

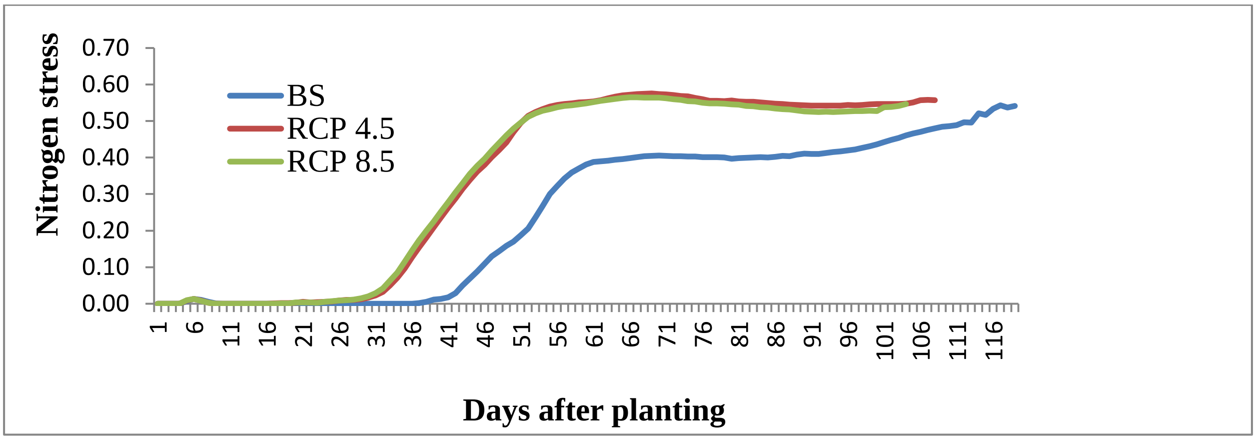


Figure 3.5: Simulated daily nitrogen stress during growing season of maize in Dassari for N0

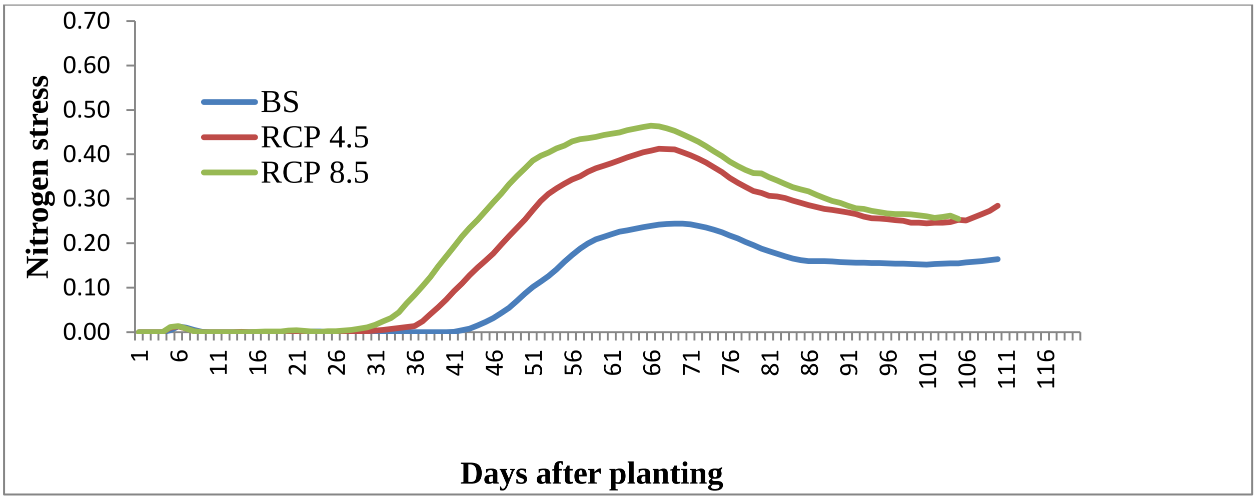


Figure 3.6: Simulated daily nitrogen stress during growing season of maize in Vea for N0

3.3.3.3.2. Recommended nitrogen fertilizer application (NREC)

The projected nitrogen stress for recommended nitrogen plots for baseline and the two climate scenarios at the three locations is summarized in Fig. 3.7 to Fig. 3.9. Except for Dano, which is projected to experience slight nitrogen stress during the juvenile stages of maize growth, the other two locations will not have any nitrogen stress during the juvenile growth stages. Mean daily nitrogen stress is expected to increase in all the three experimental locations under both climate scenarios during projected years. The projected mean nitrogen stress of 200%, 125% and 16% for both scenarios relative to the baseline is expected to occur at Vea, Dano and Dassari respectively relative to the baseline.

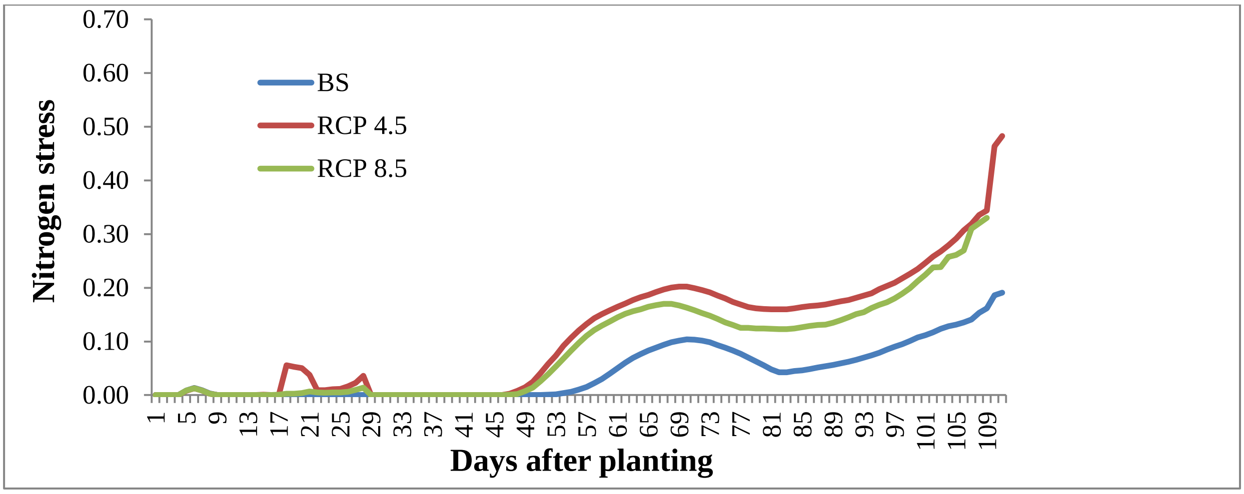


Figure 3.7: Simulated daily nitrogen stress during growing season of maize at Dano for NREC

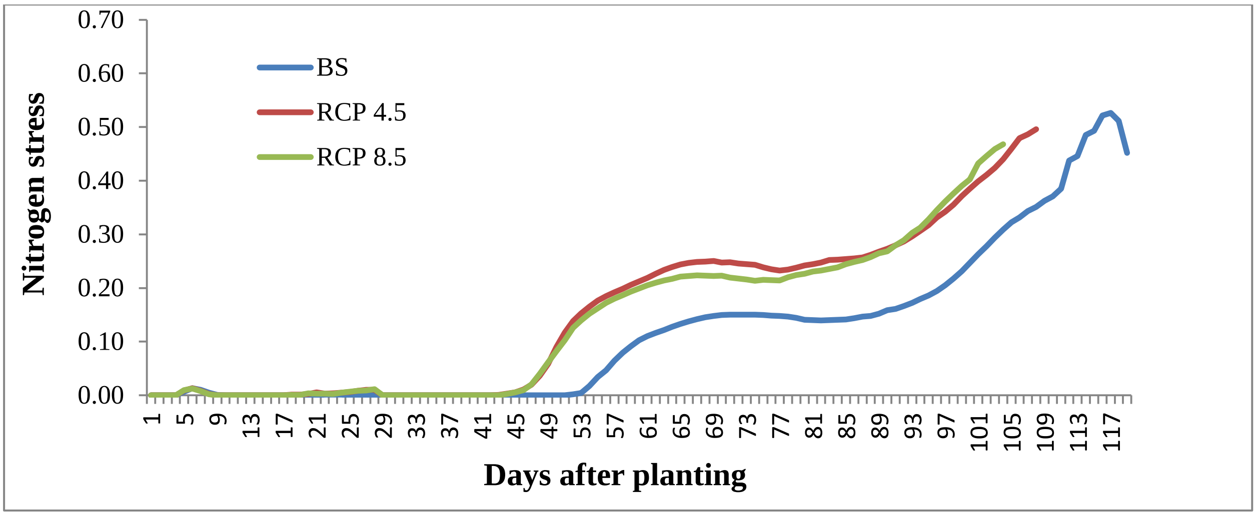


Figure 3.8: Simulated daily nitrogen stress during growing season of maize at Dassari for NREC

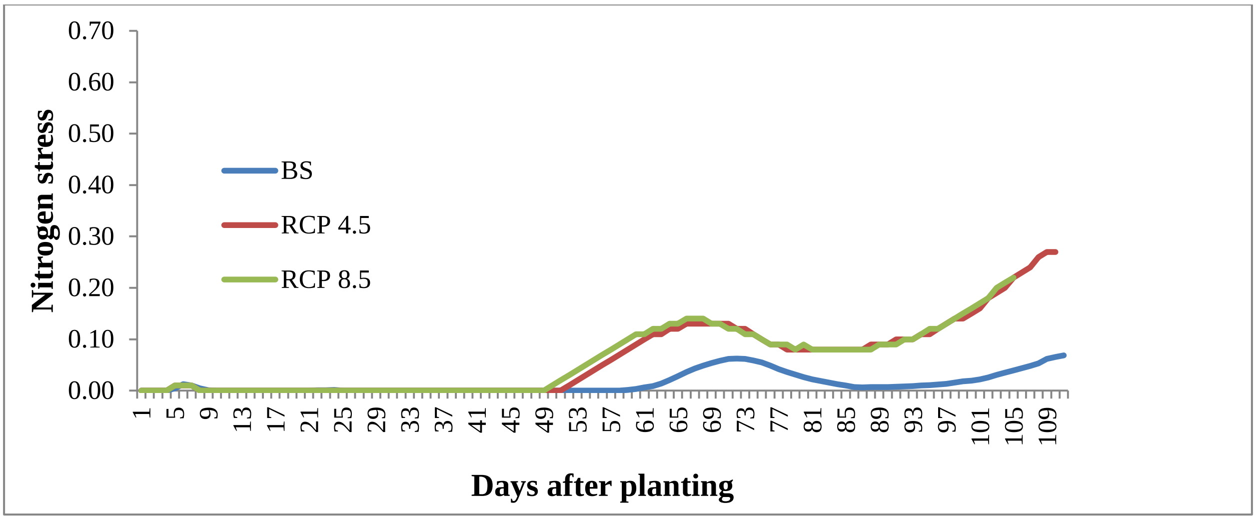


Figure 3.9: Simulated daily nitrogen stress during growing season of maize at Vea for NREC

3.3.3.4. Relationship between the N stress and the mean grain yield

Figure 3.10 shows the relationship between daily mean N stress and mean grain yield for recommended N and no N across the three sites during the impact studies. There was a fairly strong relationship between N stress and maize grain yield (R^2 = 0.6).

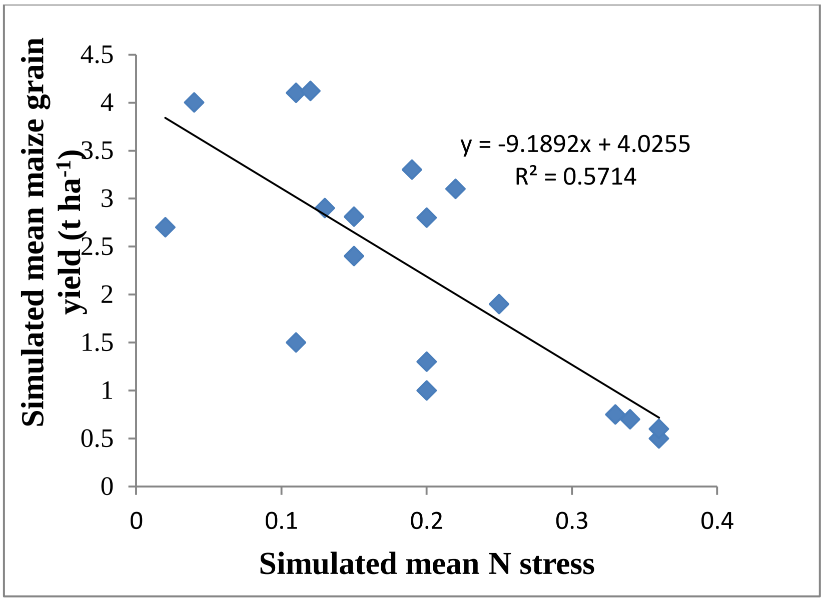


Figure 3.10: The relationship between daily simulated mean N stress and simulated mean grain yield of maize across the three sites

3.3.3.5. Simulated changes of days to physiological maturity during growing season

The expected change in MDAT is summarized in Table 3.12. The results indicate that, there is an overall tendency for maturity and faster development than in the baseline. The decrease in days to physiological maturity in the two scenarios compared to the baseline was simulated at between -8.3 to -0.4 days under RCP 4.5 and -10 to -4 days under RCP 8.5 across the three locations studied. The magnitude of the shortening of physiological maturity varies according to climate scenario, nitrogen fertilizer level and the geographical location. The highest magnitude in changes to days to physiological maturity is expected for Dassari with changes relative to baseline of -10.3 and -8.3 for NREC under RCP 8.5 and RCP 4.5 respectively. Dano is expected to experience the smallest decrease.

