UNIVERSITY OF CAPE COAST

ASSESSMENT OF POTENTIAL IMPACT OF CLIMATE CHANGE ON PEANUT YIELD IN SENEGAL THROUGH A MODELLING APPROACH

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BY

BABACAR FAYE

Thesis submitted to the Department of Agricultural Engineering of the School of Agriculture, University of Cape Coast, in partial fulfillment of the requirements for the award of Doctor of Philosophy degree in Climate change and Agriculture

DECEMBER, 2016

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:.. Date:..........................

Name: Babacar FAYE

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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31 MAI 2016

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ABSTRACT

This study assess of the potential impact of climate change on peanut yield in Senegal. Seven field experiments were conducted at three sites in the dry seasons of 2014 and 2015 and the rainy season of 2014. SIMPLACE[1] crop model was calibration and validation at two sites Bambey and Nioro and for two peanut cultivars over two years. To assess the impact of climate change on peanut growth and yield in Senegal, outputs of four Regional Climate Models were used together accounting for impacts with and without consideration of elevated CO_2. The effects of fertilizer application on peanut in three different sites, Bambey, Nioro and Sinthiou Malem were not significantly different between fertilizer levels. Under water stressed conditions, the seed yield was more affected than the biomass yield. Seed yield decreased by 33% when stress occurred at flowering period and by 50% when stress occurred during seed filling. In dry season when the plants were subjected to periodic heat stress conditions, yield simulations were markedly improved when canopy temperature was considered instead of air temperature. Projected climate change without CO_2 elevation may impact negatively biomass and seed yield for RCP4.5 and RCP8.5. However, positive yield changes result when CO_2 concentration increase of up to 5.4% and 12.4% for RCP4.5 and RCP8.5 respectively for biomass and for seed yield up to 9.6% for RCP4.5 and 13.2% for RCP8.5. Short season varieties had greater relative yield changes and can therefore be recommended in these two sites to cope with the impact of early rain cessation. It is concluded that climate change will have positive impact on peanut yield in Senegal due to the elevated of CO_2 concentration.

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[1] SIMPLACE is the shortened name for SIMPLACE< Lintul5, DRUNIR, CanopyT, HourlyHeat>

Keywords:

Climate change,

SIMPLACE framework,

Peanut,

Canopy temperature,

Air temperature,

CO_2 concentration change,

Senegal

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DEDICATION

To my

family and in memory of my mother

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LIST OF ABBREVIATIONS

AGB	Above Ground Biomass
ANACIM	Agence Nationale de l'Aviation Civile et de la Météorologie
ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems SIMulator
AraBHy	Arachide bilan hydrique
CEC	Cation-Exchange Capacity
CERAAS	Centre d'Etudes Régional pour l'Amélioration de l'Adaptation à la Sécheresse
CIRAD	Centre de coopération Internationale en Recherche Agronomique pour le Développement
CNRA	Centre National de Recherche Agronomique de Bambey
CO_2	Carbon Dioxide
CORDEX	Coordinated Regional Climate Downscaling Experiment
CWSI	Crop Water Stress Index
DAPSA	Direction de l'Analyse, de la Prévision et des Statistiques Agricoles
DAS	Days After Sowing
DSP	Double superphosphate
DSSAT	Decision Support System for Agrotechnology Transfer
DVS	Development Stage
DUL	Drained Upper Limit
EPIC	Environmental Policy Integrated Climate
FAO	Food and Agricultural Organization

GDP	Gross Domestic Product
HI	Harvest Index
IDE	Integrated Development Environment
INRES	Institute of Crop Science and Resource Conservation
IPCC	Intergovernmental Panel on Climate Change
ISRA	Institut Sénégalais de Recherches Agricoles
ITA	Institut de Technologie Alimentaire
K_2O	potassium oxide
LAI	Leaf Area Index
LL	lower limit
MOST	Monin-Obukhov Similarity Theory
NA	Not Available
P_2O_5	single superphosphate tripe
RCBD	Randomized Complete Block Design
RCD	Regional Climate Downscaling
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
SPI	Standardized Precipitation Index
SARRA-H	Système d’Analyse Régionale des Risques Agroclimatiques version « Habillé »
SIMPLACE	Scientific Impact assessment and Modeling PLatform for Advanced Crop and Ecosystem management

SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TTh	Total hourly critical Temperature
UCC	University of Cape Coast
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use

CHAPTER ONE

GENERAL INTRODUCTION

Study background

Sub-Saharan Africa (SSA) is one of the world regions most challenged by food insecurity for a wide range of reasons, including soil fertility, climatic conditions, poor market infrastructure, lack of investment opportunities for producers, widespread poverty, among others. Agriculture in SSA countries is regularly affected by extremes climate like drought and heat stress, and is expected to be further affected by climate change. Additionally, increasing food production and security is difficult as the region's soils are characterized by low soil fertility caused by human activities. While, globally, agricultural practices are responsible up to 28% of degraded soils, in SSA, this form of degradation may account for more than 50% of degradation (Kurayemen, Gyata and Emmanuel, 2013). Therefore, as result of increasing pressure on agricultural land, soils become more degraded as higher nutrient outflows are not compensated (Wopereis, Tamélokpo, Ezui, Gnakpénou, Fofana et al., 2006).

Agriculture in Senegal remains one of the most important sectors of economic activity. Approximately 58% of the population live in rural areas and 70% of this rural population depends on agriculture, though it comprises less than 14% of Senegal's gross domestic product (GDP) (Branca, Tennigkeit, Mann and Lipper, 2012). The Senegalese agricultural sector is comprised primarily of smallholder farmers practicing rainfed agriculture with low productivity. Currently less than 5% of producers apply irrigation despite the introduction of new irrigation technologies.

Peanut is the country's primary industrial crop and constitutes the principal source of agricultural incomes for the majority of farmers (Pélissier, 1966). A reduction of 25.8% of the production is observed when we compare the mean production from 1972 to 1975 with the mean from 1996 to 2000 (Revoredo and Fletcher, 2002). Peanut production employs 70% of the rural labour force and accounts for 60 % of household agricultural income (Diop, Beghin and Sewadeh, 2004). It represented in recent years 80% of the export earnings and more than the half of the cultivated area (Dia, Diop, Fall and Seck, 2015; Ipar, 2015). The bulk of peanut production has been processed into peanut oil and peanut cake for sale, initially to France, and later to the rest of Europe (Lericollais, 1999; Warning and Key, 2002). In the export sector of oil and oil cake, Senegal, in spite of a decrease in production, due to crisis in the peanut sector, still plays a leading role with levels of export often higher than one third of the worldwide market (43% in 2001). Senegal is the world's largest supplier of peanut oil, but this market has declined as other vegetable oils are increasingly used as substitutes. Senegal and Argentina remain the world's leading exporters of peanut oil (Diop et al., 2004). However, the contribution of peanut to the GDP dropped to 6.5% of the agricultural GDP in 2006 (MAS, 2012). In terms of its importance as a cash crop, peanut remains the most profitable in Senegal but its value chain indicates a declining trend between 2002 and 2006 with a loss of cultivated area of 16% (MAS, 2012).

Peanut is grown in all districts in the country but the central part named the “peanut basin” constitutes the core of production. The sandy soil is the main soil in this area called “sol Dior” which is poor in nutritive elements, most notably acute phosphorus deficiency (P_2O_5) (Blondel, 1971). A decline in production factors is also noted, including the degradation of soil fertility, the decrease of rainfall, problems of inputs distribution, out-of date agricultural equipment and low and instable incomes (MAS, 2012).

Presently, it is essential to consider the effects of climate variability and climate change on agricultural production. This is reflected in the Sahel by a significant decrease in average annual rainfall during the last three decades of the twentieth century, together with high year to year variability, and also by increase in temperatures (CSE, 2011). This phenomenon is expected to intensify in the future.

According to the IPCC (2014c), the increase of global mean surface temperature world-wide by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be between 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5. In West Africa the increase of temperatures are clear and are projected to rise faster than the global average increase during the 21st century (Christensen, Hewitson, Busuioc, Chen, Gao et al., 2007). While, for Rainfall some models are predicting decrease whereas, others are predicting an increase for the same emissions scenario and period (Webber, Gaiser and Ewert, 2014).

The variation of high temperature and decrease of rainfall is known to have negative effect on agricultural productivity, soil degradation, as well as deforestation in West Africa (Challinor, Wheeler, Garforth, Craufurd and Kassam, 2007; IPCC, 2014a; Nyong, Adesina and Elasha, 2007; Roudier, Sultan, Quirion and Berg, 2011; Sultan, Roudier, Quirion, Alhassane, Muller et al., 2013). Consideration of drought and high temperature events is common in climate impact analysis in this area to evaluate likely impacts of climate change on crop production (Lobell and Burke, 2008). In addition to these two variables, carbon dioxide increase due to greenhouse gas emissions will have large effects on plant growth which result in complex responses to water availability. Plant water status is generally improved at elevated CO_2 levels. Some evidence suggest that crop transpiration rates decrease with elevated CO_2 (Van de Geijn and Goudriaan, 1996), meaning crops will use less water while in a non-water limited condition, probably enabling growth for a slightly longer period as droughts develop. Whole-plant transpiration was reduced under elevated CO_2 for both a soybean (C3) and sorghum (C4) crop (Prior, Runion, Marble, Rogers, Gilliam et al., 2011). Increase of CO_2 concentration is known to have positive effect on crop and particularly on peanut in optimal conditions by increasing photosynthesis and reducing the stomatal conductance (Vanaja, Srinivas, Lal, Satish and Reddy, 2013).

Despite the possible positive influence of elevated CO_2, a large body of evidence suggests that even by 2020, in some African countries, yields from rainfed agriculture could be reduced by up to 50% as a consequence of climate variability and change (IPCC, 2007), with the result that access to food in many African countries is projected to be severely compromised. The impact of climate change on farmers and their livelihoods could be drastic (IPCC, 2007).

Studies have shown that climate change will affect agriculture and will be more pronounced in developing countries whose agricultural systems are vulnerable and depend essentially on rainfall (Adger, Huq, Brown, Conway and Hulme, 2003; Lybbert and Sumner, 2010; Mendelsohn, 2008; Ravindranath and Sathaye, 2002).

Problem statement

Declining crop yields in the context of climate change have led agricultural researchers to try to identify strategies that aim to increase or maintain the productivity of cropping systems. Among key strategies is the introduction of improved short cycle varieties, varieties with heat and drought tolerance, agricultural technologies such as conservation agriculture, changing sowing dates, fertilizer application. In the Sahel, soil degradation, poor soil structure and frequent periods of drought are key problems that lead to yield decline problems (Breman, 1998; Mando, 1998; Ouédraogo, Mando and Zombré, 2001). In addition, warmer temperatures with climate change and a decrease of rainfall in the western Sahel (Senegal) by about 15% (Adiku, MacCarthy, Hathie, Diancoumba, Freduah et al., 2015) will cause yield declines if adaptations are not adopted. A decrease of rainfall can be attributed to erratic start of the rainy season, longer interruptions of rainfall in the open season (dry spells) or early cessation of rains which can constitute a form of drought in the Sahel. In Senegal, the decrease in the productivity of peanut due to soil degradation, seed quality, deficiencies of inputs distribution (Montfort, 2005; Noba, Ngom, Guèye, Bassène, Kane et al., 2014), is expected to be further exacerbated by climate change. Moreover, the decrease in productivity due to decreased rainfall associated with high temperature remains unclear in the context of climate change. In this region, the rotation of peanut and millet is the dominant cropping system, accounting for 62% of the harvested area (Jalloh, Nelson, Thomas, Zougmoré and Roy-Macauley, 2013). Additionally, the evolution of greenhouse gases emissions, mainly the CO_2 concentration, should be accounted for C3 plants such as peanut which are more responsive at higher CO_2 concentrations than C4 plants (Burkey, Booker, Pursley and Heagle, 2007; Jablonski, Wang and Curtis, 2002; Kimball, Kobayashi and Bindi, 2002; Prasad, Allen Jr and Boote, 2005).

Then, assessing the impact of climate change on peanut yield in Senegal as well as investigating adaptation strategies such as new crop length cycle, changing sowing date become important. To build the scientific basis upon which such assessments are conducted, we consider the effects of high temperatures (under well-watered and typical rainfed conditions), together with the effects of elevated CO_2 concentration. In doing so, we propose and evaluate a model structure that accounts for the interaction of high temperature and crop water status through consideration of crop canopy temperature. From this model basis, the effects of climate change and possible adaptation strategies are investigated for different time frames and climate change scenarios. Such scientific analysis forms an important part of the process to identify strategies to improve peanut yields, and also farmer livelihood.

Objectives

The main objective of this study is to assess the potential impact of climate change on peanut yield in Senegal, West Africa. To achieve this main objective of the study, the following specific objectives are investigated to:

- assess the effects of fertilizer application and water availability on peanut development, growth and yield in Bambey, Nioro and Sinthiou Malem in Senegal;
- evaluate the performance of the SIMPLACE< Lintul5,DRUNIR,CanopyT, HourlyHeat> crop model to simulate peanut growth and yield under irrigated and rainfed conditions at two different sites (Bambey and Nioro) in Senegal
- quantify the interaction of high temperatures and water availability on peanut seed yield formation by using canopy temperature versus air temperature under combined heat and drought stress conditions;
- quantify the impacts of climate change on peanut yield at two locations (Bambey and Nioro) in Senegal using four regional climate models under the new IPCC RCPs scenarios (4.5 and 8.5). The baseline period considered is (1981-2010) and the scenario period is (2016-2045) ;
- evaluate possible adaptation strategies for Bambey and Nioro sites to minimize the negative impacts of climate change.