Table 3.12: Simulated days to physiological maturity (MDAT) during the maize growing season at Dano, Dassari and Vea under RCP 4.8 and RCP 4.5 climate scenarios

season at Dano, Dassari and Vea under RCP 4.8 and RCP 4.5 climate scenarios

Location	Nitrogen	Baseline (days)	Scenario			
			RCP 4.5		RCP 8.5	
			MDAT (days)	Change (days)	MDAT (days)	Change (days)
Dano	NREC	110.8	110.4	-0.4	106.8	-4
	N0	110.8	110.4	-0.4	106.8	-4
Dassari	NREC	116.3	108	-8.3	106.0	-10.3
	N0	113.8	106.9	-6.9	104.8	-9
Vea	NREC	113.6	108.6	-5	106.4	-7.2
	N0	113.3	108.6	-5	106.4	-6.9

MDAT = days to physiological maturity, NREC=recommended nitrogen fertilizer, N0=no nitrogen fertilizer

Minus sign (-) means decreased number of days to physiological maturity relative to the baseline

3.3.3.6. Impact of simulated climate scenarios on total aboveground biomass (TAGB) and grain yield

Across location and scenarios the simulations show a general tendency of decreasing grain yield relative to the baseline (Fig. 3.11). At Dano for NREC, both RCP 4.5 and RCP 8.5 predict grain yield to decrease by -61% and -45% respectively whereas with no N fertilization, it is expected to decrease by -77% and -67% for RCP 4.5 and RCP 8.5 respectively. At Dassari, use of recommended N fertilizers would results in -38% and -36% yield decreases for RCP 4.5 and RCP 8.5 respectively whereas the grain yield losses for N0 are greater with -61% and -62% for RCP 4.5 and RCP 8.5 respectively. Vea will experience smaller reductions (–12% and -10%) in grain yield for RCP 4.5 and RCP 8.5 respectively with NREC. Yield losses under N0 are greater at -55% and -62% respectively for RCP 4.5 and RCP 8.5. TAGB will follow a similar trend with the highest decline of -72% and -59% expected under RCP 4.5 and RCP 8.5 at Dano. At Dano and Dassari, larger reductions are expected in grain yield and TAGB for NREC plots compared to Vea.

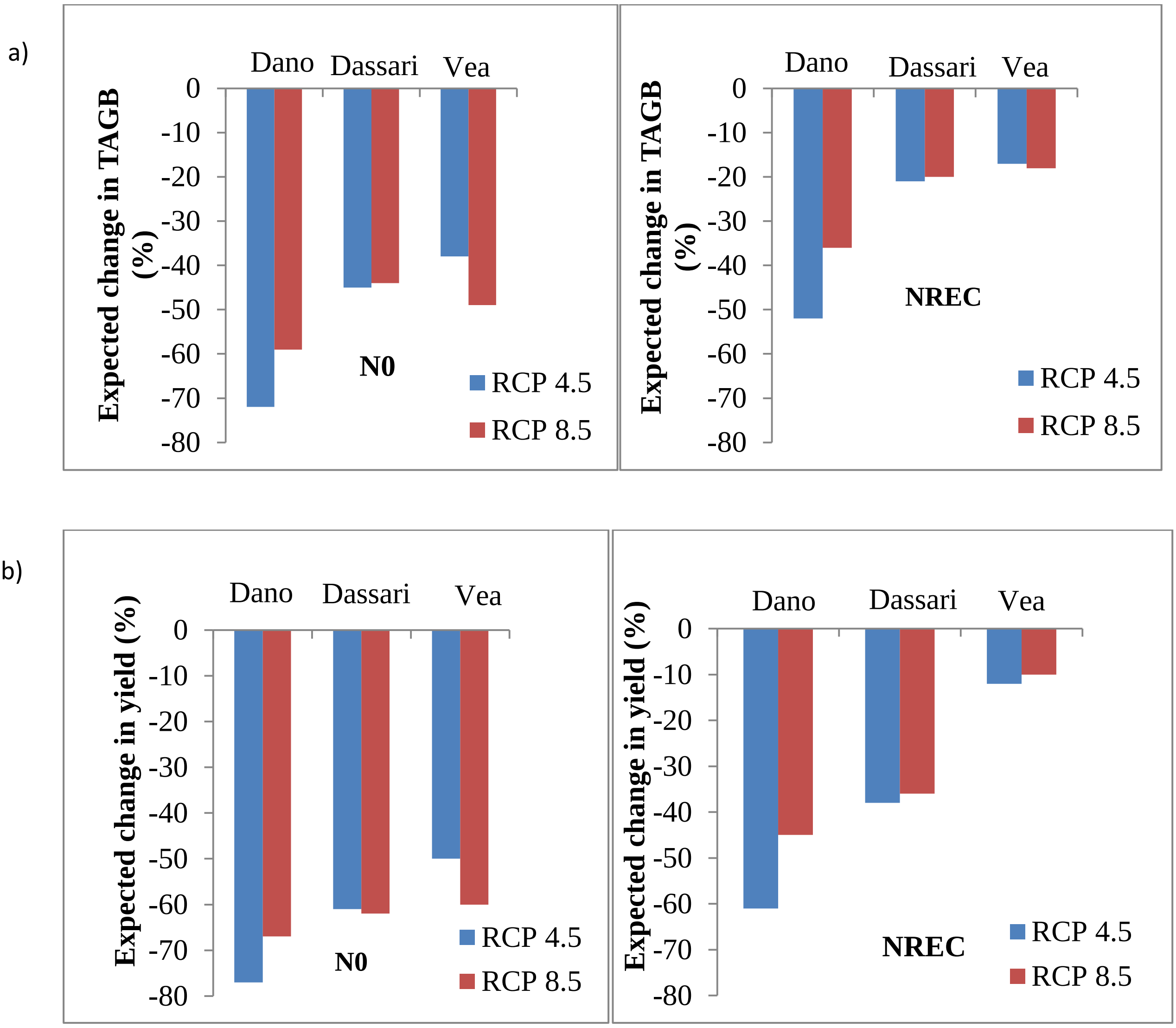


Figure 3.11: Expected mean changes (%) in (a) total aboveground biomass (TAGB) and (b) grain yield for N0 and NREC under RCP 4.5 and RCP 8.5 scenarios at Dano, Dassari and Vea

3.4. Discussion

3.4.1. Climate scenario output by Geophysical Fluid Dynamics Laboratory (GFDL)

The high mean climate scenario precipitation output ranging from 40 to 47% and temperature ranging from 0.7 to1.7^{o}C relative to baseline over the simulation period of 2040-2060 in the Sudan savanna in these studies provide a platform to make comparison with previous studies undertaken with other GCMs by other climate scientist. Using agricultural systems simulator (APSIM) to simulate maize in North Western part of Ghana with nine GCMs (CCCMA, CSIRO, CNRM, GISS, GFDL, IPSL, MIUB, MPI and MRI) for the period between 2045-2065 Tachie-Obeng *et al.*, (2013) observed an increase in temperature being consistent across all the models used in simulation. This translated into decrease in maize grain yield up to -42.6% and authors attributed the reason to shortened crop cycle, thus less biomass accumulation. The same is true for our study which was carried out under similar weather conditions. Also based on application of CERES-Maize model in combination with HadCM2 model, Jones and Thornton, (2005) predicted an overall decrease of maize grain yield of -10% over Latin America and Africa by 2050, with an impact varying between -30 and +2% over sub-Saharan African countries (-14% on average). They attributed the decrease to increase in temperature. Our climate scenarios projected a decrease in yield of -50% (N0) and -33% (NREC) across sites. On the other hand Porter *et al.*, (2014) using empirical large scale relationships between climate and yields extrapolated with projections from 16 climate models, to project crop yields changes in sub-Saharan Africa by 2050. Their report predicted yield decrease on the order of -20% for C4 cereals, which in their study is entirely controlled by temperature increase. Our result is consistent with their report on the basis of both scenarios predicting grain yield decreases but varied based on magnitude between the yield reductions. The high rainfall amount projected by our scenarios remains inconsistent with many studies. These results indicate the need to narrow the uncertainty in precipitation predictions from climate models in order to be able to provide reliable agricultural impact assessment in the Sudan Savanna. For instance whiles our studies predicted an increase in rainfall ranging from 40% to 47% in all the study areas under the two scenarios, in assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian Savannas of West Africa with 35 climate scenarios projected precipitation ranged from -20% to + 20% in 35 stations (Sultan *et al.*, 2013). Furthermore, Akurut *et al.*, (2014) considering potential climate impacts of climate change on precipitation, combined 26 GCMs with RCP 4.5 and RCP 8.5. In their studies precipitation decreased and was predicted to be <10% for RCP 4.5 and <20% for RCP 8.5 for their studies in Lake Victoria, East Africa. From the above discussions, it is imperative to use a wide range of GCMs, irrespective of their resolution in order to suffiently capture the uncertainties in this study.

3.4.2. Crop growth simulation

Our results show that despite correctly simulating mean values, CERES-Maize model was not able to capture the large part of variation in MDAT during calibration and validation for either NREC or N0 treatments except in Vea 2012. This resulted in low model performance for MDAT. These results contradict work by Soler *et al.*, (2007) who reported close prediction of phenology in maize by using CERES-maize in different environments. The observations indicate that MDAT was affected by N application, which is presently not considered in the DSSAT model neither in other crop simulation models. There seem to be a need to incorporate such relationships for simulating phenology in low input systems in the tropics. To some extent the model overestimated TAGB as well as grain yield during the calibration process for plots with NREC in 2014 across the 3 sites with better model performance than for the plots with N0. This contradicts with work by (Srivastava *et al.*, (2012) and He *et al.*, (2011) who reported underestimations for diverse crops under optimal N input using the EPIC model. However, as the experiment was conducted on farmers' fields, abeit it with researcher controlled weeding and pest control, yields were likely limited by factors not considered in the model. Good evaluation performance for in 2012 indicates the calibration process for this case in 2014 was satisfactory. This is consistent with a report by Timsina and Humphreys (2006), Liu *et al.*(2011) and Yang *et al.* (2013) that the DSSAT model showed poorer performance for no fertilizer N than with N fertilizer treatments. This may be due to the DSSAT model being more sensitive to N stress than the real crop growth under zero fertilizer N conditions. Some outliers reported in the simulated results may be due to conditions that are not taken into account by the CERES- Maize model like damage by birds and other animals.

3.4.3. Climate change impact on growth and productivity of maize

The grain yield and TAGB changes due to climate change at three sites is presented in Fig. 3.11, each with distinct precipitation, temperature (T_{min} and T_{max}) and soil conditions. The apparent impact of climate change on maize crop in this study was a decline in TAGB and grain yield due to higher temperatures relative to baseline temperatures across 3 sites under RCP 4.5 and RCP 8.5 climate scenarios as well as increased rainfall and N stress. Our results (Table 3.10 and Table 3.12) validated the statement that higher temperatures around the optimum temperature translate into faster maize development and earlier maturation thus, maize crop intercepted less solar radiation before it completed the growing cycle (Brassard and Singh, 2008). The comparatively higher temperatures of RCP 8.5 than RCP 4.5 (Table 3.10) resulted in shorter DMAT for RCP 8.5 than RCP 4.5. According to Kucharik and Serbin (2008), under future climate, for every degree rise in temperature in the US maize Belt region, maize and soybean yields are potentially expected to reduce by 13 and 16% respectively largely due to faster development rates. In addition, an average change of -9.5% in yield for 2046-2065 was observed by Tachie-Obeng *et al.* (2013) in Ghana under nine climate scenarios. The authors attributed reduction in yield to the fact that in the warm tropics, further increases in temperature may shorten crop life cycles and accelerate crop development rates, implying higher respiration losses, less biomass accumulation and lower crop yields. Higher temperatures also lead to soil desiccation via increased evaporation, increase the saturated vapour deficit and require larger amounts of water vapour to bring the air to saturation. Water stress is a wide spread phenomenon in West Africa and according to Heisey and Edmeades, (1999) estimated 25% of lowland tropical maize regions is affected annually resulting in low yields of crops. The CERES-Maize model did not predict any water stress conditions (results not reported) during photosynthesis and partitioning of assimilate during the growing cycle of maize across sites under both climate scenarios between 2040 and 2060 as precipitation amounts increase significantly at all sites for the model studied here. Despite the large increase in rainfall, the model did not predict waterlogging stress.

Even though the three study areas belong to the same climate ecological zone, slight variability exist and this translated into differences in simulated impacts on future TAGB and grain yields across sites. At Dano, larger decreases in TAGB and grain yield relative to baseline were projected compared to Vea and Dassari.