Hypotheses

- ✓ Water stress and fertilizer application play a key role on peanut yield determination

We assume that water stress consistently reduces grain yield when it occurs during the reproductive phase, with the result that application of fertilizer will improve yield in non-water limited conditions only.

- ✓ Canopy temperature should be used in simulating crop yield to account the interaction of heat stress and crop water status.

As during the current dry season, and more frequently in the future during the rainy season, peanut is grown at maximum air temperatures greater than optimum, with the result that heat stress must be accounted for. While, crop temperature is related to air temperature, the rate of transpiration together with other weather factors can cause the crop to be either cooled below or heated above air temperature. Simulation of canopy temperature can account for this interaction and lead to more robust yield estimates.

- ✓ Climate change will negatively impact peanut yield

  Higher mean temperatures in the future have effect to accelerate the growth of peanut and potentially lead to heat stress. Likewise, higher temperatures lead to higher rates of evapotranspiration, that without a change in rainfall amount will cause more drought stress. All factors act to reduce peanut yield.

- ✓ Short season peanut varieties and early sowing dates are more adapted in the context of climate change to cope with the effect the erratic and or early cessation of rainfall under rainfed condition in both sites but dry spell will have negative impact on peanut in the study area due to the early start of rainy season.

Thesis structure

The thesis is structured into six main chapters. The general introduction gives an overview of peanut production and climate change in Senegal, provides an overview of the problem and states the objectives and hypotheses. Chapter 2 highlights some relevant literature of studies carried out on peanut, impact of climate and adaptations. Chapter 3 gives a description of the study area and provides the materials and methods employed in the study. It describes the model development and parameterization, presents the process of model calibration and model validation on peanut in two different sites in Senegal. Chapter 4 presents results for the statistical analysis of the field experiments data, shows the effect of water stress and fertilizer application on peanut yield reduction. It presents the results of model evaluation and assesses the potential impact of climate change on peanut yield in Senegal and proposes one adaptation strategy to reduce the negative impact of climate change. Chapter 5 discusses the results of the study. Finally, chapter 6 summarizes the main findings of the thesis with respect of the objectives. Furthermore, it presents the contribution to knowledge and outlook for further research.

CHAPTER TWO

LITERATURE REVIEW

This part reviews some literature related to peanut production in Senegal as well as the key climatic effects on peanut growth. Finally, it reviews crop modeling approaches for climate impact assessment.

Importance of peanut in West Africa

Peanut (*Arachis hypogaea L.)* is one of the world's most important legumes, grown primarily for its high quality edible oil and protein (Kambiranda, Vasanthaiah, Katam, Ananga, Basha et al., 2011). It is cultivated in over 100 nations around the world with the main producers being China and India, having more than 60% of total production while Africa has 25% of the production (Noba et al., 2014). Approximately, 90 % of the world's peanut production occurs in the tropical and semi-arid tropical regions, with large parts of the world's peanut production regions characterized by high temperature and low or erratic rainfall (Hamidou, Halilou and Vadez, 2013).

Most of the production is domestically used and only small proportion of the world production is devoted to imports and exports, therefore, the world trade market can be considered as a residual market (Revoredo and Fletcher, 2002). The proportion of peanut used for food purposes increases compared to the proportion used to produce vegetable oil. Africa is the more affected for this changes due to the lower quality of the production which contained an important level of aflatoxin (Bankole and Adebanjo, 2004; Martin, Bâ, Dimanche and Schilling, 1999).

The contamination of peanut to aflatoxin in Africa is also due to increase drought (Kambiranda et al., 2011). In Niger, the aflatoxin contamination in peanut was related to soil moisture stress during the pod filling and when soil temperature was around the optimum (Craufurd, Prasad, Waliyar and Taheri, 2006). West African countries are the main producers of peanut in Africa where Nigeria and Senegal occupy the first place followed by Mali and Niger (Singh, Nedumaran, Ntare, Boote, Singh et al., 2014). It is an important food crop across West Africa and it is cultivated mainly by small-householder and resource-poor farmers (Tarawali and Quee, 2014)

In the 1960's, peanut occupied a prominent place in Senegalese agriculture and was the country’s main industrial crop. With a production of 900,000 to 1,000,000tons, peanut comprised 80% of the exports (Sylla, 2010) and constituted the principal source of income in the rural areas (Noba et al., 2014). However, since the 1990s, peanut value chain has entered a deep crisis and various agricultural policies are yet to succeed in boosting the sector (Freud. et al., 1997). Peanut is grown in all districts in the country but the central part named the “peanut basin” constitutes the core of production. Soils in this area have sandy to sandy-loam texture. They are called “sol Dior” and are poor in nutrients (Blondel, 1971).

In most major peanut producing countries, a trend of increasing production is observed except for Senegal (Foncéka, 2010). The decline in peanut production in Senegal is mainly due to climate variability and lack of input supply, especially low quality of seeds. Other factors that have led to the decline of production are soil degradation, reduction of cultivated area, bad agricultural practices, lack of and poor maintenance of agricultural machinery and difficult access to credit (Gaye, 2013; Montfort, 2005).

Until the end of the 1970's, peanut was incontestably the engine of the Senegalese rural economy. It generated approximately 80% of the export earnings of the country by 1960 and decreased at only 10% in the 1990s (Freud, Freud, Jacques and and Thenevin, 1997). As the main industrial crop in Senegal, peanut constitutes the main source of agricultural income for the majority of the farmers. But this peanut value chain dropped in performance between 2002 and 2006 (MAS, 2012). Moreover, peanut continued to play a key role in the Senegalese economy. It remained the main cash crop in the country with 27.2% of the harvested area based on the three-year average for 2006–2008 (Khouma, Jalloh, Thomas and Nelson, 2013). The mean production from 1960 to 2014 is estimated to 773 000 tons (Figure1) per year, the productivity estimated to 830 kg ha^{-1} and the total cultivated area to 938 000 hectares (DAPSA., 2014). The highest rate of production occurred from 1975-1976 in contrast, the years 2002-2003 gave the lowest production. Increases in production have largely been attributed to increased production area (Figure 1).

The first research conducted in Senegal on agriculture was related to improvement of peanut production (creation of the experimental station of Bambey in 1921) because of the economic and social interest. This research focused on the selection of new varieties according to the cultivated zone

(Clavel and Ndoye, 1997; Khalfaoui, 1991) and creation of varieties adapted to drought stress (Annerose, 1988, 1990; Clavel, Baradat, Khalfaoui, Drame, Diop et al., 2007; Clavel, Da Sylva, Ndoye and Mayeux, 2013; Clavel, Drame, Diop and Zuily-Fodil, 2005). However, recent decades have witnessed a decline in the production in Senegal though still accounting for 70% of the rural labour force and 60 % of household agricultural income. Peanut production and processing represent about 2% of gross domestic product (GDP) and 9% of exports in the country (Diop et al., 2004), with a reduction of 25.8% in production the mid 1970s to the end of the century (Revoredo and Fletcher, 2002). The decline of peanut production in Senegal has been attributed to both climatic disturbances such as decrease in rainfall and increase in temperature and inadequate of input supply chains, particularly for fertilizers and high quality seeds (Foncéka, 2010). It is noted also limitations due to high temperature which is manifested by peanut abortion and to the sensitivity of peanut to low radiation which caused the decrease yield in 2007. These limitations are not well studied and need to be addressed for future adaptations.

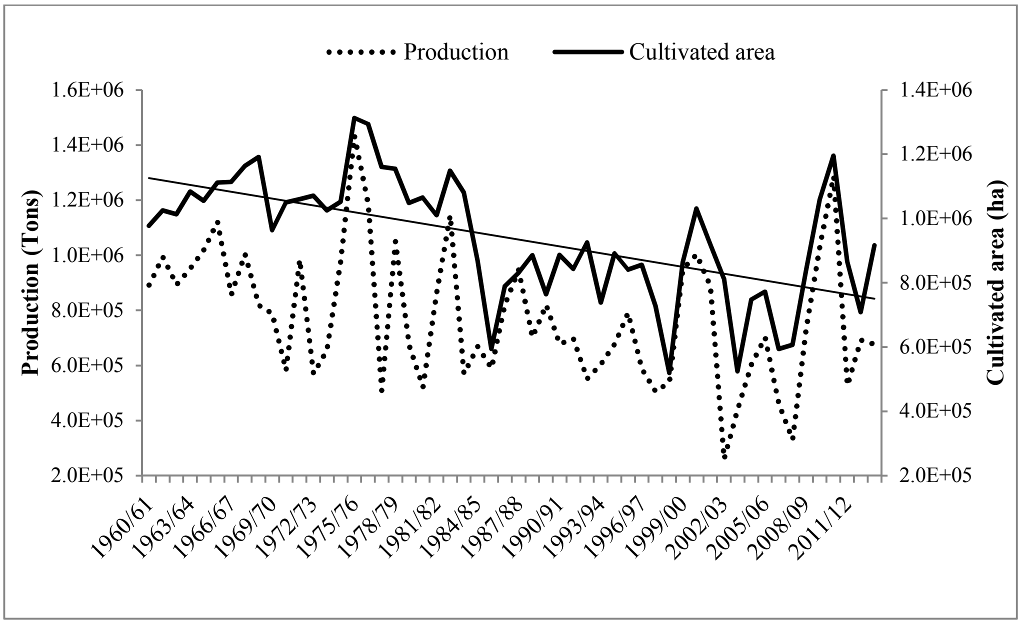

Figure 1. Peanut production and cultivated area from 1960 to 2014

Data source: DAPSA

Effect of fertilizer application and drought stress on peanut

Fertilizer application

There is evidence that fertilizer use has increased marginally since the 1980s (from 8.5 kg/ha in 1980-1989 to 13.5 kg/ha in 1996–2000) due to national policy changes (Jayne, Kelly and Crawford, 2003). However, low adoption and low intensity of use of chemical fertilizers is still a large constraint to increased production in the peanut basin from 1998 to 2005, with less than a third of the households applying fertilizers (Thuo, Bravo-Ureta, Hathie and Obeng-Asiedu, 2011).

The effect of nitrogen on peanut is known to increase vegetative growth (Farag and Zahran, 2014) and yield character but most studies are centred on phosphorus and potassium (Migawer and Mona, 2001). Both P and

K have beneficial effect on N fixation by legumes (Haghparast-Tanha, 1975). N fertilization on peanut should not be exceed 10kg/ha in newly terraced Ultisol (Campbell, Wahab and Murray, 1980). Phosphorus is the most important soil nutrients for peanut in Africa (Tarawali and Quee, 2014) particularly in semi-arid zone (Naab, Boote, Jones and Porter, 2015). It increases significantly vegetative growth, yield, seed quality and its components (Gobarah, Mohamed and Tawfik, 2006). In most cases in Africa, peanut is grown in soil with phosphorus deficiency with is a limited yield factors under on-farm conditions (Naab, Prasad, Boote and Jones, 2009; Ogeh and Oyibo, 2015).

Drought stress

The effect of drought stress on peanut has been an important subject for investigation and was used to support development of adapted varieties (Gautreau, 1982). It depends of the duration of the drought stress, the stage of peanut growth and the intensity of the stress. The effects of drought stress is known to be more drastic on peanut when occurred during the reproductive phases than the vegetative phases (Hemalatha, Rao, Padmaja and Suresh, 2013; Jongrungklang, Toomsan, Vorasoot, Jogloy, Boote et al., 2013). Drought stress in pre-flowering has minimal effect in peanut yield. While the greatest reduction in kernel yield due to drought stress occurred during the seed filling phase whereas an increase of pod yield by at least 13% occurred when drought stress was imposed during the early phase (Rao, Singh, Sivakumar, Srivastava and Williams, 1985; Stirling, Black and Ong, 1989). In addition, the yield advantage was due to improved synchrony in flowering and the increase peg to pod conversion (Nautiyal, Joshi and Dayal, 2002). Above ground biomass is affected negatively whenever the drought stress imposed. However, the leaf area of index of peanut stressed during the reproductive phase was lower than the leaf area index of peanut during the vegetative phase (Nautiyal et al., 2002). Drought at the end of the season affected more pod yield than number of mature pods which is most sensitive to mid season drought (Kenchanagoudar, Nigam and Chennabyregowda, 2002).

The mechanisms of physiological adaptation to drought were also investigated on peanut in Senegal which aimed at the selection of adapted peanut varieties (Annerose, 1988; Clavel et al., 2007; Clavel et al., 2005) and identification of the sensitivity of peanut growth to drought (Annerose, 1985; Annerose, 1990).

A part drought and high temperature stress, nutrient deficiencies mainly N, P and K caused significant yield losses in semiarid regions but they are lower than for most other crops with a general requirement of 20kg N/ha, 50-80kg P/ha, and 30-40kg K/ha (Prasad, Kakani and Upadhyaya, 2010).

Modelling crop growth and yield in West Africa

A model is a simplified representation of a system. In agriculture the common crop models used are dynamic models in that growth and development are modeled in response to growth driving (radiation, CO_2, etc.) and growth limiting (drought, nutrient limitation, high temperature) factors on a daily basis (Hodson and White, 2010). Such models not only estimate the final state of total biomass or harvest yield, but also contain quantitative information about major processes involved in the growth and development of a plant (Fosu-Mensah, 2012).

Some dynamic models are commonly used in West Africa for exploring crops management. They are used mostly on cereals to simulated crop growth, development and yield (Salack, Sultan, Oettli, Muller, Gaye et al., 2012b). SARRA-H crop model is particularly adapted in tropical area and for cereals to simulate plan growth (Baron, Sultan, Balme, Sarr, Traore et al., 2005; Salack et al., 2012b; Sultan, Janicot, Baron, Dingkuhn, Muller et al., 2008).

Kpongor (2007) evaluated the ability of APSIM on Sorghum in Ghana. It was found that APSIM is responsive to organic and inorganic fertilizer applications. Therefore, the use of inorganic and incorporation of crop residues are essential for food security attained in the study area. The same results are confirmed by MacCarthy, Sommer and Vlek (2009).

DSSAT was used in West Africa by González-Estrada, Rodriguez, Walen, Naab, Koo et al. (2008) to evaluate different crop management strategies by their capacity to sequester carbon in agricultural soils and by their contribution to household income.

Gaiser, de Barros, Sereke and Lange (2010) simulated maize yield in low input systems using the EPIC in tropical sub-humid West Africa. The model was able to assess the effects of climate and management scenarios.

On peanut, some studies have been conducted on impact assessments, nutrient uptake and diseases which the most common model used was CROPGRO part of DSSAT. It performed well in recent experiments in northern Benin by predicting and simulating the observed crop and pod dry matter when input on percent diseased leaf area and percent defoliation were provided (Adomou, Prasad, Boote and Detongnon, 2005). It evaluated peanut growth and yield in some farming zones of Ghana (Dugan and Adiku, 2006; Naab, Singh, Boote, Jones and Marfo, 2004). Craufurd et al. (2006) used CROPGRO-peanut model to simulate the occurrence of moisture stress in Niger. The model simulated accurately yield based on the fraction of extractable soil water, infection and contamination can be predicted in peanuts when soil temperatures are not limiting aflatoxin contamination. Nutrients uptake was successfully simulated on peanut by CROPGRO-peanut over West Africa.

Naab et al. (2015) showed the ability of CROPGRO-peanut model to simulate peanut growth and yield in response to soil P levels or fertilizer application on an Alfisol.

However, the validation of models is a methodological critical point since the latter has often been parameterized and validated in a context which can greatly differ from the future expected climatic conditions.

Despite the fact that many models do not (or are not well tested) simulate weed, pests and many key cropping systems, they are useful tools to explore how crops may respond to the combinations of higher temperatures, elevated CO_2, changed water availability and new management.

Modelling is an important part of research used to replicate real-time events normally too difficult and expensive to replicate on actual large scale or multiple times. Further, they are the only ways to investigate how crops will respond to future climate.

Climate change impact analysis on crop over West Africa

Long term climate data are crucial for researchers to understand the impact of climate change on agricultural production. However, such information are scarce and often not easily accessible in Africa. As such, Africa was selected as the first target region for the initial focus of the CORDEX (Coordinated Regional Climate Downscaling Experiment) experiments. Firstly, because Africa is especially vulnerable to climate change, through the sensitivity of many vital sectors on climate variability (agriculture, water management, health) and their relatively low adaptive capacity. Secondly, climate change may have significant impacts on temperature and precipitation patterns over Africa, which in turn, can interact with other environmental stressors such as land-use change, desertification and aerosol emissions. Finally, to date, only very few simulations based on regional climate downscaling (RCD) tools are available for Africa (Giorgi, Jones and Asrar, 2009).

There is growing evidence of a decline in average precipitation in West Africa since 1960, including repeated droughts, which in some cases have been partly attributed to anthropogenic climate forcing (IPCC, 2014a). Climate change is expected to be experienced in the region as significant increase in temperature (Folland, Palmer and Parker, 1986; Nyong et al., 2007). Some areas of Sahelian West Africa experience ‘significant’ rainfall decreases in JJA season under low climate scenario (Hulme, Doherty, Ngara, New and Lister, 2001). While other models actually expect increasing levels of rainfall (Webber et al., 2014). In any case, higher temperatures will lead to higher rates of soil water use through greater evapotranspiration rates.

Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability (IPCC, 2014c). The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs and will likely be in the range 0.3°C to 0.7°C (IPCC, 2014c). However, the increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5 (IPCC, 2014c).

The impact of climate change on West African rainfall is less clear. Future projections suggest a drier western Sahel (e.g., Senegal) with a reduction of 15% but a wetter eastern Sahel (e.g., Mali, Niger) (Adiku et al., 2015). West Africa is a vulnerable region where a better quantification and understanding of the impact of climate change on crop yields is urgently needed (Sultan et al., 2013).

Studies have shown that climate change will affect agriculture and will be more pronounced in developing countries whose agricultural systems are vulnerable and depend essentially on rainfall. However, increase of temperature is known in Sub-Saharan Africa as the key driver of future climate change impact analysis (Roudier et al., 2011; Schlenker and Lobell, 2010; Tingem and Rivington, 2009) and elevated atmospheric CO_2 concentrations (Webber et al., 2014).

In this region, temperature increases above 2°C (relative to a 1961–1990 baseline) are estimated to counteract positive effects on millet and sorghum yields of increased precipitation (for B1, A1B, and A2 scenarios) (IPCC, 2014b).

One of the main effects of high temperature in this region have effect to accelerate the development of peanut and shorten the reproductive duration which have effect on reducing yield. Other negative effects of hot temperature above the optimum are known to be the reduction in radiation use efficiency (Prasad, 1999) on peanut and (Cicchino, Edreira, Uribelarrea and Otegui, 2010; Edreira and Otegui, 2012; Edreira and Otegui, 2013; Reynolds, Pierre, Saad, Vargas and Condon, 2007; Rezaei, Webber, Gaiser, Naab and Ewert, 2015) on cereals as respiration increases more than photosynthesis as temperature rises above. Finally, high temperatures above 34°C reduce pollen production and pollen viability (Prasad, Craufurd and Summerfield, 1999b) and fruit-set when bud temperature greater than 33°C (Prasad, Craufurd, Kakani, Wheeler and Boote, 2001) for peanut. The sensitivity of peanut to heat stress extends from 6 d before anthesis until 15 d after flowering and a day temperature of 38 °C imposed during the reproductive phase is supra-optimal and reduces early reproductive yield (Prasad, Craufurd and Summerfield, 1999a).

While the field evidence now indicates positive effect of increase of CO_2 concentration for C3 crops such as wheat, rice and groundnut which increase the crop productivity in the range of 15-20% under optimal growing conditions (Tubiello, Schmidhuber, Howden, Neofotis, Park et al., 2008). The increasing level of CO_2 increases growth and photosynthesis in C3 plants, but in C4 plants net leaf photosynthetic carbon dioxide exchange rate is nearly saturated by elevated CO_2 at current ambient CO_2concentration (Vanaja et al., 2013). Pod and seed yield are increased by 30% owing to an increase total number of pods or seeds due to increased photosynthesis and growth in elevated CO_2. However, when the temperature thresholds are reached, crop yields will decrease despite enhanced CO_2 for both C3 and C4 plants (Singh et al., 2014). Future CO_2 levels will favour C3 plants with little benefit for C4 crops when water is not limiting (Tubiello, Soussana and Howden, 2007). While the opposite will be expected under water limited and temperature increases and the net effects remain uncertain.

The impact on crop yields in West Africa remain highly uncertain when elevated temperatures, higher CO_2 and changed precipitation occur simultaneously (Roudier et al., 2011) which is due to both variety of methods, models and assumptions that have been used to assess climate change impacts on crop yields (Webber et al., 2014), as well as scientific uncertainty in process interactions at the canopy scale (Tubiello et al., 2007).

In Senegal, agriculture is mainly rainfed (Sall, Bâ and Kane, 2013) which is characterized by a short rainy season (three to four months) where peanut is the main crop. Growing season conditions are characterized by low precipitation and high temperature which caused a decline of the productivity of peanut. The two abiotic stresses, drought and high temperature, are the main yield limiting factors in semiarid regions (Prasad et al., 2010). Pollination is one of the most sensitive phenological stages to temperature extremes across all species and during this developmental stage, temperature extremes would greatly affect production (Hatfield and Prueger, 2015). During the growing season from June to September, the maximum temperature is around 35°C which is slightly around the optimum mean diurnal temperature required 30°C and 35°C for photosynthesis and vegetative respectively (Craufurd, Prasad, Kakani, Wheeler and Nigam, 2003; Prasad et al., 2010).

Modelling heat stress on crop for climate change studies

Assessing the impact of climate change and climate variability through modelling approaches is an important tool for agricultural activities which are strongly sensitive to climate. Computer modelling can help to explore adaptations of agricultural practices to minimize negative effects of climate change.

Common crop models used to simulate potential yield are extended to assess the climate change on crop. APSIM is used on maize in Ghana (Fosu-Mensah, 2012), and on sorghum in Ghana (MacCarthy and Vlek, 2012) to evaluate the impact of climate on yield. Sultan et al. (2013), assessed the impact of climate change on sorghum and millet yields in West Africa with SARRA-H crop model.

Millet, sorghum, rice, cassava and maize were simulated with EPIC crop model in West Africa by (Adejuwon, 2005). The model could be used satisfactorily for climate impact assessment adaptations to climate change and climate variability but for vulnerability assessment further field experiments are needed.

Roudier et al. (2011) describe some studies conducted on crop in West Africa in the context of climate change impact assessment. But none of these studies have considered canopy temperature and have therefore neglected the interaction of drought and heat stress. Our study is therefore unique considering the effect of heat stress together with water status in SIMPLACE by simulating canopy temperature to calculate heat stress. Other authors have found that canopy temperature is better than air temperature for estimating heat stress impact (Siebert, Ewert, Rezaei, Kage and Grass, 2014). This is important for West Africa where daily maximum air temperatures are close to 35° C and an error of even a few degrees can lead to large errors of overestimation of heat stress (if transpiration is high) or underestimation of heat stress (if plants are drought stress) (Rezaei et al., 2015).

On wheat, a high and significant correlation for canopy temperature was found during the reproductive stage and biomass. Meanwhile, an important development of root up to 65% was noted (Pinto and Reynolds, 2015). The comparison of canopy temperature and air temperature can be use as indicator to crop water stress index (CWSI) which may prove useful as guide for irrigation (Durigon and van Lier, 2013; Jackson, 1982). The cumulative sum thermal time as indicator of heat stress in the model is well simulated if canopy temperature is considered instead of air temperature for cereals. However, the comparison is not linear, it depends of the crop, management and location (Webber, Ewert, Kimball, Siebert, White et al., 2016).

As drought and heat stress occur simultaneously, canopy temperature could be used for the impacts of heat stress on yield simulation to appreciate uncertainties but representative data in the field will be needed to evaluate the performance of models by shift from air temperature to canopy temperature (Rezaei et al., 2015).

None of this study addresses the effect of canopy temperature on peanut in West Africa.

Impact of climate change on peanut yield and adaptation

As climate change is expected to further exacerbate yield declines, it is important to develop strategies to adapt peanut growth in this region in the context of climate change. Information about climate is very important and need to be processed and made understandable for the extension services. It will help to know the period most appropriate for sowing because of dry spell when the first rainfall occurs earlier. In addition to climate information, adaptation strategies relative to agronomic traits such as new adapted varieties with drought resistance, varieties with heat tolerance, different varieties with new cycle length, new planting day, fertilizer application and irrigation supply in some cases have to be investigated to sustain productivity in the context of climate change. Crop models can assist to identify which trait and management adaptation can increase peanut productivity under climate change (Singh et al., 2014).

Climate variation has a negative effect on peanut production in West Africa (Barbier, Yacouba, Karambiri, Zoromé and Somé, 2009; Eregha, Babatolu and Akinnubi, 2014; Mohamed, Van Duivenbooden and Abdoussallam, 2002; Paeth, Capo-Chichi and Endlicher, 2008; Van Duivenbooden, Abdoussalam and Ben Mohamed, 2002), with drought and high temperature stress constituting the main yield limiting climatic factors (Prasad et al., 2010). Many studies have been conducted on drought and heat stress in West Africa (Hamidou et al., 2013; Hemalatha et al., 2013; Singh et al., 2014), though few simultaneously investigate both water limitations and heat stress (Hamidou et al., 2013). Under climate change, heat stress and water stress occurring simultaneously are considered to be two major environmental factors limiting peanut growth and yield (Hamidou et al., 2013). Leaf temperatures of water stressed oats were found to be 2.5-4°C warmer than well-watered oats. In an arid areas canopy temperature may be more than 10°C below air temperature where in humid climates it will be near to or higher than the air temperatures (Jackson, 1982).

To improve the peanut yield and anticipate climate change impacts, crop models are commonly used for policies decision support. Recent improvements for their application in West Africa with peanut include responsiveness to abiotic stresses, such as soil phosphorus, disease and nutrient deficiencies (Naab et al., 2015; Prasad et al., 2010). CROPGRO-peanut model was successfully used to quantify the yield potential and yield gaps associated with yield-reducing stresses and crop management in Ghana (Naab et al., 2004), peanut contamination in Mali (Boken, Hoogenboom, Williams, Diarra, Dione et al., 2008) and low phosphorus soils in Ghana (Naab et al., 2015).

Singh et al. (2014), investigated the potential benefits of drought and heat tolerance in peanut for India and West Africa using CROPGRO-peanut model. Heat tolerance is not a cultivar coefficient in model. To achieve a shift in tolerance to high temperature, changes were made in the peanut species file.