The role of nitrogen fertilization in projected climate change was apparent in this study. All the climate scenarios show a diminishing future TAGB and grain yield under both no N and recommended N fertilization relative to the baseline (Fig. 3.11). In addition to the shortened growth season, the lower grain yields and TAGB under climate change across the three sites studied may be attributed to nitrogen stress conditions predicted by the CERES-Maize model relative to the baseline (Fig. 3.4 to Fig. 3.9). High rainfall simulation by the scenarios resulted in strong leaching of soil nitrogen. According to Abd El-Lattief (2011), N is highly mobile thus it is subjected to greater losses from the soil plant system under high rainfall conditions and even under best management systems, 30-50% of applied N is lost hence, the farmer is compelled to apply more than the actual need of the crop to compensate for the lost (Abd El-

Lattief, 2011).There exist a wide gap between the recommended N and no N in terms of yield and TAGB accumulated relative to the current climate change conditions as observed in our results. Under the same conditions of increased temperature and rainfall, it is hypothesized that soils with no N will experience greater N stress over years as compared to soils that received nitrogen. Our model estimated higher relative losses in TAGB and grain yield under plots where no N fertilizer was applied compared to recommend N fertilizer plots by 2050. Our results indicate that, the existing farming practice where no N fertilizer is applied will not be able to increase or stabilize yield under the face of current climate change in the Sudan savanna of West Africa. This finding is in line with many reports on the role nitrogen play in climate change mitigation. For example Pathak (2011) indicated nitrogen fertilization as the major driver in increasing food production in India and stated that over years, increasing use of nitrogen correlated positively with increased food production with R^2=0.95. The correlation between the daily mean N stress and mean grain yield in Fig. 5 gave R^2 value of 0.58 indicating that among others, the contribution of nitrogen stress in reducing yield was 58% across sites under the two scenarios. The results of our study are important in that they suggest negative climate impacts under the high rainfall scenario investigated here will be largest for systems using low levels of nitrogen fertilization. However, other studies need ti investigates if this is true for scenarios in which crop water stress increases due to reduced growing season precipitation. Further, the results presented here are the average impacts of climate change. Actual food security for subsistence households can be negatively impacted in years with extreme events (floods or droughts) and it is important to understand how yields are impacted in this cases, under both cases of recommended and no nitrogen application. Our studies in Kenya demonstrated that yield reduction in drought years were the same for high and low input systems (Rötter and Van Keulen, 1997), with the risk of crop failure constituting a large barrier for farmers to apply fertilizer.

Generally, our results indicate that in Dano higher decrease in TAGB and grain yield by RCP 4.5 relative to baseline under both N0 and NREC as compared to RCP 8.5. This may be attributed to higher expected nitrogen stress condition under RCP 4.5 in Dano as compared to RCP 8.5 by 2050. Similarly, Dassari also experienced high rainfall in RCP 4.5 than RCP 8.5. This resulted in greater losses of nitrogen and thus, translated into low grain yield and TAGB. The differences in TAGB and grain yield estimated by the model could not be explained by rainfall since rainfall values were relatively close to each other by RCP 4.5 and RCP 8.5. The magnitude of nitrogen stress differs between the 3 experimental locations and this had an influence on TAGB and grain yield between the locations studied relative to the baseline. The high decrease in both yield and TAGB at Dano compared to Vea and Dano relative to baseline may be due to higher nitrogen stress expected in Dano. Whiles under recommended N application no nitrogen stress is expected during the juvenile stages of the growth of maize in Vea and Dassari under both climate scenarios, the opposite is true for Dano (Fig. 8). Uhart and Andrade, (1995) reported that grain yield and grain number per ear significantly decreased under N stress conditions. They suggested grain loss, seed sterilization and increase in abortion as the likely reasons for the decrease in yield. In Dassari and Vea moderate to slight negative changes results from TAGB and grain yield relative to baseline of -37% (NREC) and -61% (N0) and -11% (NREC) and -58.5% (N0) respectively as compared to Dano which recorded a higher reduction (Fig 3.11). The comparatively low N stress conditions expected at Vea (eg. NREC) (Fig. 3.9) is the reason behind the low decrease in yield from the baseline as compared to Dassari and Dano. In increasing order of N stress, under both climate scenarios Vea < Dassari < Dano. Across the three sites, the response of maize to N mineral fertilizer decreased with progressing climate change, implying a decrease in optimal fertilizer rate in the future. Our research suggests that in future improved crop and soil fertility management will remain important for enhanced maize yield production in the Sudan Savanna of West Africa.

Chapter four

4.0. How can adaptations reduce negative impacts of climate change across sites in the Sudan Savanna of West Africa?

4.1. Introduction

The ability of farmers in West Africa to continue using current farming practices in cultivating cereals like maize is questionable, taking into consideration future climate change. The latest IPCC synthesis report, suggests with high confidence that warming is inevitable (IPCC, 2007). A number of studies considering climate change have shown that an increase in temperature of 1^oC to 2^oC in dry tropical regions such as the Sudan Savanna will cause a decrease in crop yield (Lobell *et al.*, 2008; IPCC, 2007). Climate change without adaptation strategies is expected to have a very large negative crop yields. Cereal yields of lower latitude such as the Sudan savanna are likely to fall between 10% and 20% by 2050 due to global warming and maize is of no exception. Maize is an important staple crop in West Africa and an integral part of a number of food items in Ghana (CSIR-FRI, 1986). The crop is therefore critical to determining food security in the region. Improving maize productivity will be key reverse West Africa's negative trend in per capita food production. According to IPCC, report (2007) and Thornton *et al.*,(2009) crop yield from rain-fed agriculture may be reduced by 50% by 2020. Most previous climate impact studies in West Africa have been limited to assessing impacts on current agricultural systems without accounting for potential adaptation strategies. For example, Fosu-Mensah, (2012) estimated climate change impacts on maize production in a sub-humid tropical region of Ghana without considering adaptation options. Roudier *et al.*, (2011) also analyzed a meta-database of future yield change of 16 published papers dealing with impact of climate change in West Africa with consideration to few strategies to reduce the negative impacts. Likewise, Sultan *et al.*(2013) did not account for adaptations when assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian Savannas of West Africa. Mizina *et al.*, (1999) reported that adaptation is certainly an important component of any policy response to climate change in the agricultural sector.

Given importance of climate adaptation, the IPCC Fifth Assessment Report (AR5) stresses the need to consider the impacts and adaptations to climate change (IPCC, 2014) and adaptive cropping systems to improve food security. Farmers in the Sudan Savanna lack the investment capacity thus, it is important to select management adaptation strategies that are already available to farmers given current constraints. The use of crop residues from previous cropping cycle is one option that may improve yields and stabilize them in years with extreme conditions (see chapter 2). However, it is unknown how the practice of using crop residues combined with different levels of nitrogen will affect yield levels under climate change compared to the traditional practices (no N, no residues but with CR). With this context, the objective of the study was to evaluate recommended nitrogen (NREC) combined with improved residue management (IRM) under contour ridges (CR) and high nitrogen application rates (N2REC) with improved residue management (IRM) under contour ridges as potential adaptation strategy to improve maize yields under climate change. Maize was selected since is one of the main staple crops in West African Sudan Savanna.

4.2. Materials and methods

4.2.1. Study area

The study area is in the Sudan Savanna of Ghana, Benin and Burkina Faso as described in details in chapter 2.

4.2.2 Experiment for model calibration

Observation from two potential adaptation management practices, recommended (60 kg N ha^{-1}) (NREC) and high nitrogen (120 kg N ha^{-1}) (N2REC) with improved residue management (IRM) under contour ridges (CR). The analysis was conducted 2 landscape positions (footslope and upslope). The control treatment was no N fertilizer application (N0) with standard residue management (SRM) and contour ridges (CR). All treatments were replicated four times at both upslope and footslope sites. Based on our adaptation options considered, we evaluated adaptation in the baseline as proposed Lobell, (2014). Residues from previous planting of cotton were applied non-incorporated two weeks after planting of maize at the three sites. Fertilizers were broadcasted and incorporated immediately 25 days and 45 days after planting as recommended by Fosu-Mensah, (2012). Potassium and phosphorus were applied non-limiting. An early maturing (90 days) drought tolerant maize cultivar Dorke SR, was used for the experiments. Planting was done on June 24, 2014 in Dassari, June 26, 2014 in Dano and July 1, 2014 in Vea for the calibration. Planting density was fixed at 62,500 plants ha^{-1} with 0.8 m between rows and with two plants per hole at 0.4 m distance within rows. Maize was thinned (2 plants / hole) at 15 days after planting and reseeded as necessary to achieve the above density. Pest and weeds were controlled to remove any stress. Maize was monitored and phenological data as well as management information were collected, including sowing date, date of fertilizer application, date of anthesis/flowering and date of physiological maturity. The phenological stages were noted when 50% of plant population attained that stage. Harvesting was done at physiological maturity. Maize yield was estimated from a net area of 9 m^2 (4 rows of 3 metres length) in the center of the plot to avoid border effects. A sub-sample (10) of cobs per plot was shelled and oven dried at 70^0C for 2 days to determine grain moisture content. Total aboveground biomass accumulation over the growing season was taken on $2m^2$ plots at 2 to 3 week intervals, starting one month after sowing and oven dried to convert fresh weight to dry matter. The soil information is reported in Chapter 3 (Table 3.1 to 3.4).

4.2.3. Model calibration

As in chapter 3, we used the CERES-Maize model embedded in DSSAT V. 4.6 for the adaptation studies. The model was chosen because it is well accepted and widely used in the crop modeling community to evaluate various adaptation options (Tubiello and Ewert, 2002).

The genetic parameters used for calibration were the same as the one captured in chapter 3 (Table 3.5). A modification of the soil fertility factor (SLPF) was considered during the calibration as this factor varied between the three locations studied. Data were collected in 2014 from WASCAL meteorological stations and used in the model calibration for daily records of precipitation (mm); maximum and minimum air temperature (°C), and solar radiation (MJ m^{-2}). The agreement between observed data and simulated values was evaluated using:

1. The coefficient of determination (R^2) which can be interpreted as the proportion of the variance in the observed data that is attributable to the variance in the simulated data.

2. Root mean square error (RMSE) by Willmott and Matsuura, (2005):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}}$$

(3) Index of agreement (d) statistics by (Willmott, 1981):

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{M}\right| + \left|M_i - \bar{M}\right|\right)^2}$$

Where S_i is the simulated value, M_i is the measured value, n is the number of values, and M is the average of the measured values.

4.2.4. Climate change scenarios

The same climate scenario information derived from the general circulation model (GCM) GDFL and regional circulation model (RCM) RegCM4 used in Chapter 3 was employed here. A description of how the projected temperature and precipitation data compare to climate data in the baseline is given in Chapter 3.

4.3. Results

4.3.1. Model calibration

4.3.1.1. Model calibration under no nitrogen treatment, contour ridges and standard residue management (N0 CR SRM) (current practice) at the three sites

The model overestimated days to physiological maturity (MDAT) in both Vea and Dano by 2 and 6 days with index of agreement of 0.4 and 0.2 respectively for N0 during calibration. Dassari was however, underestimated by 8 days with an index of agreement of 0.5. The Dassari location recorded relatively high RMSE values which indicates low accuracy in simulation for MDAT (Table 4.1).

The model was able to simulate total aboveground biomass (TAGB) in good agreement with observations during calibration with a coefficient of determination (R^2) of 0.7, for all sites. The index of agreement for Vea, Dano and Dassari of 0.9, 0.8 and 0.84 respectively indicated good model performance (Table 4.1). The model performance in simulating grain yield was good at both Vea and Dano with R^2 of 0.7 and 0.7 during calibration for N0. However, the simulation of grain yield in Dassari was underestimated by -36%.

Table 4.1: Comparison of observed and simulated results during model calibration under no nitrogen application (N0) (current practice) at the three sites (contour ridges and standard residue management)

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
		Vea	112	114		0.4	2.8	8
Maturity	day	Dano	107	113		0.2	6.3	8
		Dassari	112	104		0.5	10.4	8
		Vea	1344	1542	0.7	0.9	659.4	8
Mat Yield	Kg ha $^{-1}$	Dano	1644	1164	0.7	0.6	749.9	8
		Dassari	2327	1473	0.1	0.5	1147.1	8
		Vea	3054	3579	0.7	0.9	1165	8
TAGB	Kg ha $^{-1}$	Dano	3989	4291	0.7	0.8	692	8
		Dassari	6099	5944	0.7	0.8	588	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N = number of subplots

4.3.1.2. Model calibration under recommended nitrogen application, contour ridges and improved residue management (NREC CR IRM) at the three sites

Simulation results of days to physiological maturity (MDAT), grain yield and TAGB for the NREC treatment during calibration is shown in Table 4.2. In contrast to N0 treatment, MDAT at Dassari was underestimated by 4 days with index of agreement value of 0.4 and RMSE value of 4.8. MDAT at both Vea and Dano were overestimated by 12 and 5 days respectively. The model simulated TAGB faily well for all the three locations studied with coefficient of determination (R^2) values of 0.4, 0.5 and 0.6 for Vea, Dano and Dassari respectively. Index of agreement values ranging from 0.4 to 0.6 shows moderately good performance of the model. The model overestimated TAGB in all three sites studied by 16%. Grain yield was underestimated at Vea and Dassari with both having an index of agreement value of 0.4. R^2 varied from 0.1 to 0.5 for the three locations for grain yield.

Table 4.2: Comparison of observed and simulated results during model calibration under recommended nitrogen application, contour ridges and improved residue management (NREC CR IRM) at the three sites

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
		Vea	102	114		0.2	11.7	8
Maturity	day	Dano	107	112		0.3	5.0	8
		Dassari	108	104		0.4	4.8	8
		Vea	2481	2126	0.2	0.4	1390	8
Mat Yield	Kg ha $^{-1}$	Dano	2370	2946	0.5	0.5	1304	8
		Dassari	4676	3948	0.1	0.4	1213	8
		Vea	4361	4460	0.4	0.6	1645	8
TAGB	Kg ha $^{-1}$	Dano	5470	6984	0.5	0.6	1884	8
		Dassari	9497	11077	0.6	0.4	1753	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N = number of subplots

4.3.1.3. Model calibration under high nitrogen application, contour ridges and improved residue management (N2REC CR IRM) at the three sites

After calibration for the N2REC treatment, the model overestimated days to physiological maturity (MDAT) in both Vea and Dano by 12 and 5 days with both having index of agreement value of 0.2. Dassari was however, underestimated by 4 days with an index of agreement of 0.3. Vea recorded relatively high RMSE which indicate low accuracy in simulation for MDAT (Table 4.3).