However, CROPGRO-peanut is the main crop model used in West Africa in published studies. It does not consider canopy temperature when simulating the impacts of heat stress on seed yield, despite evidence of the potential importance of this consideration (Lobell, Hammer, McLean, Messina, Roberts et al., 2013; Siebert et al., 2014; Webber et al., 2016).

CHAPTER THREE

MATERIALS AND METHODS

Study area

The study was conducted in Senegal in three different agro climatic zones with all trials conducted at the Senegalese Institute of Agricultural Research (ISRA) sites (Figure 2). The first site was the Bambey research station located on 14°42' N and 16°29' W. The second site was the Nioro research station located on 13°45' N and 15°46' N. The third site was the Sinthiou Malem research station located on 13°49' N and 13°54' W. Bambey and Nioro belong to Senegal's Peanut Basin zone which constitutes the country's most important peanut production area.

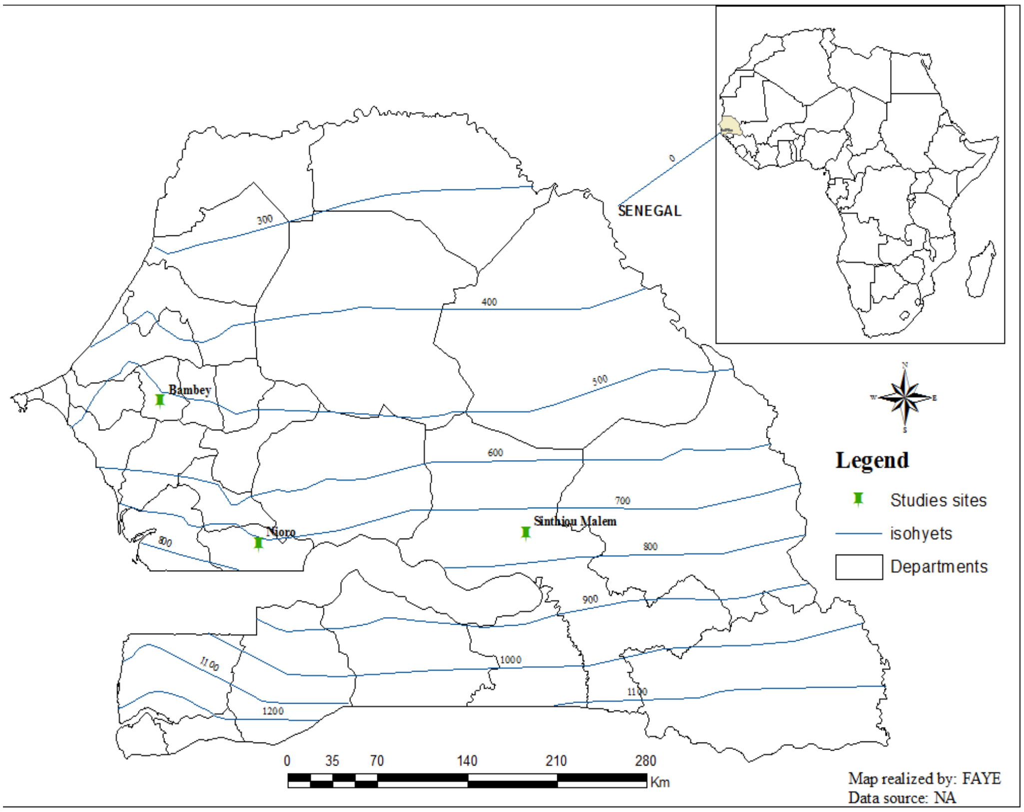

Figure 2: Study area, normal rainfall period 1961-1990mm

The zone is characterized by a Sudano-Sahelian climate (Bambey) to a Sudanian climate (Nioro and Sinthiou Malem) where the variation in rainfall ranges between 400 to 800mm per year (Ganry and Gueye, 1992).

The rainy season is uni-modal and the rain is mostly concentrated in three to four months between June to September with August being the month with highest amount of rainfall (Figure 3). The rainy season in 2014 was relatively short in Bambey and Nioro with a concentration of rain from August to September. In Sinthiou Malem rainfall was well distributed from May to October with an amount of water of 696 mm received during the year 2014. The amount received in Bambey was 407mm, whereas the amount received in Nioro was 513 mm (Figure 3).

The minimum temperature varies between 18 to 20°C in December to January, while the maximum temperature varies between 40 to 42°C and occurs from April to May. The monthly maximum temperatures were greater in Sinthiou Malem with a maximum value of 42.6°C in April which is the hottest month for all the sites, whereas, the lowest monthly minimum temperatures was at Bambey 16.1°C in January. Maximum solar radiation occurs from March to April (25 MJ m^{-2} day^{-1}) and the minimum solar radiation values were observed from November to December with a minimum value of 14 MJ m^{-2} day^{-1} achieved in Bambey. The mean air relative humidity is low during the dry season but during the rainy season, it is higher and varies between 70 to 80 %.

There are three different types of soil in the study area depending on the average percentage of silt and clay in the top 40 cm layers. Tropical ferruginous soils commonly called "sol Dior" which are found mainly in Bambey (Clay + Silt <12%),tropical ferruginous leached soils commonly called "sol Deck-Dior" at all sites (12% < Clay + Silt < 15%), and tropical ferruginous hydromorphic soils commonly called "sol Deck" found mainly in Nioro and Sinthiou Malem (Clay + Silt >15%). These soils are low in nitrogen content, with percentage nitrogen ranging between 0.02 and 0.03% and generally low in available phosphorus which is less than 30 ppm (AGETIP, 1995).

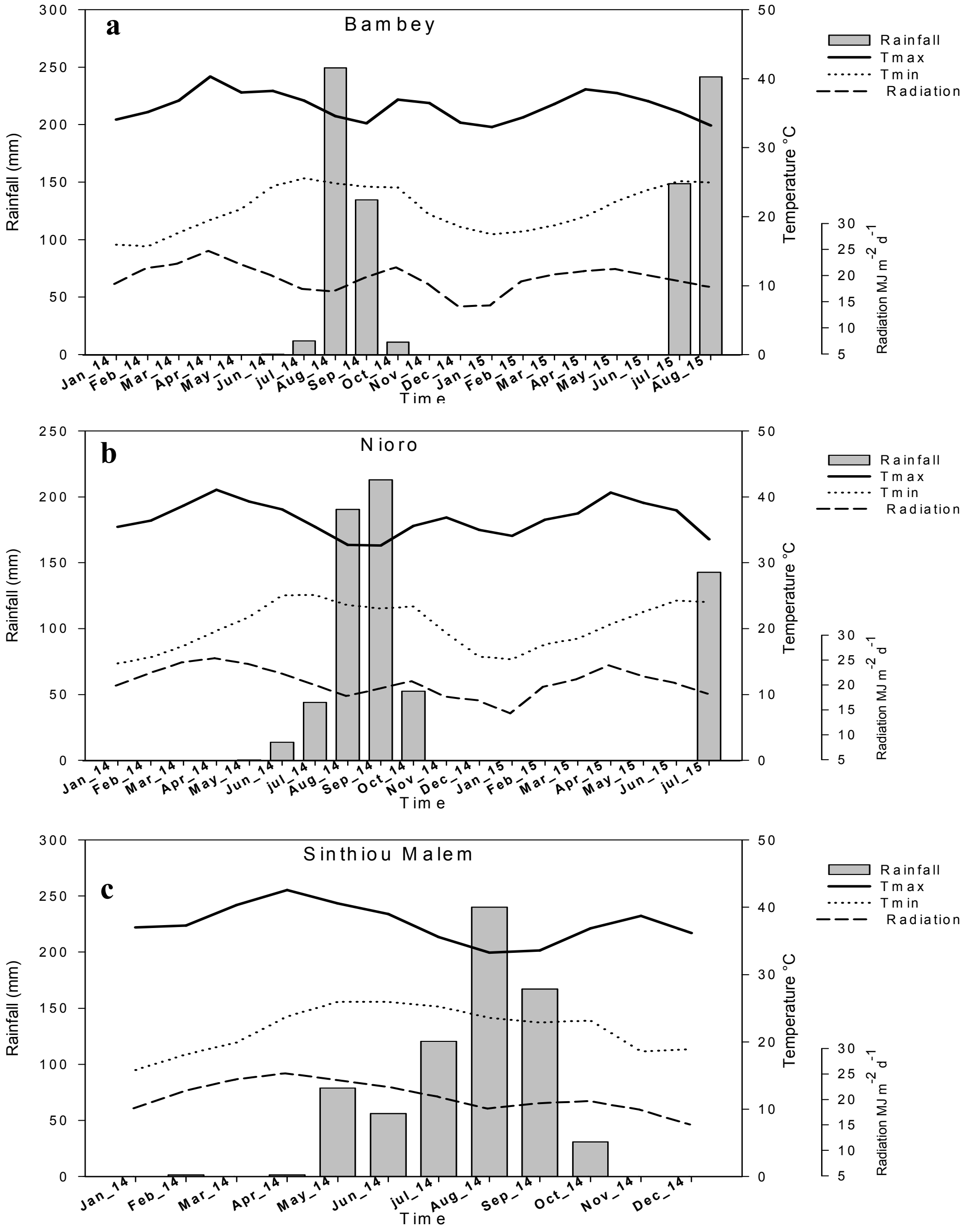

Figure 3: Seasonal cycle for climate variables during the growth season 2014 and 2015

Bambey (between January 2014 and August 2015), Nioro (between January 2014 and July 2015) and Sinthiou Malem (between January and December 2014), with monthly rainfall (bars), monthly maximum (solid lines) and minimum temperatures (dashed lines) and monthly radiation (dotted lines).

Source: CNRA Bambey and ANACIM

Description of the experimental procedure

Field experiments were conducted in Bambey, in Nioro and in Sinthiou Malem, during the dry seasons of 2014 and 2015 and the rainy season of 2014. A total of seven field experiments were carried out in these three sites. Two dry season field experiments in Bambey and in Nioro and one rainy season field experiment in each site (Table 1). The peanut cultivars selected were Fleur 11 (V1) variety and 73-33 (V2) variety which are known to be early (90 days) and medium (110 days) maturity cultivars respectively. Composite fertilizer 6-20-10 was applied just after sowing as recommended by the National Agricultural Research Institute of Senegal at a dose of 150kg/ha. Nitrogen (N) as total nitrogen, phosphorus (P) as single superphosphate tripe (P_2O_5) and potassium (K) as potassium oxide (K_2O) during the dry season. However, during the rainy season single doses of N (urea 46%), P (DSP 24% P_2O_5) and K (KCL with 60% K_2O) where applied in treatment T4 and T5 (Table 1). The three irrigation levels were: E, irrigation was applied at field capacity on plants with no water stress; S1, irrigation was applied on plants with water stress during the flowering period 25 days after sowing; and S2, irrigation was applied on plants with water stress during seed filling 70 days after sowing. Experimental units measured $16m^2$ (4x4m). Row spacing was 50 cm between rows (inter-row) and 15 cm in the rows (intra-row).

Before sowing each year, the field was disc-ploughed to a depth of 12 cm, harrowed and levelled. In dry season 2014, during the soil preparation, 5750kg/ha of cow manure was incorporated in the soil before sowing at both sites.

The seeding was done by hand at a depth of about 4 cm with two seeds per seed hole. Seeds were treated with Saxal fungicide to protect them from insects. Thinning to one plant per seed hole was done after emergence at 11 days after sowing (DAS). Weed control was done by hoe and pests were controlled by chemical pesticides where attacks occurred.

Phenological observations were taken at interval of 7 days to determine parameters such as, day of emergence, day of flowering, beginning of peg, beginning of pod formation, beginning of seed and physiological maturity as described in Boote (1982). Total dry matter was determined in leaves, stems and pods at different stages of the growing season on weekly basis. Final harvest was determined at maturity on each plot from an area of 3.9m^2. Time series of leaf area index were measured before each biomass sampling at both sites with a Plant Canopy. Analyzer (LAI 2000) early in the morning or late in the afternoon and with a Sun Scan (Webb, Nichol, Wood and Potter, 2008) in Sinthiou Malem in full sunshine.

In Bambey, the soil was of sandy texture to about 1.5 m depth and in Nioro of sandy loam texture to about 1.5m soil depth. Ten composite soil samples were collected in 10 cm intervals from 0 to 100cm depth using an auger. Analyses were done in the CNRA Bambey soil laboratory to estimate physical and chemical properties. Weather stations were located at each site at less than 1kilometre distance from the field experiments and rainfall, maximum and minimum air temperature, sunshine hours, maximum and minimum relative humidity and wind speed were measured. These are the climate input data used in the model.

Table 1: **Summary of the treatments in the seven field experiments**

Sites	Seasons	Irrigation Levels	Fertilizer Levels	Variety Levels	Repetition	Design	Planting Month
Bambey	Rainy season 2014	No irrigation	Six (T0, T1, T2, T3, T4, T5)	Two (V1,V2)	Four	RCBD	August
Nioro							July
Sinthiou Malem							July
Bambey	Dry Season 2014	Three (E,S1,S2)	Two (T0, T3)	Two (V1,V2)	Four	Split Split plot	March
Nioro		One (E)	Four (T0, T1, T2, T3)	Two (V1,V2)	Four	RCBD	March
Bambey	Dry Season 2015	Three (E,S1,S2)	Two (T0, T3)	Two (V1,V2)	Four	Split Split plot	February
Nioro							February

Footnote: T0 without fertilizer, T1 with 33% of recommended dose, T2 66% with recommended dose and T3 which represent the recommended dose that is 150kgha^{-1}of 6-20-10 NPK, T4 same level of T3 without Phosphorus and T5 same level of T4 with 50% of phosphorus.

Split Split plot = split split plot design with irrigation level in the main plots, cultivar levels in sub plots and fertilizer levels in sub sub plots

RCBD = Randomized Complete Block Design under factorial design

Effects of fertilization rate and water availability on peanut in Senegal

This sub chapter assesses the effects of fertilizer response and water stress on peanut development, growth and yield in Senegal. To achieve this aim, field studies were conducted in three different parts in Senegal (i) to evaluate the most sensitive period of peanut to water stress on yield reduction and (ii) to determine the effect of mineral fertilizer rate on peanut in Senegal.

Datasets in Bambey during the dry season 2014 and 2015 and in Nioro during the dry season 2015 were used to achieve the first objective. For the achievement of the second objective, datasets in Bambey, Nioro and Sinthiou Malem during the rainy season in 2014 were used in addition to dataset in Nioro during the dry season in 2014.

Field measurements of crop parameters

Measurements taken during the growing seasons in the field regarded phenological observations, leaf area index, time series of biomass sampling soil moisture measurement. Final harvest yields were determined at maturity.

Phenological observations

Visual observations of crop vegetative (V) and reproductive events (R) were taken at weekly intervals.

Days to 50% emergence was determined when 50% of the seeds had emerged in all plots.

The vegetative stage was determined by counting the number of developed nodes on the main stem (Boote, 1982). The determination of the reproductive stage was based on the Biologische Bundesanstalt, Bundessortenamt et CHemische Industrie (BBCH) scale (Meier, 2001) and development stages proposed by (Boote, 1982). These development stages were beginning of bloom (R1), beginning of peg (R2), beginning of pod (R3), full pod (R4), beginning of seed (R5), full seed (R6), beginning of maturity (R7), harvest maturity (R8) and over mature pod (R9). A given stage was considered achieved when 50% of the plants sampled had achieved the specified node number or have one or more flowers, pegs, pods, or seeds exhibiting the specified trait. A total of five plants were selected and tagged in the yield square and followed during the growing season for each plot.

The observed emergence occurred on average in all the sites at 6 days after sowing (DAS). However, the rate of emergence was higher during the rainy season with the early emergence occurring at five days after sowing if the quantity of rain received before sowing was more than 20mm in the case of Sinthiou Malem and Bambey. During the dry season, if during the first irrigation the soil was not very humid, emergence was delayed up to eight days after sowing. The appearance of the first leaf occurred on average two to three days after emergence. The two varieties had the same number of leaves in the main stem (Figure 4). Vegetative stage is defined as one developed node with one tetrafoliate leaf unfolded and its leaflets flat (Boote, 1982). The observed flowering date occurred on average in all the sites and for both years, for Fleur 11 from 24 DAS during the rainy season and 30 DAS during the dry season and for 73-33 from 32 DAS during the rainy season to 36 DAS during the dry season.

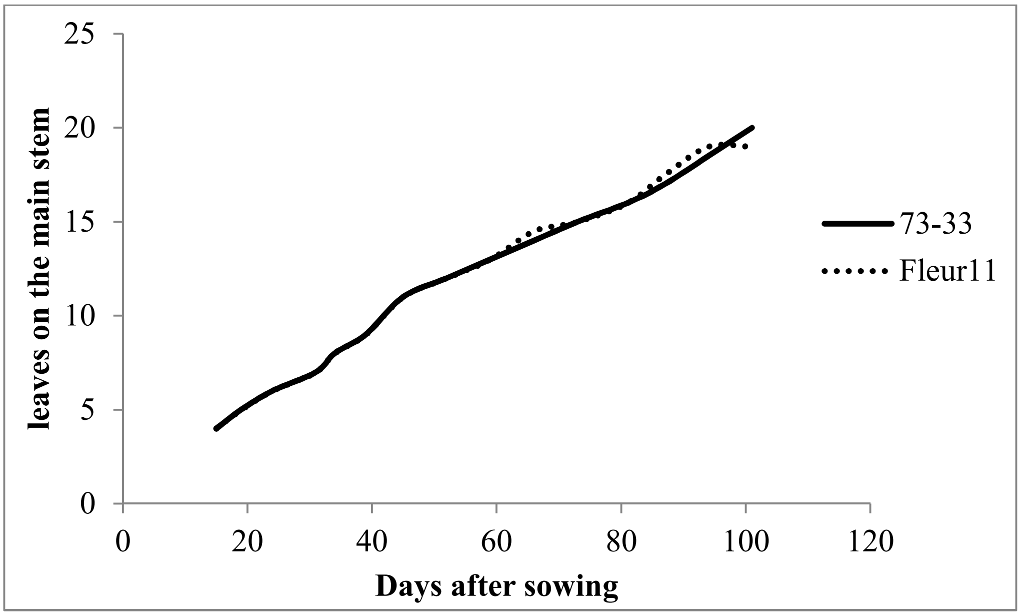

Figure 4: Number of leaves in the main stem of Fleur 11 and 73-33

Leaf area index

A time series of leaf area index (LAI) was measured every ten days to two weeks with a LAI 2000 in Bambey and Nioro and with a Sun Scan in Sinthiou Malem. Three measurements were made nondestructively in the centre of each plot and the average LAI was determined.

Biomass sampling

A time series of biomass partitioning into leaves, stems, and pods was determined on the same dates as LAI. Samples were taken randomly and destructively on five plants in the extremes of the plot (Figure 5). Samples were oven-dried at 65°C for 48 hours.

The determination of the final yield and biomass was done in the centre of each plot in which yield was sampled at an area of 2m length by 1.95 width (3.9m^2). Yield components were divided into four major parts: number of plants per square metre, number of pods per plant, number of seeds per pod, average weight of seeds.

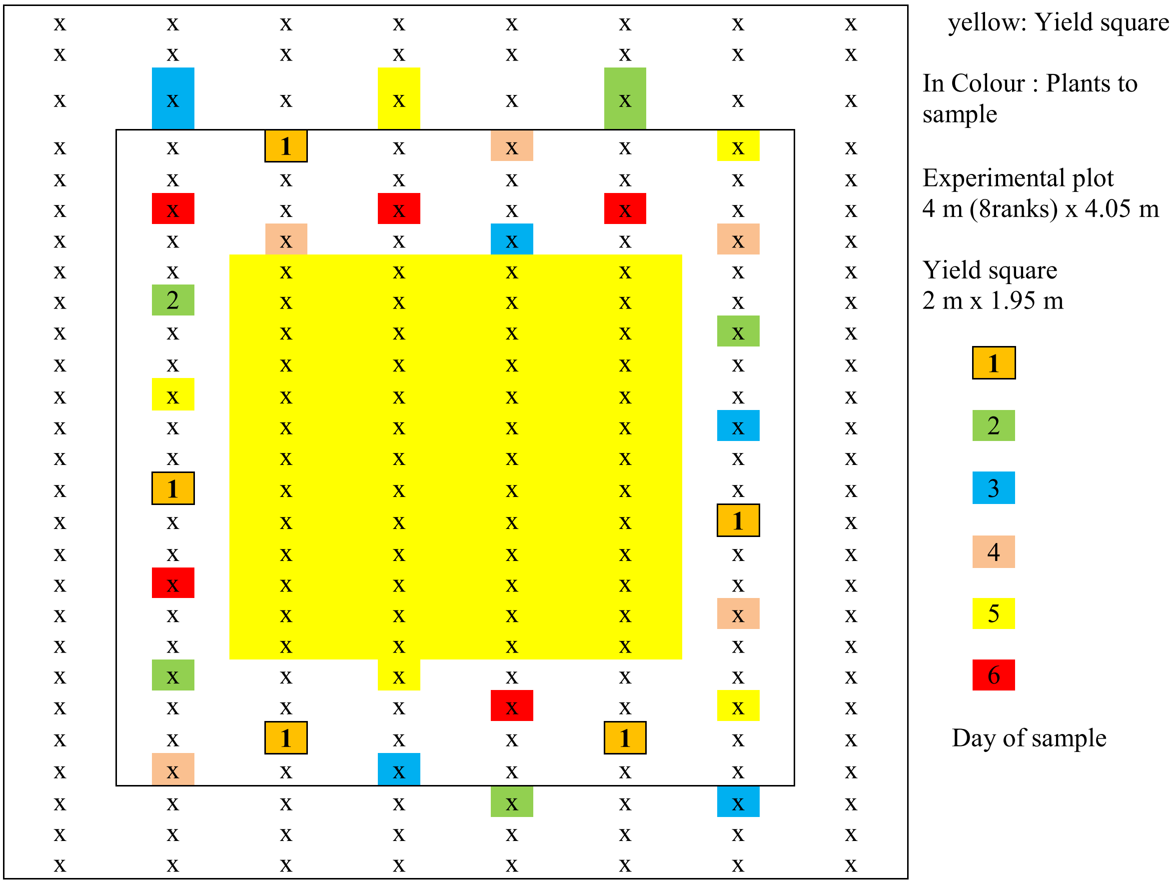

Figure 5: Experimental plot design

Soil sampling and analysis

Before sowing, initial soil sampling was carried out at each site to determine the physico-chemical characteristics. Composite soil samples were collected at different depths (in 10 cm intervals) from 0 to 100cm with two samples per block, depths through which selected crop efficient root cannot exceed. These samples were placed in sample bags. Ten composite samples were collected at each sites. Sample composite was described as the mixture of all the different depth and each depth constituted one sample. For instance, 0-10cm depth constituted one sample and so on.

Samples were air-dried, kept in polythene bags and brought to the laboratory for physical and chemical analysis. In 2014 the analysis was done in ISRA's plant-soil laboratory and in 2015 in the National Institute of Pedology. The final output was used for analysis and model development

Bulk density

Bulk density was determined for each depth to undisturbed samples. A mound of ground was taken and weighed (P1). By putting this mound of ground in the drying oven, it dried at 105°C for 24 hours, we obtained the water content by making P1- P2 (P2 = oven dry soil). The volume V of the cylinder inserted in the ground.

$$Bulk\ \ density\ \ (g.cm^{-3}) = \frac{P2}{V} \qquad Eq.1$$

Soil moisture measurement in-situ

Soil moisture content was measured only in Bambey during the dry seasons of 2014 and 2015. It was measured to a depth of 160 cm at 10 cm intervals twice a week by a diviner 2000. It is a portable soil moisture monitoring system. It comprises a data display unit and a portable probe. Readings were taken through the wall of a PVC access tube. Data was collected from a network of 24 access tubes installed in sites.

Data analysis

The data were processed using Sigma plot 12.0 for figures and R 3.2.2 (https://www.r-project.org/) in RStudio, which is an Integrated Development Environment (IDE) for R for the statistical analysis (Team, 2014). The analysis of variance was used to analyze the differences between treatments. The Tukey's HSD test was performed to determine the significant differences of means between treatments at 5% after proceeding the analysis of variance (ANOVA).

Model development

Experimental data

Data used in this section were described in detail in the section description of the experimental procedure. Data for Bambey and Nioro are considered for model calibration and evaluation. The peanut cultivars selected were Fleur 11 (V1) variety and 73-33 (V2) variety.

Soil properties

The model used NMINS, PMINS and KMINS as total mineral soil N available at start of growth period (gm^{-2}), total mineral soil P available at start of growth period (gm^{-2}) and total mineral soil K available at start of growth period (gm^{-2}) respectively. The value of 0.025 was used as fraction of soil mineral N, P and K coming available per day for the plant. Data analysis for chemical soil properties were used to calculate the available amount of NPK. (Table 2) in the top 1metre soil which effective peanut root cannot exceed for nutrients supply. It was noticed an important amount of N, P and K in both sites during the year 2014 compared to year 2015.

During all field experiments, the application of N, P and K had no effect on yield.

Table 2: Parameters of soils properties

	2014		2015	
	Bambey	Nioro	Bambey	Nioro
N (g m^{-2})	8.26	8.66	9.07	10.12
P (g m^{-2})	42.01	17.72	3.8	6.95
K (g m^{-2})	67.43	68.95	9.79	9.26
%C	0.13	0.3	0.24	0.289

Weather data

At both sites, mean solar radiation was greater during the dry season than during the rainy season for the growth season. The maximum mean value of 24.16 MJ m^{-2} d^{-1} was recorded in Nioro during the dry season 2014. The same tendencies were observed for the minimum, mean and maximum temperature. The average maximum temperature of 39.64°C in the dry season 2014 was recorded at Nioro. These results show that the maximum value of radiation and temperature were observed when the growing season was from March to July compared to the values observed when the growing season was from February to June. The rainy season was cooler than the dry season due to a higher relative humidity. Plants during the dry season 2014 suffered more from heat stress than plants during the dry season 2015. However, plants received less water in rainy season, therefore they suffered more for water stress than heat stress (Table 3). Daily data of solar radiation, minimum, mean and maximum temperature, precipitation and wind speed were recorded at each sites for model running except in Nioro where no wind speed was recorded. Therefore, the values used in the model were from a nearby station at Sinthiou Malem, where the wind speed was considered as similar.