The model was able to simulate total aboveground biomass (TAGB) with relatively good agreement with observed during calibration with R^2 of 0.6, 0.5 and 0.7 for Vea, Dano and Dassari respectively. The index of agreement for Vea, Dano and Dassari of 0.9, 0.6 and 0.6 respectively indicated good model performance (Table 4.3). The model performance in simulating grain yield was poor in Vea, Dano and Dassari having R^2 of 0.3, 0.2 and 0.2 respectively.

Table 4.3: Comparison of observed and simulated results during model calibration under higher nitrogen application, contour ridges and improved residue management (N2REC CR IRM) at the three sites

Variable	Unit	Location	Obs	Sim	R^2	d-stat	RMSE	N
Maturity	day	Vea	102	114		0.2	12.6	8
		Dano	107	112		0.2	5.1	8
		Dassari	108	104		0.3	4.6	8
Mat Yield	Kg ha $^{-1}$	Vea	2706	2332	0.3	0.7	1088	8
		Dano	2816	3215	0.2	0.4	1179	8
		Dassari	4353	4093	0.2	0.5	777	8
TAGB	Kg ha $^{-1}$	Vea	4767	4937	0.6	0.9	1189	8
		Dano	5753	7634	0.5	0.6	2483	8
		Dassari	9279	11437	0.7	0.6	2428	8

Obs=Observed Sim=Simulated, R^2=Coefficient of determination, d-stat=Index of agreement, RMSE=Root Mean Square Error, TAGB=Total Aboveground Biomass, N = Number of subplots

4.3.2. Simulated nitrogen stress under baseline climate and climate change scenarios

4.3.2.1. No nitrogen fertilizer application, contour ridges and standard residue management (N0 CR SRM) (current practice)

Fig. 4.1 to Fig. 4.3 show maize growing season projected nitrogen stress for baseline and two climate scenarios for the three sites during the growing season of maize for plots that received no nitrogen fertilizer. Nitrogen stress which is an index ranges from 0 to 1.The model indicates 0 as no nitrogen stress and maximum nitrogen stress as 1. There is virtually no nitrogen stress during the early growth stages of maize crop for Dano, Dassari

and Vea. Nitrogen stress is expected to increase in all the three sites under both climate scenarios during projected years. The daily cumulative mean highest nitrogen stress of 0.4 is projected at Dano under RCP 4.5 with the lowest of 0.2 under RCP 4.5 at Vea. Growing cycle daily mean nitrogen stress is expected to increase by 72%, 140% and 26% for Vea, Dano and Dassari respectively relative to the baseline of the three locations under RCP 4.5. The anticipated cumulative daily mean change in nitrogen stress during the growing season for the RCP 8.5 relative to the respective baseline for Vea, Dano and Dassari will be 100%, 100%, and 32% respectively.

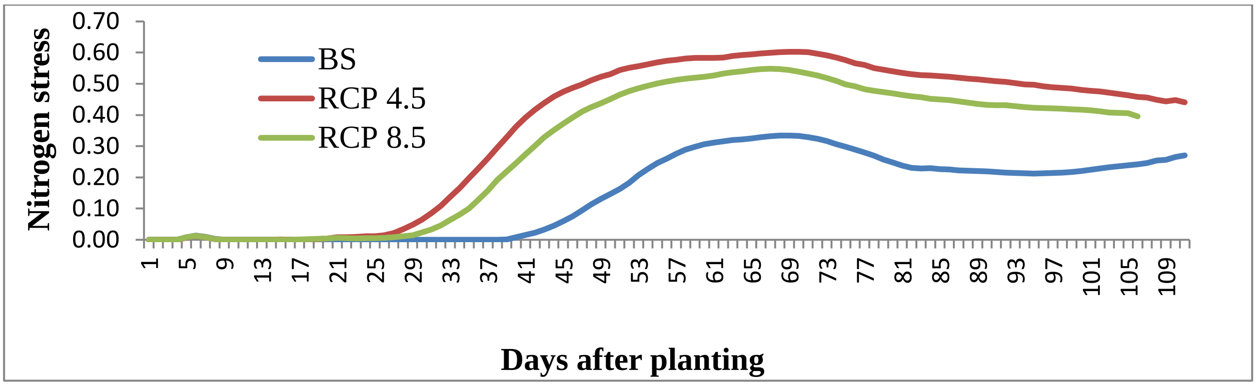


Figure 4.1: Simulated daily nitrogen stress during maize growing season of maize at Dano for N0 plots

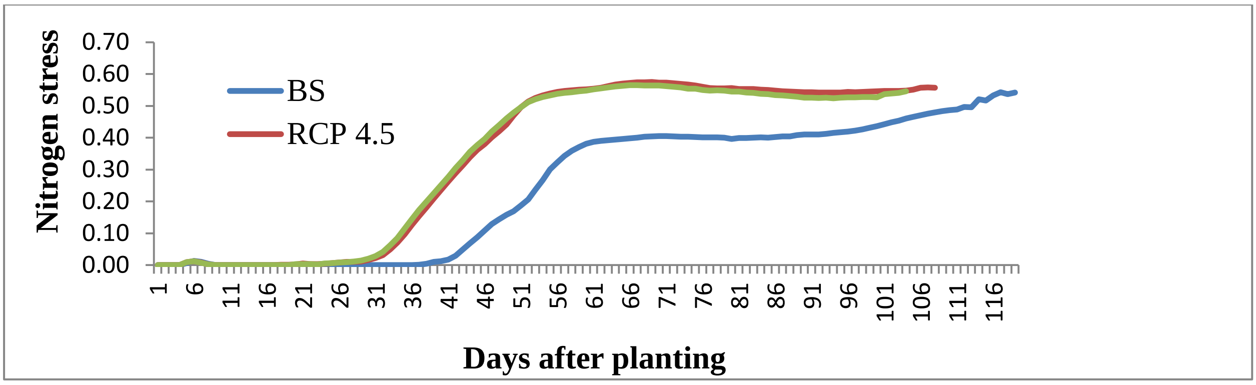


Figure 4.2: Simulated daily nitrogen stress during maize growing season of maize at Dassari for N0 plots

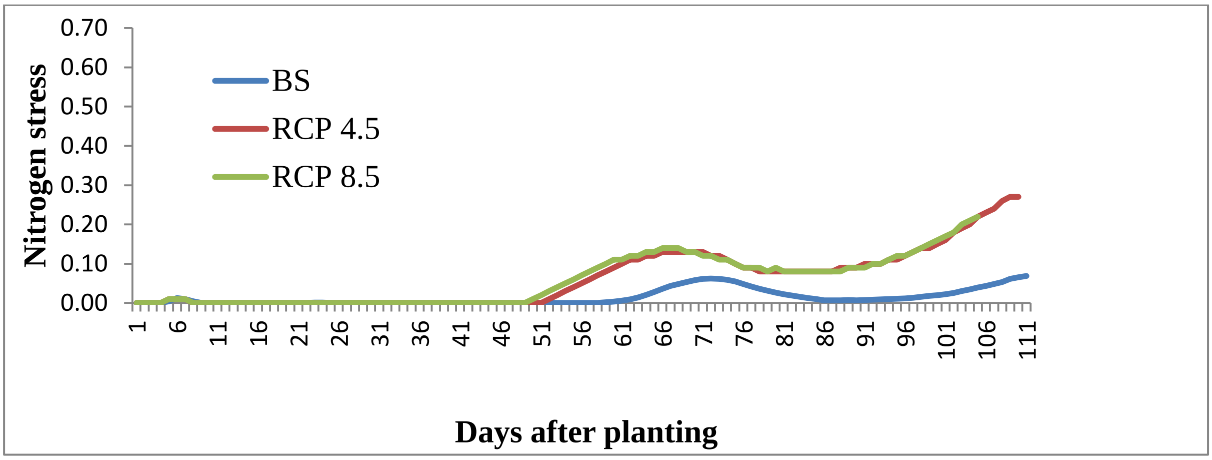


Figure 4.3: Simulated daily nitrogen stress during maize growing season of maize at Vea for N0 plots

4.3.2.2. Recommended rate of nitrogen fertilizer application (adaptation N^{o} 1)

Fig. 4.4 to Fig. 4.6 shown maize growing season simulated nitrogen stress for baseline climate for two climate scenarios during the growing season of maize for NREC single and split dose nitrogen fertilizer application at Vea, Dano and Dassari. There is relatively low nitrogen stress for baseline during the growing cycle of maize at Vea as compared to RCP 4.5 and RCP 8.5 for both single and split nitrogen fertilizer application. Nitrogen stress is lower in split dose nitrogen fertilizer application across 3 experimental sites as compared to single dose nitrogen application. Cumulatively, across sites for the baseline and the two climate scenarios, nitrogen stress in single dose application of recommended rate is 7% higher than split nitrogen fertilizer application. There is no apparent expected difference between nitrogen stress under the two climate scenarios across sites for both split and single dose nitrogen application. Nitrogen stress is high in Dassari and lowest in Vea with both climate change scenarios for both single and split nitrogen fertilizer application.

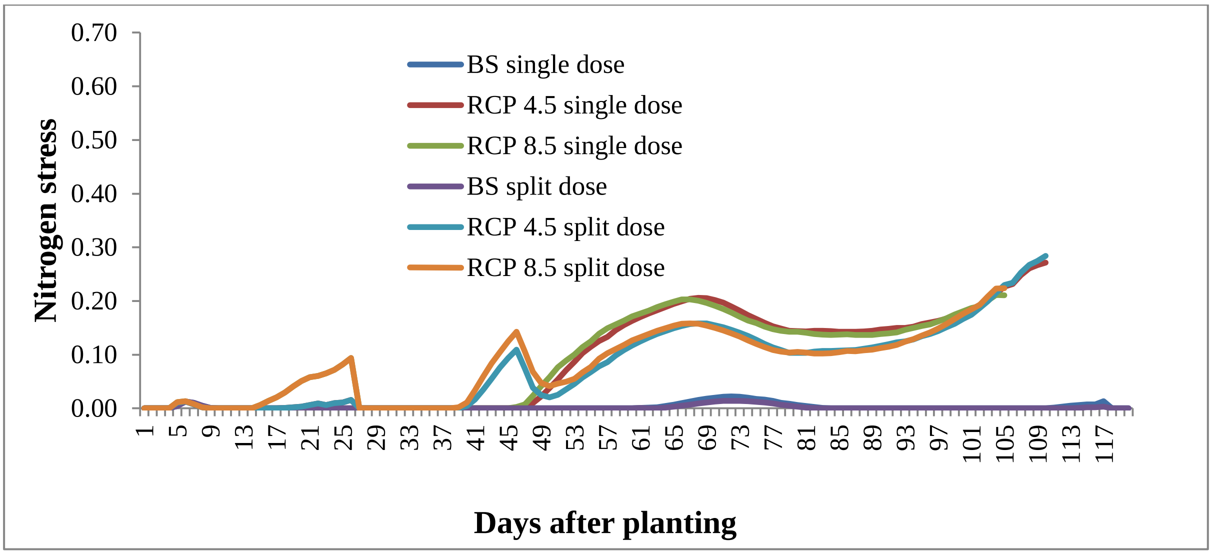


Figure 4.4: Simulated daily nitrogen stress during the growing season of maize under NREC single and split dose nitrogen fertilizer application (adaptation N° 1) at Vea

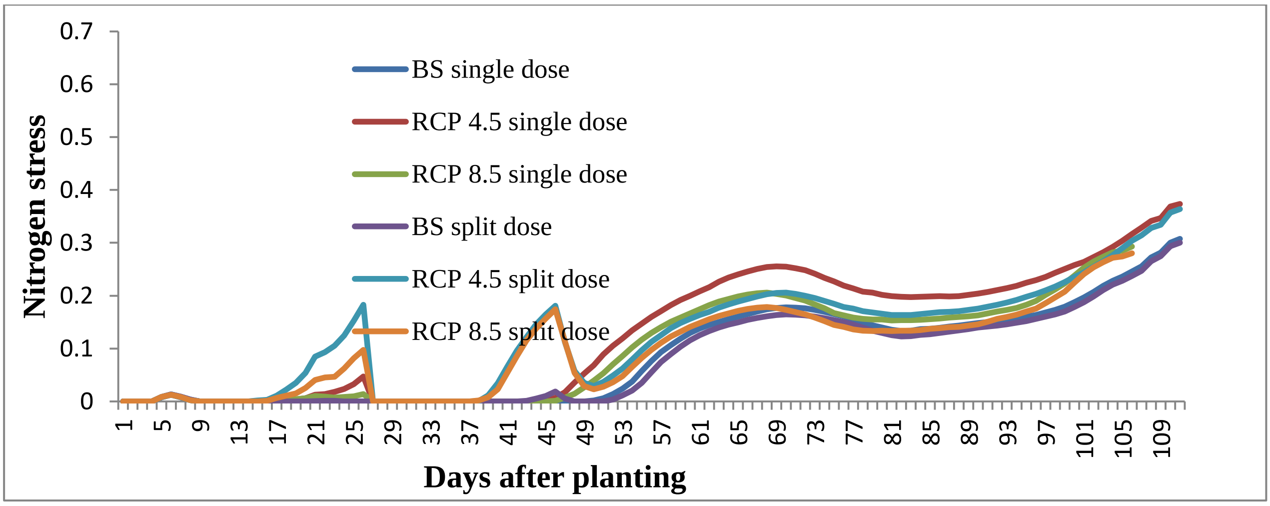


Figure 4.5: Simulated daily nitrogen stress during the growing season of maize under NREC single and split dose nitrogen fertilizer application (adaptation N° 1) at Dano

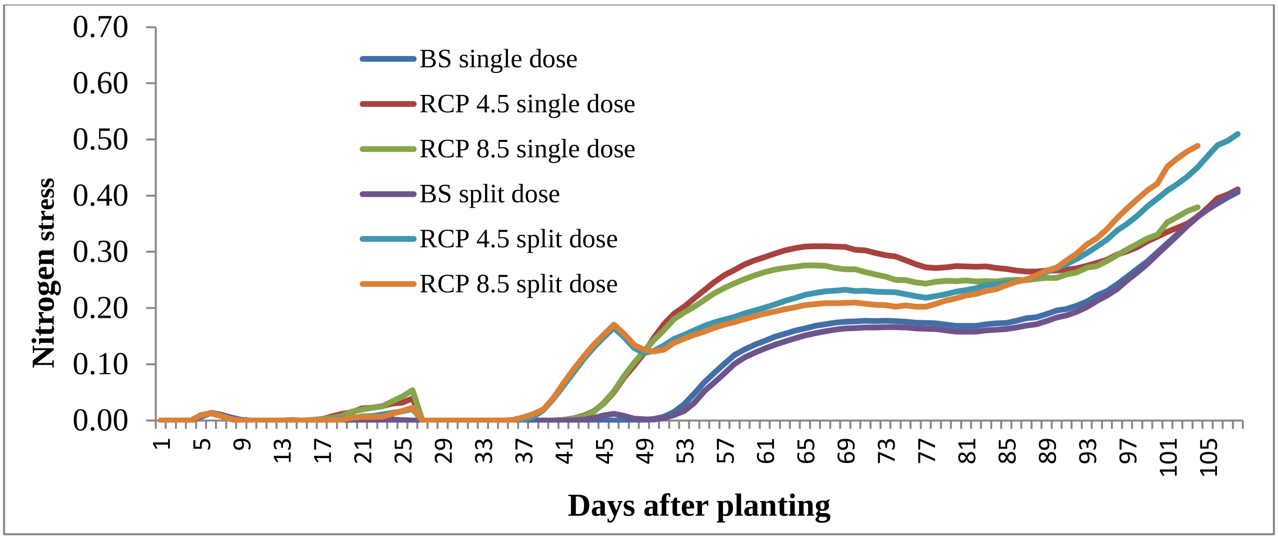


Figure 4.6: Simulated daily nitrogen stress during the growing season of maize under NREC single and split dose nitrogen fertilizer application (adaptation N^o 1) at Dassari

4.3.2.3. High rate of nitrogen fertilizer application, (adaptation N^o 2)

The projected nitrogen stress for high nitrogen rates (single and split applications) for baseline and the two climate scenarios for the three locations is summarized in Fig. 4.7 to Fig. 4.9. Baseline had the lowest simulated nitrogen stress during the growing season of maize across the 3 experimental sites as compared to RCP 4.5 and RCP 8.5 regardless of nitrogen fertilizer application being single or split application. Nitrogen stress in split dose application plots was expected to be lower than single nitrogen fertilizer application by 67% during the growing cycle of maize. Vea site had the lowest nitrogen stress under baseline and the two scenarios with the highest nitrogen stress being recorded in Dassari site.

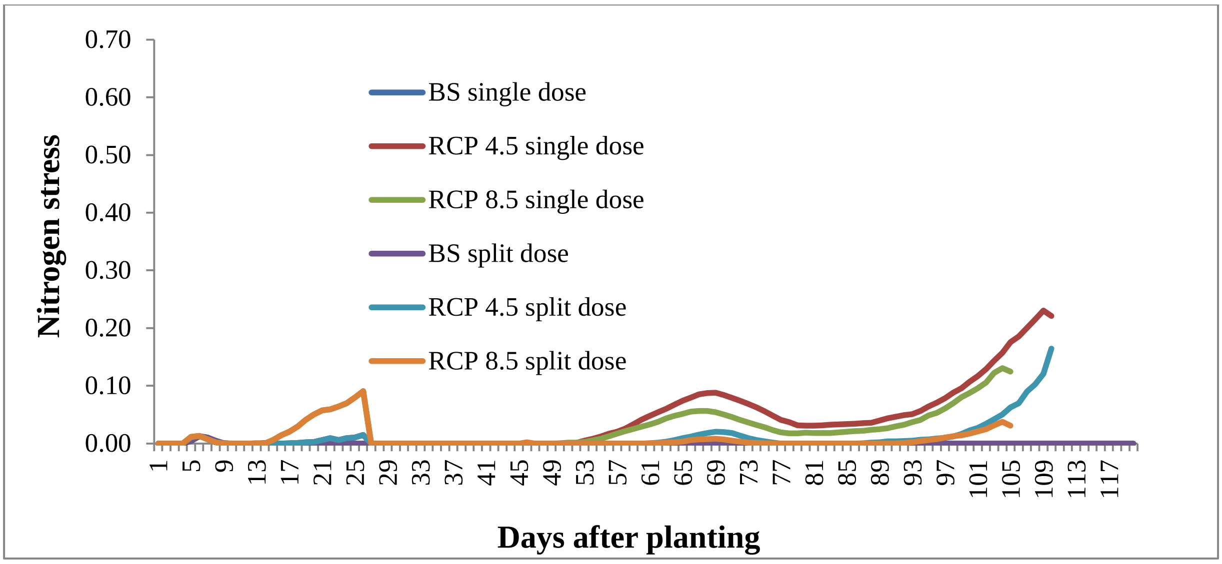


Figure 4.7: Simulated daily nitrogen stress during the growing season of maize under N2REC single and split dose nitrogen fertilizer application (adaptation N° 2) at Vea

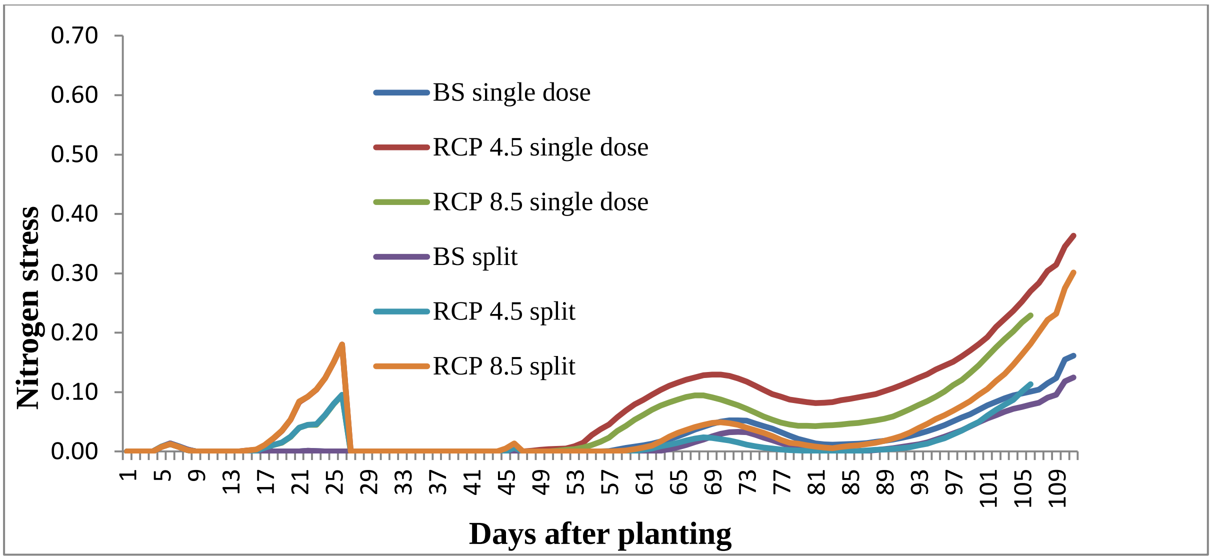


Figure 4.8: Simulated daily nitrogen stress during the growing season of maize under N2REC single and split dose nitrogen fertilizer application (adaptation N° 2) at Dano

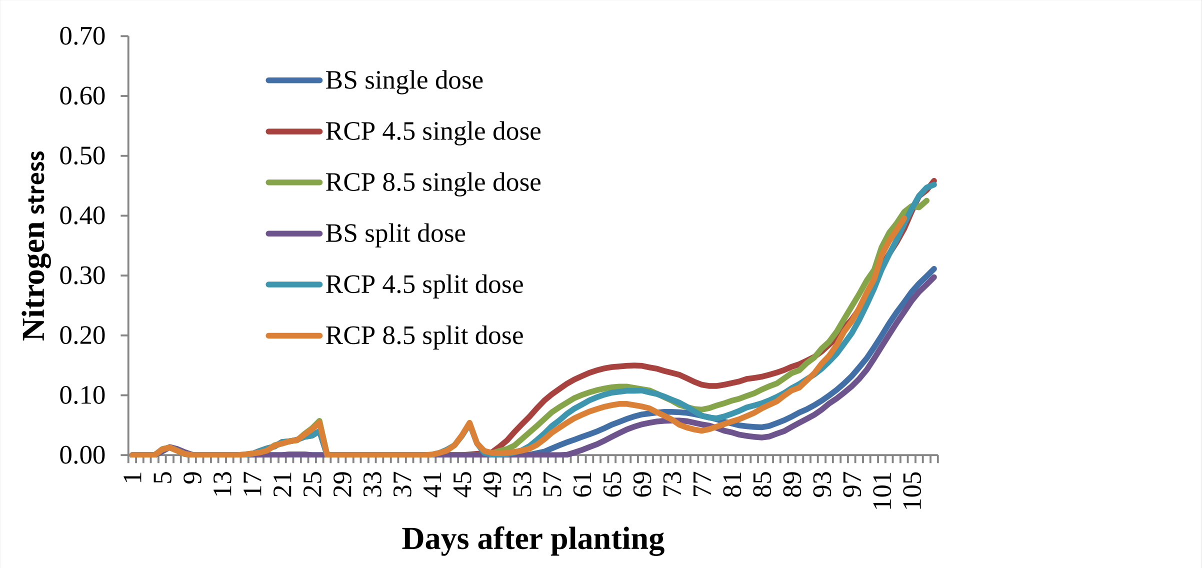


Figure 4.9: Simulated daily nitrogen stress during the growing season of maize under N2REC single and split dose nitrogen fertilizer application (adaptation N^{o} 2) at Dassari

4.3.3. Impact of climate change on grain yield and Total above ground biomass on current farmers practice and two adaptive management practices under climate change

Baseline TAGB is highest as compared to two scenarios across sites under both adaptation options regardless of nitrogen application as split or as single dose (Table 4.4). Cumulatively, baseline TAGB of 28% was the same for both climate scenarios. The agronomically effective adaptive option (N2REC split) had about 2.6 times higher TAGB than the current farmers practice (N0) under the two scenarios across the three sites. There is no apparent expected difference between the two scenarios in TAGB. Expected grain yield followed a similar trend as occurred in TAGB (Table 4.5). Baseline grain yield is expected to be higher than the two climate scenarios. The adaptation option N2REC, split is expected to be about 4 times higher in grain yield than the current practice during simulation.

Table 4.4: Effect of current farmers practice (N0) and two management adaptations (adaptation N° 1, NREC and adaptation N° 2, N2REC) under climate change on simulated maize TAGB (t ha^{-1}) at Vea, Dano and Dassari

Site	Scenario	Current practice (N0)	Adaptation N°1 Application method		Adaptation N° 2 Application method	
			Single	Split	Single	Split
Dano	Baseline	7.8	11.9	12.0	12.0	12.0
	RCP 4.5	4.8	7.7	8.2	9.6	10.2
	RCP 8.5	3.9	7.5	7.8	9.5	9.9
Dano	Baseline	7.1	10.2	10.5	12.7	12.9
	RCP 4.5	1.9	7.4	7.4	9.6	10.9
	RCP 8.5	2.8	7.7	7.6	9.5	10.3
Dassari	Baseline	6.4	11.7	12.1	15.0	15.4
	RCP 4.5	3.5	8.5	8.9	12.7	14.0
	RCP 8.5	3.5	8.9	9.1	13.4	14.0

Table 4.5: Effect of current farmers practice (N0) and two management adaptations (adaptation N° 1, NREC and adaptation N° 2, N2REC) under climate change on simulated maize grain yield (t ha^{-1}) at Vea, Dano and Dassari

Site	Scenario	Current practice (N0)	Adaptation N°1 Application method		Adaptation N° 2 Application method	
			Single	Split	Single	Split
Dano	Baseline	2.7	4.4	4.4	4.4	4.4
	RCP 4.5	1.3	2.6	3.1	3.7	4.0
	RCP 8.5	1.0	2.4	2.8	3.5	3.7
Dano	Baseline	2.0	3.6	3.7	4.8	4.8
	RCP 4.5	0.4	2.4	2.7	3.8	4.5
	RCP 8.5	0.6	2.5	2.6	3.6	3.9
Dassari	Baseline	1.9	4.7	4.9	6.5	6.7
	RCP 4.5	0.7	2.6	3.0	5.1	5.9
	RCP 8.5	0.7	2.8	3.2	5.5	5.8

4.3.4. Response of grain yield and TAGB to adaptation management practices

At Vea, across the two scenarios, simulations indicated that adaptation options tested could reduce the negative impacts of climate change. (Fig.4.10). For the first adaptation option (NREC), single and split nitrogen dose fertilizer application reduced negative changes in yield by 23% and 40% respectively under both scenarios. The situation for TAGB was similar, with split fertilizer application reducing negative impacts more than the single dose application due to climate change. The second adaptation option (N2REC) resulted in the least impacts in both grain yield and TAGB. For the grain yield, single dose application reduced negative changes in yield by 68% whereas changes in reduction in yield by split application was 87%. The ability of split nitrogen application of high nitrogen rates (N2REC) to reduce negative change of TAGB was 22% greater than the single dose application under both scenarios in Vea.