Table 3. Weathers conditions observed during the growing seasons in 2014 and 2015 at Bambey and Nioro

Season	Sites	Rainfall (mm)	Mean daily solar radiation (MJ m^{-2})	Mean daily minimum temperature (◦C)	Mean daily average temperature (◦C)	Mean daily maximum temperature (◦C)	Irrigation (mm)
Dry season 2014	Bambey	0	22.3	21.3	30	38.72	588
	Nioro	13.8	24.2	21.4	30.53	39.64	609.8
Rainy season 2014	Bambey	407	19.5	24.3	29.78	35.23	28.8
	Nioro	513	19.2	23.6	28.56	33.55	26.2
Dry season 2015	Bambey	0	20.5	20.1	28.55	36.96	602.4
	Nioro	0	21.7	20.1	29.33	38.58	615.5

Model description

The peanut hourly heat stress model implemented in SIMPLACE (Scientific Impact Assessment and Modeling PLatform for Advanced Crop and Ecosystem management) modeling framework (Gaiser, Perkons, Küpper, Kautz, Uteau-Puschmann et al., 2013) was linked to the LINTUL5 model, the water balance model, DRUNIR, from the Lintul2 crop growth model, the hourly canopy temperature model, CanopyT, and a biomass translocation model. The combined model solution was named as SIMPLACE<Lintul5, DRUNIR, CanopyT, HourlyHeat> (Figure 6).

Diurnal is a function used to transform daily weather inputs to hourly values using sinusoidal functions (Ephrath, Goudriaan and Marani, 1996; Van Oort, Saito, Zwart and Shrestha, 2014).

LINTUL5 is a relatively simple crop growth model which calculate crop growth and yield under potential, water and nitrogen, phosphorus and potassium limited growing conditions. It is a generic model which can be used for many different annual crop types growing under a large range of soil and weather conditions (Wolf, 2012). It simulates growth as a function of intercepted radiation and radiation use efficiency, which is a function of daily mean temperature, water or nutrient limitation and atmospheric CO_2 concentration. Crop development is a function of daily accumulated thermal time above a base temperature and crop specific thermal requirements from emergence to anthesis and from anthesis to maturity. Additionally, development until anthesis is moderated by a photoperiod response. LINTUL5 crop growth simulate crop development stage (DVS) and progression from emergence (DVS = 0.0) to anthesis (DVS = 1.0) and maturity (DVS = 2.0) (Webber, Zhao, Wolf, Britz, de Vries et al., 2015b). Development until anthesis is moderated by a photoperiod response.

DRUNIR is used to simulate uptake. It replaces the very similar water balance model in LINTUL5 to enable the model to be run successively over many seasons and/or years (Webber et al., 2016). Crop water demand was simulated with the LINTUL implementation of the Penman method 1948 (Chen, Gao, Xu, Guo and Ren, 2005; Penman, 1948).

In the CanopyT model, T_c is based on a solution of an hourly energy balance at the crop surface, correcting for atmospheric stability conditions using the Monin-Obukhov Similarity Theory (MOST) (Monin and Obukhov, 1954) together with simplifying assumptions about the variation of canopy temperature with water stress (Webber et al., 2016). To avoid explicit calculation of stomatal / canopy resistance to heat and vapour transfer (r_c), T_c is calculated twice; once assuming no water stress and a small constant value of r_c, and a second time assuming complete water stress and near infinite r_c. Actual T_c is calculated by interpolating between these two values as a function of the crop water stress factor. The hourly crop water stress factor is calculated as the ratio of actual hourly transpiration to potential hourly transpiration.

The method used to calculate biomass re-translocated in storage organs was described in detail by Soltani and Sinclair (2012). Grain growth is simulated by assuming that from the beginning of seed growth (BSG) to physiological maturity, all new dry matter produced goes to grain production.

The second source for grain growth is translocation of a cultivar specific fraction of vegetative biomass.

The hourly heat stress model reduced yield when the hourly temperature was above the temperature at which reduction in final yield occurred due to kernel abortion. It is based on the calculation of the total hourly critical temperature (TTh) in the sensitive period (around flowering) of the crop with

$$TTh = \sum (T - T_{critical}) \qquad Eq.2$$

Where

T can be either hourly air temperature or hourly simulated canopy temperature and

$T_{Critical}$ is the critical temperature above which reduction in final yield occurs

The yield reduction was determined by the following expression:

$$AdjYield = \mathrm{Re}\, dFactor * Yield \qquad Eq.3$$

Where

AdjYield is the storage organ yield adjusted for high temperatures near flowering

Yield is the storage organ yield"

RedFactor is the yield reduction factor due to cumulative high temperatures above $T_{Critical} < 1$

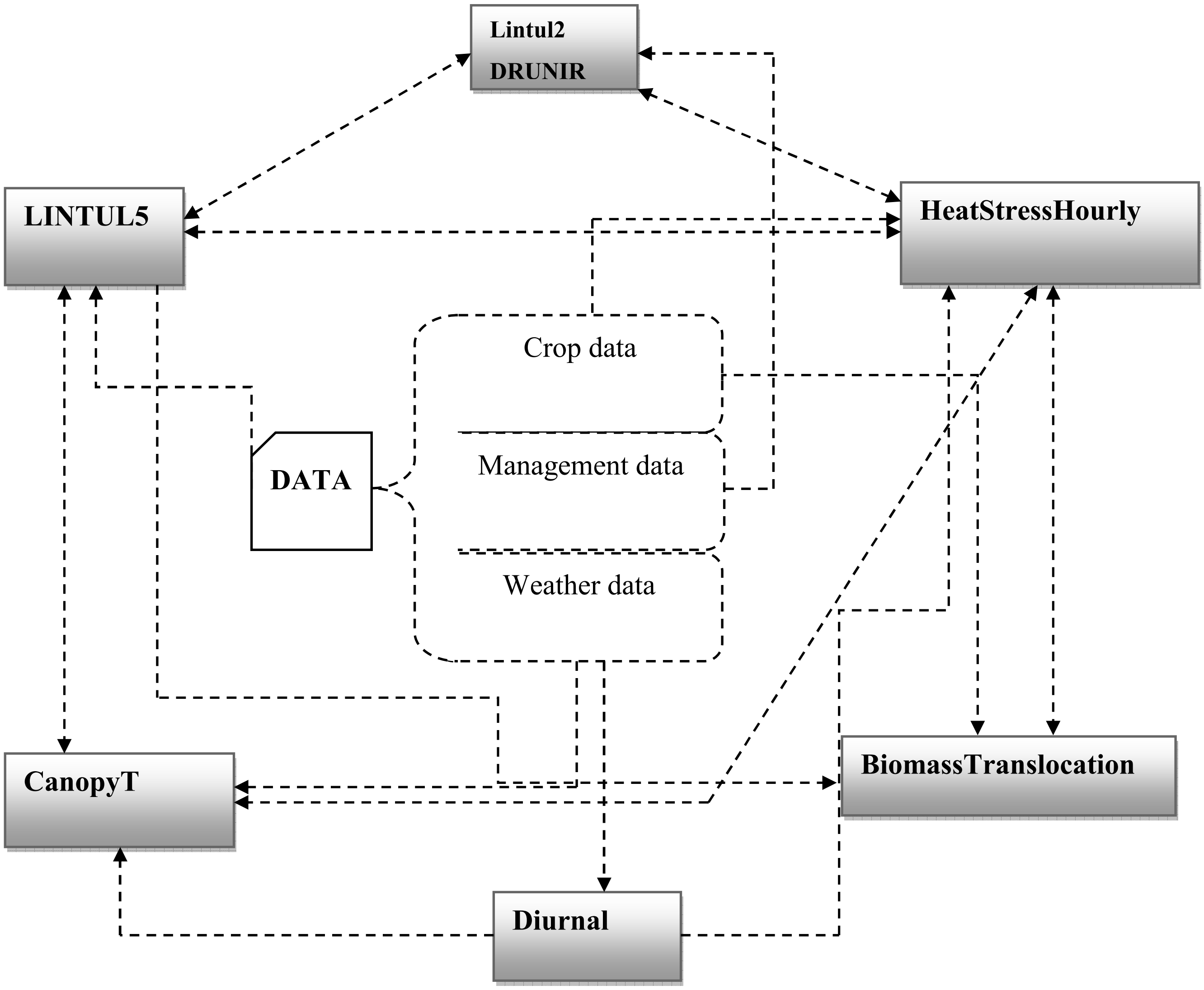

Figure 6: Scheme of the SIMPLACE model solution combining various sub-models

SIMPLACE<Lintul5, DRUNIR, CanopyT, HourlyHeat>

Model parameterizations

The parameters used in the model are based on the literature and from measurements in the field. For those which were not found in the literature and were not measured, default values were used and sometimes were manually adjusted during the calibration process in order to adapt them to local conditions. The parameters of the model are given in Table 4.

Table 4: Parameters of the model used for peanut

Parameters	**Values used in the model**		**Value range in literature**	**Units**	**References**
	Fleur 11	73-33			
Temperature sum from emergence to anthesis (TSUM1)	422	510	NA – variety dependent	C day	
Temperature sum from anthesis to maturity (TSUM2)	1285	1330	NA – variety dependent	C day	
Radiation use efficiency* (RUE)	1.4-2.1	1.7-2.0	1.45-2.66	g MJ^{-1}	(Collino, Dardanelli, Sereno and Racca, 2001), (Kiniry, Simpson, Schubert and Reed, 2005), (Haro, Otegui, Collino and Dardanelli, 2007)
Specific leaf area (SLATB)	0.016-0.018	0.016-0.018	0.015-0.027	m^2g^{-1}	(Songsri, Jogloy, Holbrook, Kesmala, Vorasoot et al., 2009), (Sheshshayee, Bindumadhava, Rachaputi, Prasad, Udayakumar et al., 2006)

			0.015-0.017	m^{2}g^{-1}	(Kalariya, Singh, Chakraborty, Ajay, Zala et al., 2015)
			0.001-0.002	hakg^{-1}	(Belko, 2006)
Maximum Relative increase in LAI (RGRLAI)	0.015	0.012	0.02	haha^{-1}d^{-1}	
fraction of above-ground dry matter to leaves as function of DVS (FLTB)	0.1-0.6	0.1-0.6	0.1-0.6	g g-1	Adjust default values with field data
fraction of above ground dry matter to stems as function of DVS (FSTB)	0.19-0.4	0.17-0.4	0.17-0.4	g g-1	Adjust default values with field data
fraction of above- ground dry matter storages. organs. as function of DVS (FOTB)	0.0-0.71	0.0-0.73	0.0-0.73	g g-1	Adjust default values with field data
maximum amount of reserves to be remobilized with no stress (FRTDM)	0.05	0.05	0.05		
Reduction factor due to heat stress	0.0025	0.0025	0.0025		
maximum N concentration in leaves as function of development stage (NMXLV)	0.03-0.06	0.03-0.06	0.03-0.062	g g-1	(Sinclair, Bennett and Boote, 1993), (Benton Jones, Jr and Mills, 1991)
maximum P concentration in leaves as function of development stage (PMXLV)	0.00253-0.006	0.00253-0.006	0.0025-0.006	g g-1	(Benton Jones et al., 1991), (Reuter, 1997)
maximum K concentration in leaves as function of development stage (KMXLV)	0.104-0.044	0.104-0.044	0.104-0.044	g g-1	Default values

maximum N concentration in storage organs	0.0392	0.0392	0.039 - 0.04	g g-1	(Dey, Pal, Bhatt and Chauhan, 2004)
			0.025-0.047	g g-1	(Hafner, Ndunguru, Bationo and Marschner, 1992)
			0.026-0.045	g g-1	(Reuter, 1997)
maximum P concentration in storage organs	0.0039	0.0039	0.039-0.041	g g-1	(Dey et al., 2004)
			0.027-0.035		(Konlan, Sarkodies-Addo, Asare and Kombiok, 2013)
maximum K concentration in storage organs	0.0091	0.00914	0.0087-0.00914	g g-1	(Wu, Lu, Jones, Mortley, Loretan et al., 1997)
fraction of crop N uptake by biological fixation (NFIXF)	0.8	0.8	0.53-0.97		(Sinclair, Leilah and Schreffler, 1995)
			0.8		(Wolf, 2012)
Temperature at which reduction in final yield occurs due to kernel abortion (TCritical)	38	38	38	°C	(Prasad, 1999)
Optimal (critical) N concentration as fraction of maximum N concentration (FRNX)	0.5	0.5	0.5-1	gg^{-1}	(Shibu, Leffelaar, Van Keulen and Aggarwal, 2010)
optimal P concentration as fraction of maximum P concentration (FRPX)	0.5	0.5	0.5-1	gg^{-1}	(Shibu et al., 2010),

optimal K concentration as fraction of maximum K concentration (FRKX)	0.5	0.5	0.5-1	$g\ g^{-1}$	(Shibu et al., 2010)

Footnote

RUETB: 2.1 (Fleur11) or 2.0 (73-33) from emergence to anthesis, decreasing linearly to 1.4 or 1.7 from anthesis to maturity
SLATB: 0.018 from emergence to anthesis, decreasing linearly to 0.016 from anthesis to maturity
FLTB: 0.6 from emergence to anthesis, decreasing linearly to 0.1 from anthesis to maturity
FSTB: 0.4 from emergence to anthesis, decreasing linearly to 0.19 (Fleur11) or 0.17 (73-33) from anthesis to maturity
FOTB: 0.0 from emergence to anthesis, increasing to 0.71 (Fleur11) or 0.73 (73-33) from anthesis to maturity
NMXLV: 0.06 from emergence to anthesis, decreasing linearly to 0.03 from anthesis to maturity
PMXLV: 0.006 from emergence to anthesis, decreasing linearly to 0.00253 from anthesis to maturity
KMXLV: 0.1042 from emergence to anthesis, decreasing linearly to 0.044 from anthesis to maturity

Model calibration and evaluation

The Nioro experimental dataset was used for model calibration. The sensitive input parameters were adjusted in the model based on the observed data and in the literature review (Table 4). For model evaluation, Bambey experimental dataset were used. Model calibration and evaluation were carried out in three steps:

Step1: Calibrate and validate in condition of no heat stress and no drought stress (Rainy season experiments),

Step 2: Calibrate and validate under conditions of heat stress and no drought stress (dry season experiments with full irrigation (E),

Step 3: Calibrate and validate in condition of heat and drought stress (dry season experiments, treatments S1 and S2).