At Dano, the tendency of the adaptation options to reduce negative yield changes caused by climate change in both TAGB and grain yield was similar to Vea regardless of the climate scenario. Under recommended N rate, single dose application reduced negative changes in grain yield by 2.4 folds whereas split nitrogen application was 2.6 folds. For TAGB, single and split dose reduced negative changes by 61% and 57% respectively (Fig. 4.11). The second adaptation option (N2REC) was agronomically effective in reducing negative changes in both grain yield and TAGB. For grain yield split nitrogen application reduced negative changes by 82% whereas single application reduced them by 69%. A similar pattern was observed regarding TAGB.

At Dassari, as observed in Fig. 4.12, adaptation option NREC with split dose was able to change grain yield losses from -61.5% to -35% under both scenarios whereas that of single application reduced yield losses from -61.5% to -41% (Table 4.5). Greater reduction of the yield losses was estimated for N2REC adaptation under both scenarios. The response of TAGB to adaptation options was similar to that of grain yield with split nitrogen application estimated to be more promising in reducing TAGB losses.

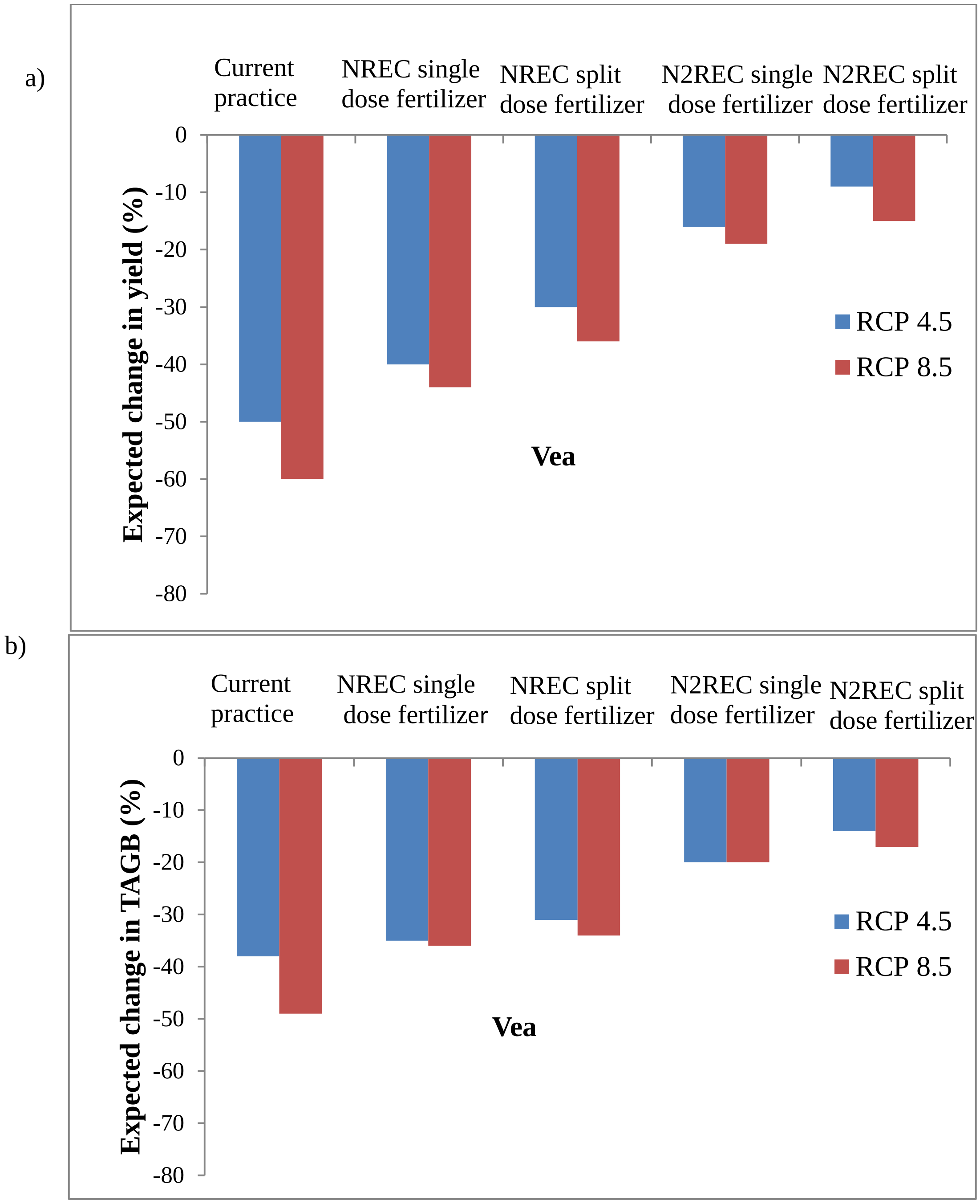
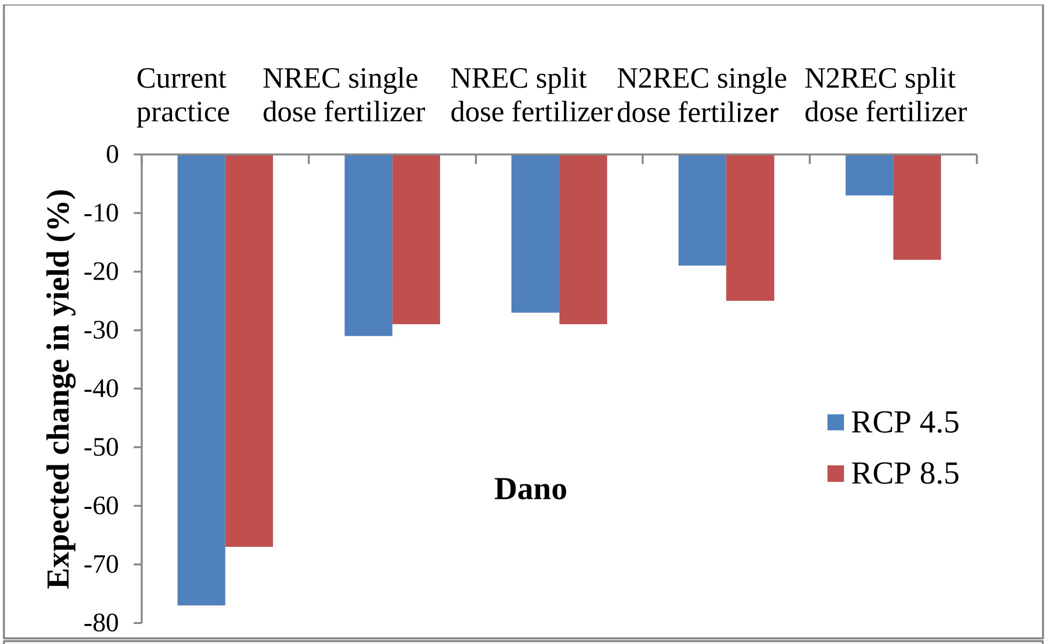


Figure 4.10: Expected change (%) in (a) grain yield and (b) TAGB with and without adaptation options at Vea. NREC= recommended nitrogen fertilizer and N2REC = high nitrogen fertilizer, current practice= N0

a)



b)

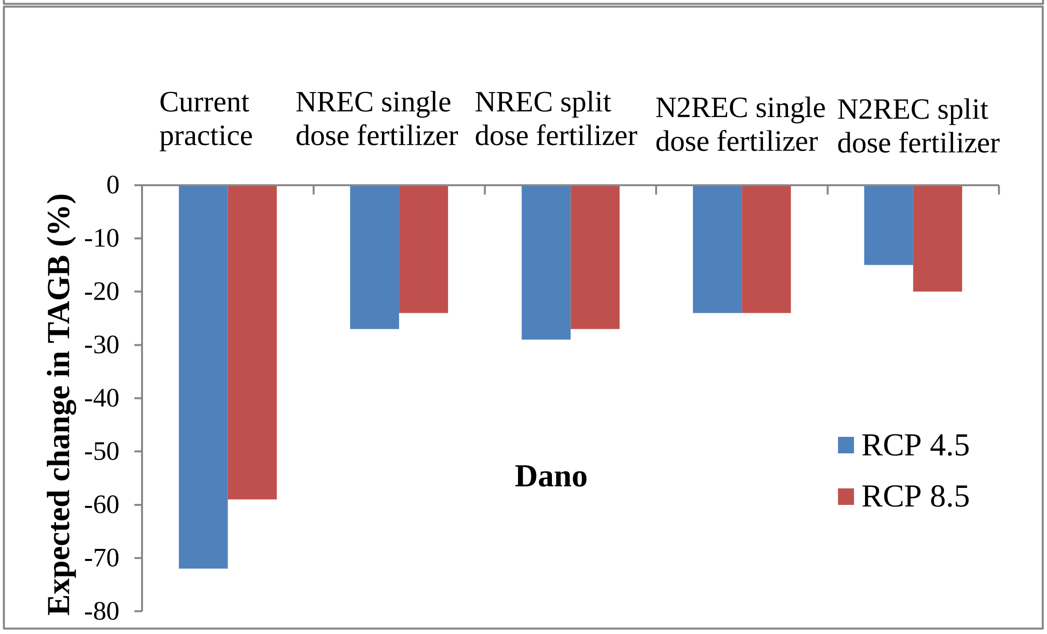


Figure 4.11: Expected change (%) in (a) grain yield and (b) TAGB with and without adaptation options at Dano. NREC= recommended nitrogen fertilizer and N2REC = high nitrogen fertilizer, current practice=N0

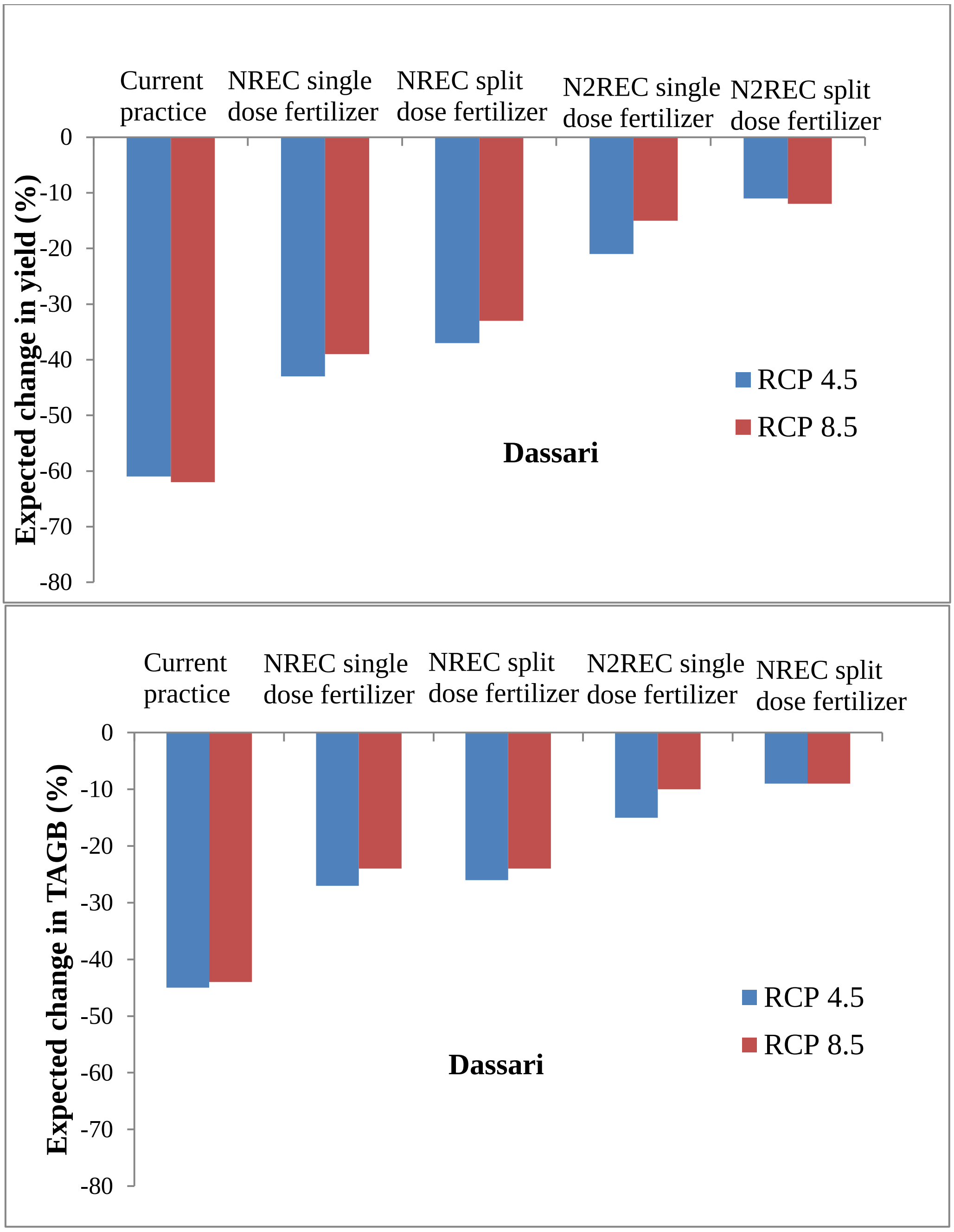


Figure 4.12: Expected change (%) in (a) grain yield and (b) TAGB with and without adaptation options at Dassari. NREC= recommended nitrogen fertilizer and N2REC = high nitrogen fertilizer, current practice=N0

4.4. Discussion

4.4.1. Changes in temperature and precipitation between baseline and climate scenarios

Under the climate adaptation simulations, both projected temperature and precipitation were relatively higher than the baseline for the two climate scenarios across the three sites (Table 3.10 and 3.11).The increased temperature reflected in the shortening of maize growing cycle by both scenarios in all the sites, thus, resulting in yields losses compared to the baseline. The increase in rainfall under the two scenarios by 2050 led to a corresponding had a corresponding increase in nitrogen stress as a result of leaching but the stress level was lower as compared to the current practice by farmers (N0) and this is evident in Fig. 4.4 to Fig. 4.9. In contrast to our work many climate change adaptation reports in West Africa have predicted a decrease in rainfall relative to the baseline. Fosu-Mensah (2012) using A1B and B1 obtained from regional Mesoscale model MM5 predicted a decrease in rainfall of 20% by 2050 in the transitional zone of Ghana, West Africa. Other studies regarding projected precipitation are inconsistent across climate models (e.g.,Douville *et al.*, 2006). The GFDL considered estimated high rainfall resulting in more nitrogen leaching but using a GCM that produces low precipitation will lead to less leaching of nitrogen. Nitrogen stress was relatively high (Fig. 4.1 to Fig. 4.3) in current farmers practice (N0) as compared to the two adaptation options (Fig.4.4 to Fig. 4.9). Additionally N-stress simulated across the three sites by both scenarios correlated strongly with cumulative mean grain yield from the three sites (Fig. 3.10). This indicates the role soil nutrient status play in climate change. The similarities in temperature and precipitation changes and subsequent reduction of negative yields loses by adaptation measures is in line with findings by Carboni *et al*., (2010) who evaluated conservation tillage and rotation with legumes as adaptation and mitigation strategies of climate change with a set of three GCMs (ECHAM5, HadCM3, and NCR-PCM) with

CERES-Wheat model embedded in DSSAT V 4.5 for the period 2025, 2050 and 2075 on durum wheat in Italy.

4.4.2. Response of maize to adaptation management practices

This study indicate that climate change without adaptation strategies (current practice) will have a large negative impact on grain yield and TAGB with grain yield reductions between 38 and 78%. According to our results exploiting adaptation options (NREC and N2REC) to avoid or reduce negative effects of climate change is an imperative step in maize cultivation in the Sudan Savannah regardless of the RCP scenarios used in the simulation. Estimated grain yields and TAGB for the baseline (1985 to 2005) across experimental locations for all the adaptation options were higher than for the climate scenarios RCP 4.5 and RCP 8.5 (2040 to 2060). Projected higher temperatures (Table 3.10) in the two climate scenarios translated into faster crop development and earlier maturation, resulting in lower crop yields as the plant intercepted solar radiation before it reached maturity and harvest (Young *et al.*, 2008; Brassard and Singh, 2008; Rawson, 1992). Additionally, increased rainfall by up to 53% (Table 3.11) in the two scenarios led to increased leaching of nitrogen and crop N stress resulting in lower grain yields in the scenarios as compared to the baseline. Substantial success in reducing losses in grain yield and TAGB was registered under adaptation option N^{o} 1 (NREC) and N^{o} 2 (N2REC) under both scenarios across experimental sites. According to Kpongor, (2007a) soils in the sub-region including Sudan Savanna region have been described as inherently poor in nutrient and soil organic carbon stocks thus adaptation option N2REC with retention of residues and high nitrogen application rate could buffer the negative impacts of climate change better than NREC. The response of TAGB and maize grain yield to nitrogen applications is higher for the baseline than future climate change scenarios, which suggests that future climate change will reduce the nutrient uptake efficiency and response to nitrogen applied. In line with our research, Luo *et al.* (2009)

indicated that increasing nitrogen levels from 25 to 75 kg ha^{-1} increased wheat yield under climate change in Australia but the estimated yield increase was less than for the baseline. Similarly, Turner and Rao, (2013) indicated that increasing nitrogen fertilizer rate from 20 to 80 kg ha^{-1} under 3^oC temperature rise increased yields of sorghum by 15-70% in Kenya, but that was less than the yield increase with the same increased N inputs under baseline climate conditions. These results suggest that in future soil fertility management will remain important for enhanced maize yield. Generally, the split nitrogen application method of adaptation option across the three sites regardless of recommended or high nitrogen application is more resilient to climate change than single nitrogen fertilizer application. According to Tolessa *et al.* (1995) split nitrogen application improves nitrogen use efficiency through reduction of leaching and volatilization. This finding is in line with the findings of numerous authors who advised two split nitrogen applications for maize production (Thomison *et al.*, 2004). Many research works on method of nitrogen fertilizer application are in favour of split applications to synchronize timing of fertilization according to the crop demand and increase grain yield (Gehl *et al.*, 2005). The N stress curves shown in Fig 4.1 and 4.2 indicate that in many circumstances a splitting into three doses may be justified or splitting in two doses with one-third and two-thirds of the amount. The model analysis of simulation indicated that the growing cycle of the short season cultivar Dorke SR is shortened due to projected increases in temperature (Table 3.12). Thus TAGB and grain yield production is reduced. Simulations based on long season duration cultivars may counteract the negative impact of climate change since a long duration cultivar will intercept more solar radiation under high rainfall conditions before reaching physiological maturity. Taking the projected mean of TAGB and grain yield over all the experimental sites, the two climate scenarios were similar. Dassari site was substantially promising in reducing negative changes in TAGB as compared to other two sites. Cumulatively, the capacity to reduce loses in TAGB by site under both climate scenarios was in the order, Dassari > Vea > Dano.

4.4.3. Implication for policy and extension services

The results show the need to explore and promote longer duration high temperature tolerant maize cultivars. These cultivars will develop under high temperature conditions, maintaining the duration of vegetative phase, which in turn will lead to increased yield. However to develop a new crop variety takes up to a decade and may demand the use of state of the art technologies like genetic engineering and marker-assisted selections. With favorable policies supporting research and development, institutions such as INERA (Burikna-Faso), INRAB (Benin) and CSIR (Ghana) and other Breeders in the Universities in these countries can take up the challenge to breed for such cultivars which may be more climate change resilient. Since the GDP contribution to research by these countries is very small, breeding must be seen in the broader context of global environment governance under Kyoto protocol. The quantity of fertilizer in sub-Saharan Africa applied to crops falls far below the global average thus, governments in these countries should restore the policy of fertilizer subsidies which has been removed as part of bailout conditions by donor agencies. Our results estimated that the use of residues as climate adaptation option is more climate resilient than no residue application. Government laws that prohibit bush burning must be strengthened to prevent indiscriminate burning of residues after each cropping cycle in the Sudan Savanna of West Africa. For extension services, there is the need to train farmers on how to apply nitrogen fertilizers taking into account the temporal variation of crop demand and of N leaching.

Chapter five

5.0. General discussion

5.1. Overall discussion

In the Sudan Savanna of West Africa, farming is a critical element of the region's economy and the main livelihood strategy of many people. Farming is severely constrained by many factors including limited infrastructure, lack of access to information and extension services, and increasing pressure on land resources which has resulted in degraded soils with crop and low productivity as the ultimate consequences. These constraints to crop production are likely to be worsened by climate change and increasing climate variability.Understanding accessible and low cost technologies to increase productivity in West Africa in the face of climate change and variability. Specifically the study investigated the potential of soil and water conservation strategies to stabilize yields in years with drought and improve yields under climate change.

In the field experiment in this thesis (chapter 2), we analyzed the potential of residue retention, tillage practices and nitrogen fertilization to (1) increase average yields and (2) stabilize yields in years with drought conditions. The adaptation options were evaluated for three major crops (maize, sorghum, and cotton) at two slope positions for three locations each with 3 growing seasons (2012, 2013 and 2014) analyzed as 9 contrasting site-seasons. The precipitation amount and distribution together with information on soil characteristics were used to rank the 9 site-season combinations in terms of level of drought stress experienced by the crops. Interactions between management options and season-site combinations were analyzed to determine the practices which stabilized yields in the driest conditions. To account for the different final yield levels and aboveground biomass across locations and across crops, yields were normalized by calculating the relative yield and relative aboveground biomass (RY and RAGB). Over all site-seasons, crops planted at the footslope had on average 31% higher relative yields and 18 % higher relative aboveground biomass than those planted upslope. The reasons behind significantly higher RY at the footslope compared to the upslope may be due to the relatively high soil volumes of the deeper soils at the footslope which acts as a reservoir for water and nutrients. This is in agreement with He *et al.* (2011) who determined that more roots at greater depths contributes to improving yield under water stress conditions. Contour ridging led to significantly higher relative yield than reduced tillage across site-seasons, however its effects depended on slope position and rainfall regimes of the site-seasons. Improved residue management lead to higher yields compared to standard residue management options over all locations and for all seasons. The reason may be attributed to nutrient recycling and the mulching effect of the residues. The observation is in accordance with Kouyaté *et al.*(2000) who also reported positve effects of residues. Recommended N produced significantly higher yields than the no N treatment but it was not worthwhile to double the recommended N rate (N2REC) as in most cases there was no significant yield benefit of applying more fertilizer.

From the above experiments carried out from 2012 to 2014, we derived input values of soil, as well as crop parameters of the maize variety DORKE SR which we used in climate impact studies with the aid of CERES-Maize model embedded in DSSAT V 4.6. Since the maize cultivar DORKE SR is not incorporated in the model, we developed the cultivar file of Dorke SR and evaluated the performance of the CERES-Maize model by comparing simulations of two years of maize experiments in Anabisi, Ghana, Tambiri, Burkina Faso and Ouriyouri, Republic of Benin. In general, across the three sites the model was able to simulate mean values of grain yield and TAGB correctly as observed in Fig. 5.1 to Fig. 5.2. However, the model was not able to capture the large part of variation in Days to maturity (MDAT) during calibration and validation for either NREC or N0 treatments except in Vea 2012, resulting in poor model performance for phenology. The results show that in the field MDAT was affected by N application, which is presently not incorporated in the DSSAT model nor in other crop models. It therefore becomes imperative to incorporate such relationships for simulating phenology in low input systems of in the Sudan Savanna of West Africa. The results indicate that DSSAT V 4.6 produced better estimates of grain yield and total aboveground biomass under recommended N fertilizer rates compared to the control treatment (N0) and this may be attributed to the DSSAT model being less sensitive to N stress than the real crop growth under zero fertilizer N conditions. Another reason could be that the turnover of nitrogen in the soil is not well represented in the model leading to an overestimation of mineral N content during the growing season.

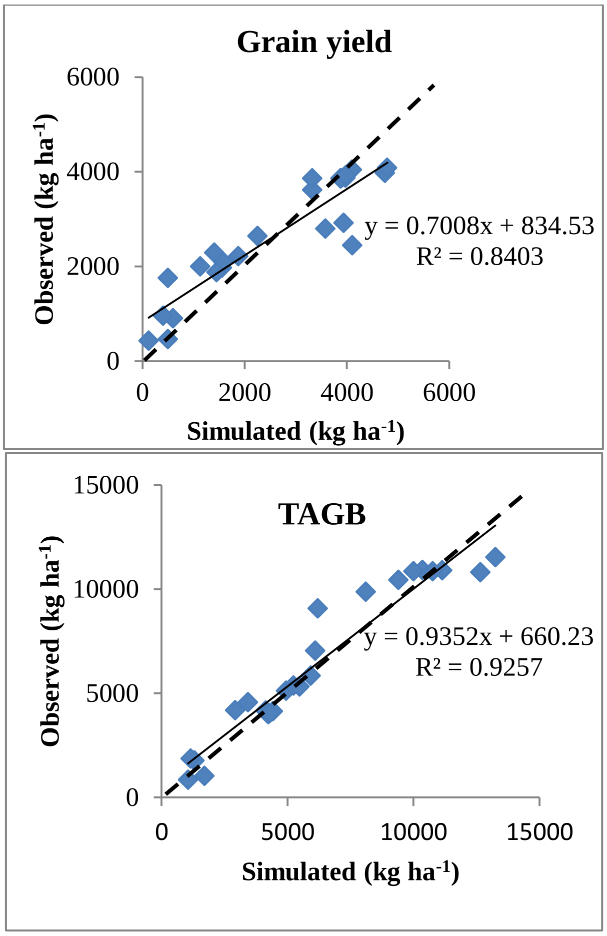


Figure 5.1: Observed and simulated TAGB and maize grain yield across the 3 sites during calibration of recommended N plots

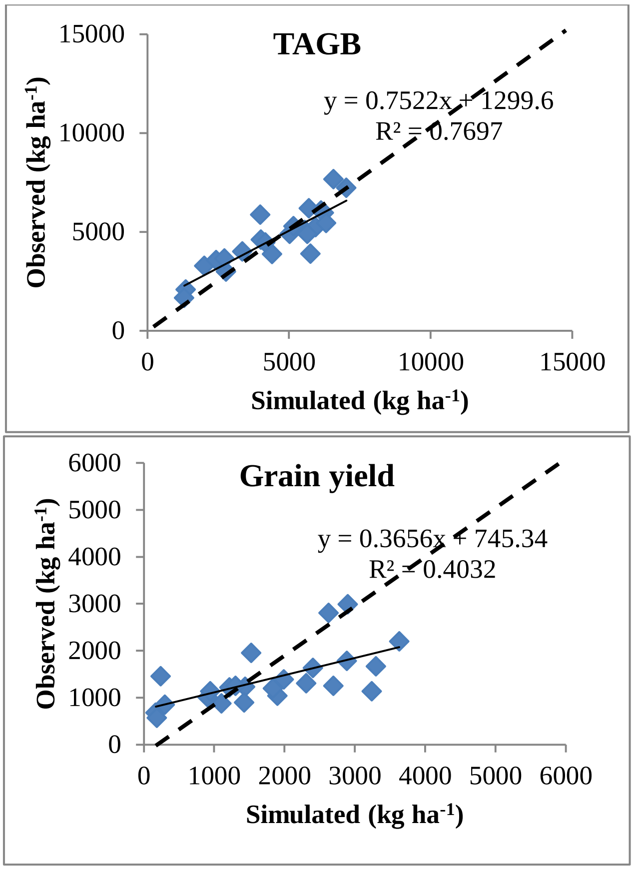


Figure 5.2: Observed and simulated TAGB and maize grain yield across the 3 sites during calibration of no N plots

In chapter 3, after the model calibration and the evaluation, a climate change impact study were undertaken to understand possible implications of climate change on maize productivity. Our results indicated that under future climate change without adaptation, maize production will decrease due to higher temperature relative to the baseline period as well as increased nitrogen stress across the 3 sites. Increase in temperature shortened the crop growth period leading to earlier maturation and lower maize yields as the crop intercepted less cumulative radiation before reaching maturity and harvest. This is in line with studies by Tachie-Obeng *et al.*, (2013) who observed low yield in maize cultivation in the North Western part of Ghana and attributed it to rise in temperature which translated into faster crop development, earlier maize maturation. In addition to short growth season, we found N stress increased in scenarios and decreased yields. The reason behind N stress contributing to lower yields by the scenarios relative to the baseline may be due to higher rainfall which led to leaching of nitrogen from the soil in the two scenarios. The agronomic benefits of nitrogen is highlighted by many authors and its deficiency negatively affected maize yield as projected by the model. According to Below (2002) nitrogen is fundamental to establish the plants photosynthetic capacity for good growth and development. Impact studies were carried out for both treatments without nitrogen fertilizer which is the current practice by farmers and treatments that received recommended N fertilizers. By 2050 higher nitrogen stress was estimated in no N treatments as compared to maize that received recommended N. The higher N stress in no N treatments translated into lower yields. The limitations of the current farm management under the future climate scenarios suggests the need to change cropping systems management in the Sudan Savanna. As shown in Figure 5.3, across the 3 sites the model simulated grain yield correlated strongly with N stress N stress (R^2=0.88) for no N plots. Thus, nitrogen stress strongly contributed to decrease in grain yield by 2050 as compared to recommended N fertilizer plots where the correlation was weak (R^2=0.27).