Yield reduction due to the combination of heat and drought stress was determined in both canopy temperature and air temperature. Plants in irrigation deficit show signs of water stress. They reduce their transpiration rates and increase canopy temperature. In that case, the yield reduction due to water stress will be better explained with canopy temperature than air temperature (Durigon and van Lier, 2013; Mason and Singh, 2014; Pinto and Reynolds, 2015; Siebert et al., 2014; Webber et al., 2016).

The simplification approach made in SIMPLACE to estimate canopy temperature is given by:

$$T_c = T_{c,L} + \left(1 - K_{ws}\right)\left(T_{c,U} - T_{c,L}\right) \qquad Eq.4$$

Where T_c is the canopy temperature, K_{ws} is the crop water stress coefficient, $T_{c,L}$ is the canopy temperature lower bounds $T_{c,U}$ is the canopy temperature upper bounds.

The calculation is described in details by Webber et al. (2016) which followed (Clawson, Jackson and Pinter, 1989) approach.

$$T_{c,U} = T_a + \frac{\left(R_n - G\right) r_a}{\rho C_p} \qquad Eq.5$$

$$T_{c,L} = T_a + \frac{\left(R_n - G\right) r_a}{\rho C_p} \frac{\gamma^*}{\Delta + \gamma^*} - \frac{\left(e^*_a - e_a\right)}{\Delta + \gamma^*} \qquad Eq.6$$

Where T_a is the air temperature at reference height, C_p is the specific heat of air, R_n is the net radiation, G is the soil heat flux, r_a is the bulk canopy resistance to heat and vapour transport, ρ is the density of air, C_p is the specific heat of air, γ^*product of psychometric constant, Δ is the slope of the saturated vapour pressure curve, $e_a^*$is the saturated vapour pressure of the air, e_a is the actual vapour pressure of air.

Model calibration procedure

To calibrate phenology, two parameters, TSUM1 (thermal time from emergence to anthesis) and TSUM2 (thermal time from anthesis to maturity) were considered to simulate the anthesis and the maturity dates (Figure 7). The date of emergence was used by the model as start day because the emergence date can be different for the same variety in the same site when the amount of water received during the sowing is not the same.

Leaf area index and biomass growth were calibrated simultaneously with the parameters RGRLAI (maximum relative increase rate in LAI) and SLATB (specific leaf area) and RUETB (radiation use efficiency for biomass production). Time series of at least five dates of measurement for Nioro observations were used from emergence to harvest based on two weeks. The partitioning coefficients which are FLTB (fraction of above ground dry matter to leaves as function of DVS), FSTB (fraction of above- ground dry matter to stems as function of DVS) and FOTB (fraction of dry matter to storages organs as function of DVS) were adjusted during the calibration process based on cultivar information (FAO, 2012) and observed field data.

Nutrient concentrations (N-P-K) are also important parameters for model performance and were taken from the literature as reported in Table 4.

The yield calibration process considered two parameters.

FRTDM (fraction of aboveground biomass to be translocated to seeds) was set in the first step, as it affects yield independent of heat and drought stress, though some evidence suggested this is actually sensitive to both stresses, with translocation increasing under stress (Maillard, Diquélou, Billard, Laîné, Garnica et al., 2015).

In the second step, RedHS, reduction factor due to cumulative high temperatures above critical temperature for heat stress calibration was calibrated for the experiments with heat stress, but minimal drought.

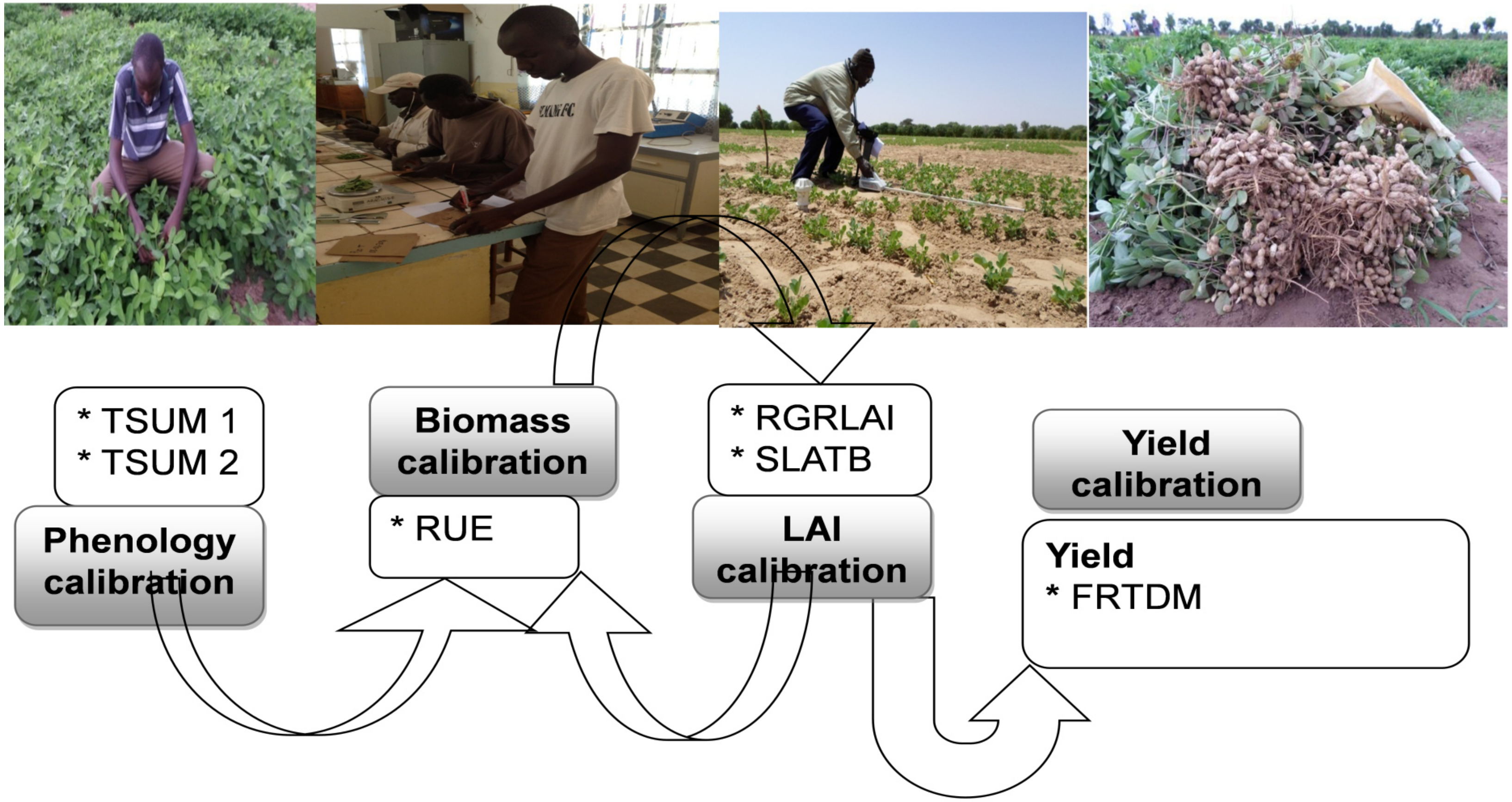

Figure 7: Model calibration procedure

Model evaluation

After model calibration using datasets from Nioro, model validation was carried out with datasets from the Bambey field experiments. The performance of SIMPLACE crop model to simulate peanut yield in Senegal was based on a comparison of observed data and simulated data using the following two statistical indicators:

- Coefficient of determination (R^2) slope and intercept of the linear regression between observed and simulated values (Gaiser et al., 2013). It can be interpreted as the variance in the observed values that is attributable to the variance in the simulated values.

$$R^2 = 1 - \frac{SS_E}{SS_T} \qquad Eq.7$$

$$SS_T = \sum \left(X_o^i - \overline{X} \right)^2 ; \qquad Eq.8$$

$$SS_E = \sum \left(X_o^i - X_s^i \right)^2 \qquad Eq.9$$

where SS_E *is the sum of squared errors,* SS_T *is the total sum of squares*
X_o^i, X_s^i *are the observed values and simulated values respectively,* $\overline{X}$ *is the observed mean values*

- Root Mean Square Error (RMSE) used to measure the deviation between the observed and simulated values (Cao, Liu, Luo, Wang, Pan et al., 2002).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(X_o^i - X_s^i \right)^2} \qquad Eq.10$$

X_o^i, X_s^i *are the observed values and simulated values respectively,*
N is the sample number

Climate change impact analysis on peanut

This study was conducted in Senegal in two different sites. They are located in the central region referred to as the "peanut basin" where peanut is intensively cultivated. The soil characteristic in these two sites has a low capacity on water holding named soil "Dior" (ferruginous tropical soils) in Bambey and "Dior deck" (leached ferruginous tropical soils) in Nioro. The seasonal rainfall sum is 500mm in Bambey and 700mm in Nioro and lasts from June to October (more than 95% of the annual rainfall) with a uni-modal distribution. August is the month with the highest amount of rainfall, with a range from 210mm to 270mm in Bambey and Nioro respectively (Figure. 8a). This amount represents more than the third of the total annual rainfall. The average monthly minimum and maximum temperature vary between 24 °C to 35 °C for Bambey and 24 °C to 34 °C for Nioro during the rainy season and between 20 °C to 39°C for Bambey and 20 °C to 40°C for Nioro during the dry season (Figure. 8c.d). The mean radiation is 19.5 MJ m^{-2} day^{-1} for Bambey and 19.2 MJ m^{-2} day^{-1} for Nioro during the rainy season and 22MJ m^{-2} day^{-1} for Bambey and 24 MJ m^{-2} day^{-1} for Nioro (Figure. 8b) during the dry season. Time series of observed daily data was obtained from the ISRA meteorological service both for Bambey and Nioro from 1981 to 2014 including maximum and minimum temperature, rainfall, incident radiation, wind speed, maximum and minimum relative humidity.

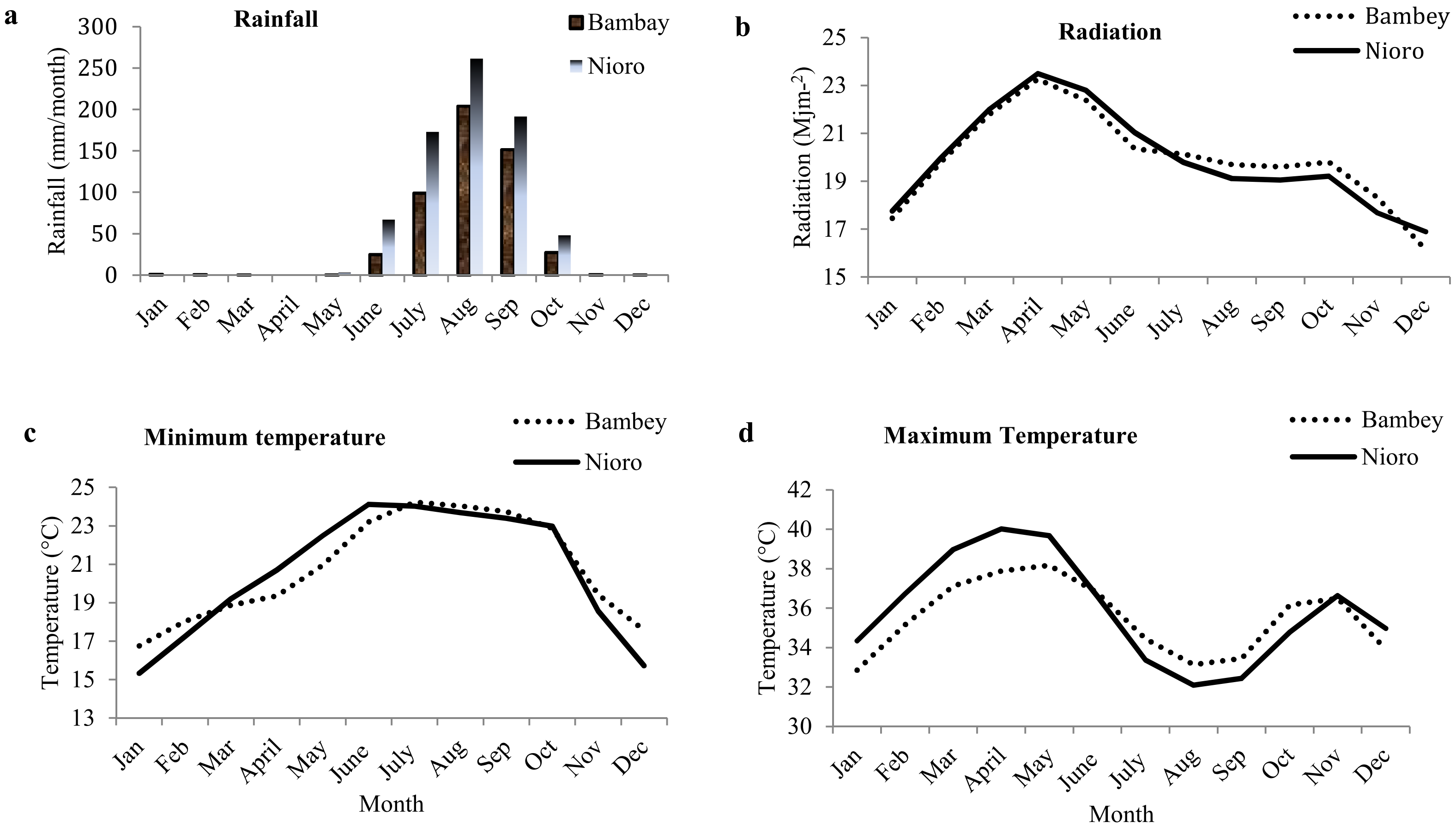

Figure 8: Seasonal cycle of rainfall, radiation, minimum and maximum temperatures over Bambey and Nioro (1981-2014)

Simulation setup

The model SIMPLACE< Lintul5,DRUNIR,CanopyT, HourlyHeat> was used to simulate daily growth and development for peanut in two sites in Senegal. The model was run for Fleur11 variety under dry and rainy season 2014 conditions in Bambey and in Nioro. Simulations were conducted for the rainy season under irrigation supply and no irrigation supply. For both seasons, simulations were conducted based on the historical period 1981-2010 (baseline) and the scenario period 2016-2045 (climate scenario). The atmospheric CO_2 was set at 369ppm for both historical and climate scenarios in the first step. It was set at 439ppm for RCP4.5 and at 469ppm for RCP8.5 (Meinshausen, Smith, Calvin, Daniel, Kainuma et al., 2011) for the climate scenarios for the second step. The correction of Radiation Use Efficiency (RUE) as a function of atmospheric CO_2 concentration was setup to 1.11 when CO_2 increased from 369ppm to 439ppm and 469ppm.