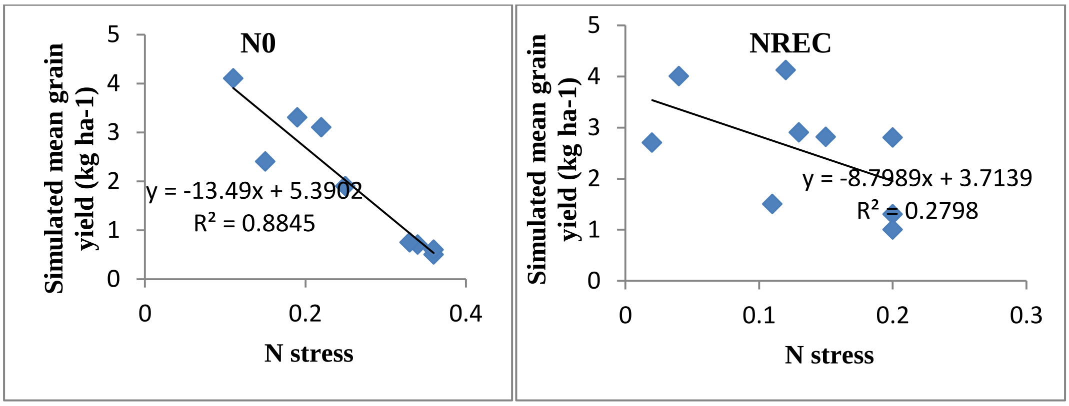


Figure 5.3: Relationship between simulated mean grain yield and N stress for no N and recommended N across the 3 sites from 2040 to 2060 under the 2 climate scenarios

By 2050, the model estimated substantial decrease in maize grain yield with no N fertilizer (N0) by 62% as compared to recommended N fertilizer plots (NREC) which was only decreased by 33%. The climate impact between the sites varied to some extent. The site in Dano as projected by the model are more prone to negative climate change impacts by 2050 and this may be attributed to the highest rainfall annual compared to the other two sites (Table 3.11) conditions which led to high leaching of N. The relatively lower leaching of N in Vea led to reduction in its vulnerability to climate change.

The climate scenario output of the GFDL climate model combined with RegCM4 in this study differed to some extent with relatively high estimated precipitation as compared to other GCMs. Other climate studies (Fosu-Mensah, 2012; Tachie-Obeng *et al.*, 2013) in West Africa, using higher number of GCMs indicate relatively lower precipitations increases. This calls for the need to broaden the base of GCMs in our climate impact studies. In other studies in Tibetan Plateau in China by Hao *et al.*, (2013), temperature and precipitation simulation abilities of GCMs was evaluated (2000-2099) based on difference between simulated and observed with 22 models from IPCC AR4. They concluded that, simulated precipitation of most models was higher than the observed values while the regional simulated values of some models are lower than the observed and thus made recommendation on further improvement of climate most models to reduce uncertainties.

Finally, to reduce the negative impact of climate scenarios produced by the GDFL-RegCM4 combination we evaluated recommended nitrogen (NREC) with improved residue management (IRM) under contour ridges (CR) as option one and high nitrogen (N2REC) with improved residue management (IRM) under contour ridges as option two to adapt to climate change in the future (2040-2060). Additionally, we explored two different methods of nitrogen fertilizer application, split and single dose to see whether they varied in their response in reducing the negative impact of climate change across the 3 sites. Our results indicate that doubling N rate (N2REC), irrespective N application method reduce the negative impact of climate change on maize productivity for all the sites and scenarios compared to NREC. Figure 5.4 shows that N2REC and NREC were able to reduce the negative impact of climate change on current maize production by 2050 in the Sudan Savanna by 75% and 45% respectively. The differences that occurred in the two N application scenarios may be due to more available nutrients in the crops that received higher nitrogen application making them more climate resilient.

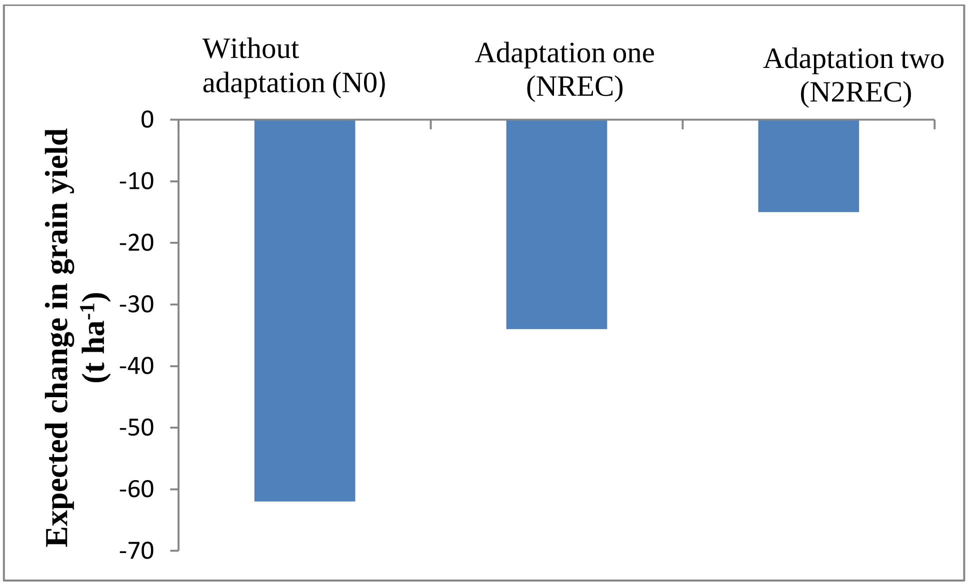


Figure 5.4: Expected mean change in maize grain yield with two adaptation options (N2REC and NREC) relative to current farming practices across Dano, Vea and Dassari under the two scenarios (RCP 4.5 and 8.5).

Generally, the split application of nitrogen across the three was more resilient to climate change as predicted by the GDFL-RegCM scenarios than single nitrogen fertilizer application. Based on work by Tolessa *et al.* (1995) split nitrogen application improves nitrogen use efficiency through reduction of leaching and volatilization. Fig. 5.5 shows that the model estimated 64% reduction for split and 56% reduction of yield loss due to climate change for single application in reducing loses as a result of climate change.

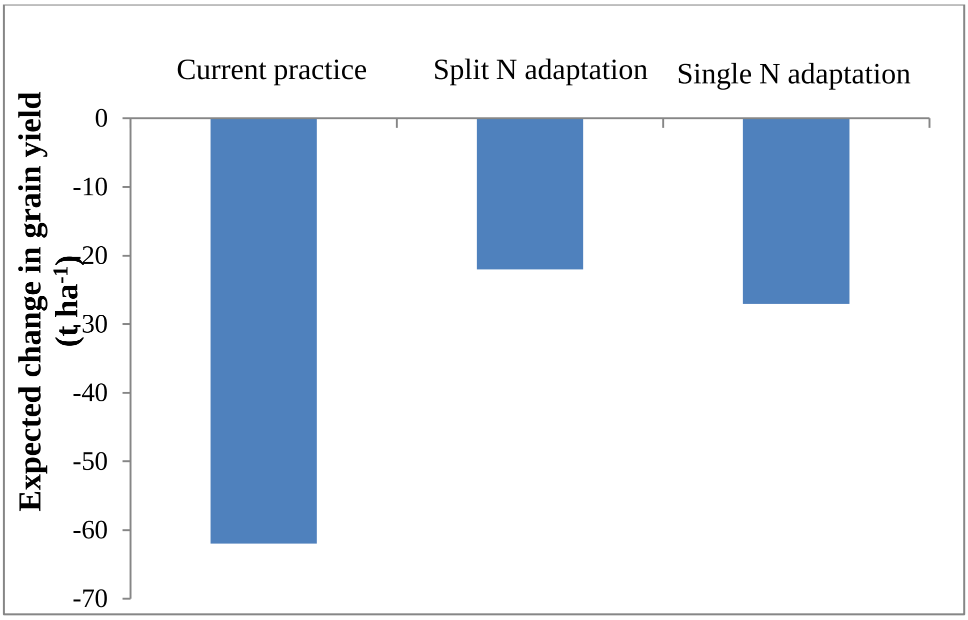


Figure 5.5: Expected mean changes in maize grain yield with two methods of N application (single and split) relative to current farming practices across Dano, Vea and Dassari under the two climate scenarios (RCP 4.5 and 8.5)

The results also revealed that there is a possibility of further reducing the negative impact of climate change on maize and even negative reduction could further translate into positive yield if N application are split into three rates and if the short duration cultivar Dorke SR is replaced with long duration high temperature tolerant cultivars. These varieties under higher mean temperature will stay longer in the field to intercept more solar radiation translating into higher yields. This will need policy backing to make it become a reality as currently there is no evidence of focused research towards this direction in Ghana, Burkina-Faso and Republic of Benin.

Chapter six

6.0. Conclusions at a glance

In an attempt to investigate the interactive effects of different soil and water conservation techniques, for both high and low intensity nitrogen fertilization rates and landscape positions on yield and yield stability of key crops (maize, cotton and sorghum) in the Sudan Savanna of West Africa, two types of analysis were considered: this consisted of empirical testing and crop modeling. From this work, the following conclusions could be drawn:

- Our results identified possible crop management adaptation strategies to adapt to current climate variability:

    - The beneficial effects of residue retention together with the inclusion of legumes as relay crops were neither influenced by site conditions nor tillage practice or fertilizer application level, which implies that residue retention, can be recommended across all soil and weather conditions for maize, sorghum and cotton to increase and stabilize yields.

    - When maintaining phosphorus and potassium at the optimum levels, recommended nitrogen fertilizer rates increased yields independent of soil and climate conditions. Any benefit of adding nitrogen above the recommended rates in wet seasons is offset in years with low rainfall.

    - Generally, for all the crops tested contour ridges gave higher yields than reduced tillage however, strong interactions with site-season and slope were observed.

    - It was revealed that adaptation of soil and crop management to improve and stabilize yields in years with drought conditions must be appropriately selected depending on site conditions (soil depth and gravel content).

- The testing of CSM-CERES-Maize model (DSSAT V.4.6) and its application was successful and this confirms that this model can be acceptable for use as a research tool in West Africa.
- Impact analysis of two climate scenarios predicting increase in temperature and substantial increase in annual rainfall (up to 56%) indicated influence of temperature increases on maize production in the Sudan savanna and this translated into faster development and earlier maturation which resulted in lower maize yield. In combination with increased N leaching and crop N stress, the DSSAT model estimated substantial decrease in maize grain yield in no nitrogen fertilizer plots (N0) by 62% as compared to recommended nitrogen fertilizer plots (NREC) which registered a decrease of 33% in the Sudan savanna region.
- Impact of climate scenarios from the GDFL climate model on maize grain yield suggest a reduction in yield of 72, 42 and 41% for Dano , Vea and Dassari for no N fertilizer and a reduction in yield of 53, 37 and 11% for Dano, Vea and Dassari respectively under recommended N fertilizer.
- Success in reducing yield loses in maize yield was higher under adaptation option N2REC (high nitrogen) than NREC (recommended nitrogen). Split application across the three sites regardless of recommended or high nitrogen application was more resilient to climate change than single dose application. During the period from 2040 to 2060 single nitrogen application method for N2REC reduced the negative impact of climate change on maize grain yield by 69%. The split application of N2REC reduced yield loses by 80% across the three experimental locations under the two climate scenarios.

- The high rainfall amount projected by the scenario outputs of the GFDL model remains inconsistent with other studies. These results indicate the need to narrow the uncertainty in climate change studies by engaging outputs from other climate models in future studies.
- There is a call for rigorous research and outreach programmes, and investment in improved technology to demonstrate and promote use of long duration high temperature tolerant maize cultivars with better resilience to climate change. Such finding present a wakeup call for policy makers and the research institutions (CSIR, INRAB and INERA) in Benin, Ghana and Burkina-Faso.

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