Table 5 presents the summary of the variables used in the model for the climate change impact analysis.

In most cases, the average sowing date in Bambey during the rainy season is from 20th to 30th July, while in Nioro it starts from 1st to 15th July.

Two adaptation strategies were tested; change of sowing date and the length of the variety cycle. Early sowing was tested by shifting fifteen (15) days before the current sowing date and shortening the length of the variety by five (5) days by changing the temperature sum from anthesis to maturity from 1285 to 1185. The adaptation strategies were tested only under rainfed condition. The effect of heat stress in the model was simulated by comparing the yield with canopy temperature and the yield with air temperature.

Table 5: Variables used in the model for climate change impact analysis

Sites	**Seasons**	**Period**	**Irrigation**	**CO_2 (ppm)**	**Start date**	**End date**	**Em** (Doy)
Bambey	Dry Season 2014	Historical	*Full irrigation*	369	*03.19.1981*	*12.31.2010*	*85*
		scenario		369	*03.19.2016*	*12.31.2045*	*85*
		RCP4.5		439			
		RCP8.5		469			
Nioro		Historical		369	*03.14.1981*	*12.31.2010*	*79*
		scenario		369	*03.14.2016*	*12.31.2045*	*79*
		RCP4.5		439			
		RCP8.5		469			
Bambey	Rainy Season 2014	Historical	*Irrigation supply*	369	*08.06.1981*	*12.31.2010*	*224*
		scenario		369	*08.06.2016*	*12.31.2045*	*224*
		RCP4.5		439			
		RCP8.5		469			
		Historical	*No Irrigation*	369	*08.06.1981*	*12.31.2010*	*224*
		scenario		369	*08.06.2016*	*12.31.2045*	*224*
		RCP4.5		439			
		RCP8.5		469			
Nioro		Historical	*Irrigation supply*	369	*07.16.1981*	*12.31.2010*	*204*
		scenario		369	*07.16.2016*	*12.31.2045*	*204*
		RCP4.5		439			
		RCP8.5		469			
		Historical	*No Irrigation*	369	*07.16.1981*	*12.31.2010*	*204*
		scenario		369	*07.16.2016*	*12.31.2045*	*204*
		RCP4.5		439			
		RCP8.5		469			

Footnote
Em is emergence date

Simulations were conducted in SIMPLACE<Lintul5,DRUNIR, CanopyT,HourlyHeat> for both sites Bambey and Nioro in dry season 2014 and in rainy season 2014 for both baseline (1981-2010) and scenario periods (2016-2045) for 30 years. The model and model calibration process is described in detail in previous sub-chapter. The model was run for the scenario period with and without CO_2 elevation in two separate simulation steps. The peanut hourly heat stress model implemented in SIMPLACE modelling framework (Gaiser et al., 2013) was linked with the LINTUL5 model, the water balance model, DRUNIR, from the Lintul2 crop growth model, the hourly canopy temperature model, CanopyT, and a biomass translocation model. Diurnal is used to transform daily weather inputs to hourly values using sinusoidal functions (Ephrath et al., 1996; Van Oort et al., 2014).

Climate model input

Observed data analysis

Standardized Precipitation Index was used for precipitation to determine periods of anomalously wet and dry events (Faye, Sow and Ndong, 2015). The following equation was used:

$$SPI = \left[\frac{X_i - X_m}{\mu_i}\right] \qquad Eq.11$$

Where, X_i is precipitation in year i

X_m and μ_i are mean and standard deviation during the period to the annual observed precipitation respectively.

Temperature anomalies were calculated by:

$$\Delta T = T_i - T_m; \qquad Eq.12$$

Where, T_i is temperature in year i

T_m is mean temperature during the period to the annual observed precipitation.

Scenario data analysis

In this part, the inter-annual variability of precipitation and temperature simulated for the Regional Climate Models were analyzed. A mean for the four RCMs was calculated each year.

Input data

The climate dataset required for the model to simulate crops were precipitation, minimum, mean and maximum temperature, solar radiation and wind speed on daily basis. The RCMs data are available in the context of the Coordinated Regional Climate Downscaling Experiment (Giorgi et al., 2009) over Africa on a 0.44° grid for the period 1950–2100. The Representative Concentration Pathways (RCP4.5 and RCP8.5) climate scenarios of the latest IPCC report were considered in this study. Climate models data from a set of simulations (historical and scenario) conducted with four RCMs (DMI-HIRHAM5, KNMI-RACMO22T, MPI-CLM[2], SMHI-RCA4) were used to assess the impact of climate change on peanut yield (Table 6). The data from the period 1981-2010 has been taken as reference or baseline (Cget, 2015; Vanuytrecht, Van Mechelen, Van Meerbeek, Willems, Hermy et al., 2014), and 2016-2045 has been taken as scenario period. The baseline period was determined by combination model results of the historical simulations (1981–

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[2] is the shortened name for the RCM, **CLMcom-CCM4-8-17**

2005) with the first five years of the projection run (2006–2010) under RCP4.5 (Dosio and Panitz, 2015). There was an assumption that results using the first five of the RCP 8.5 were very similar. Due to the well known biases of RCMs output (Gbobaniyi, Sarr, Sylla, Diallo, Lennard et al., 2014; Hay, Wilby and Leavesley, 2000; Mbaye, Haensler, Hagemann, Gaye, Moseley et al., 2015; van Roosmalen, Sonnenborg, Jensen and Christensen, 2011) the bias corrected climate simulations was checked by using the delta change method before using them in the crop model. This method consists of perturbing observed data with absolute or relative change factors derived between RCM data for the present day climate and a projected climate scenario (Hay et al., 2000). The delta change method is widely used in many climate change impact studies (Akhtar, Ahmad and Booij, 2008; van Roosmalen et al., 2011) for developing local climate change projections (Gago Da Silva, Gunderson, Goyette and Lehmann, 2012; Gleick, 1986; Horton, Gornitz, Bader, Ruane, Goldberg et al., 2011; Teutschbein and Seibert, 2012; Watanabe, Kanae, Seto, Yeh, Hirabayashi et al., 2012; Wilby, Charles, Zorita, Timbal, Whetton et al., 2004).

Historical time series of observed climate variables was used for each site for the reference or baseline period 1981-2010 (Vanuytrecht et al., 2014). The source of the data was obtained from the CNRA Bambey and ANACIM.

The climate scenario was generated using the delta change method for a future period (2016-2045). This was done on a monthly basis. A multiplicative correction was used for precipitation (Eq.13), whereas an additive correction was used to adjust temperature (Eq.14) (Teutschbein and Seibert, 2012).

Here is the expression of the precipitation corrected:

$$P^{*}_{scen}(d) = P_{obs}(d).\left[\frac{\mu_m(P_{scen}(d))}{\mu_m(P_{ctrl}(d))}\right] \qquad Eq.13$$

Where $P^{*}_{scen}(d)$ is the daily precipitation in the scenario runs corrected by the delta change method,

$P_{obs}(d)$ is the daily observed precipitation,

$\mu_m(P_{scen}(d))$ is the mean simulated daily precipitation for the scenario period of a given month,

$\mu_m(P_{crtl}(d))$ is the mean simulated daily precipitation for the baseline period of a given month,

The expression of the temperature corrected is the following:

$$T^{*}_{scen}(d) = T_{obs}(d) + \mu_m(T_{scen}(d)) - \mu_m(T_{ctrl}(d)) \qquad Eq.14$$

$T^{*}_{scen}(d)$ is the daily temperature during the scenario period corrected by the delta change method,

$T_{obs}(d)$ is the daily observed temperature,

$\mu_m(T_{scen}(d))$ is the mean simulated daily temperature for the scenario period of a given month,

$\mu_m(T_{ctrl}(d))$ is the mean simulated daily temperature for the baseline period of a given month,

Table 6: List of RCM used and their details

	DMI-HIRHAM5	**CLMcom-CCM4-8-17**	**KNMI-RACMO22T**	**SMHI-RCA4**
Institution	Danish Meteorological Institute	Climate Limited_area Modelling Community (CLM-Community)	Royal Netherlands Meteorological Institute	Swedish Meteorological and Hydrological Institute, Rossby Centre
Short name	HIRHAM5	CCLM4	RACMO22T	RCA4
Driving model	ICHEC-EC-EARTH	MPI-M-MPI-ESM-LR	ICHEC-EC-EARTH	NOAA-GFDL-GFDL-ES2M
Resolution/Projection	0.44° Rotated pole	0.44° Rotated pole	0.44° Rotated pole	0.44° Rotated pole
Advection scheme	semi-lagrangien	Fith order upwind (Baldauf, 2008)	semi-lagrangien	eulerian
Convection Scheme	(Tiedtke, 1989)	(Tiedtke, 1989)	(Tiedtke, 1989)	(Kain and Fritsch, 1990, 1993)
Radiation scheme	(Fouquart and Bonnel, 1980)	Ritte(Ritter and Geleyn, 1992)r	(Fouquart and Bonnel, 1980)	(Sass, Rontu and Räisänen, 1994; Savijärvi, 1990)
Vertical coordinates	Hybrid3.1	Terrain following/3.5	Hybrid/40	Hybrid/40
References	www.dmi.dk/dmi/tr06-17	www.clm-community.eu	http://www.knmi.nl/research/regional_climate/models/racmo.html	http://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552/rossby-centre-regional-atmospheric-model-rca-1.16562

Harvest yield estimation

For the evaluation of climate change impacts, four RCMs were used for baseline (1981-2010) and for both climate scenarios RCP4.5 and RCP8.5 (2016-2045). The yields were simulated at both sites Bambey and Nioro with 30 years data. The simulations were conducted under fully irrigated conditions (dry season) and rainfed condition (rainy season) with and without irrigation. The final yield was calculated for each simulation as an average for the period in each of the scenarios and baseline periods.

$$\overline{Yield} = \frac{\sum_{i=1}^{n} Yield}{n} \qquad Eq.15$$

Where $\overline{\text{Yield}}$ is the average final yield across *n* years.

Yield is the yield for the year *i* and *n* is the number of years.

The method was derived from studies carried out by (Balkovič, van der Velde, Schmid, Skalský, Khabarov et al., 2013; Deryng, Conway, Ramankutty, Price and Warren, 2014; Zhao, Webber, Hoffmann, Wolf, Siebert et al., 2015) on climate impact analysis. In addition, the impact of climate change on yield was evaluated by calculating the relative yield change as following:

- Under irrigated condition

$$\Delta Yield = \frac{Yield_{scen} - Yield_{Baseline}}{Yield_{Baseline}} * 100; \quad [\%] \qquad Eq.16$$

Where ΔYield is the relative yield change.

$\text{Yield}_{\text{scen}}$ is the yield for the climate scenarios.

$\text{Yield}_{\text{Baseline}}$ is the yield for the baseline scenarios.

- Under rainfed condition

$$\Delta Yield_{Rainfed} = \frac{Yield_{scenRainfed} - Yield_{BaselineRainfed}}{Yield_{BaselineRainfed}} * 100; \quad [\%] \qquad Eq.17$$

Where $\Delta \mathrm{Yield}_{\mathrm{Rainfed}}$ is the relative yield change.

$\mathrm{Yield}_{\mathrm{scenRainfed}}$ is the yield for the climate scenarios.

$\mathrm{Yield}_{\mathrm{BaselineRainfed}}$ is the yield for the baseline scenarios.

- Under rainfed conditions without irrigation and with different sowing date

$$\Delta Yield_{sowingdate} = \frac{Yield_{newsowingdate} - Yield_{currentsowingdate}}{Yield_{currentsowingdate}} * 100; \quad [\%] \qquad Eq.18$$

In order to test the effect of shifting the sowing date under future climate conditions, seed yield was calculated for each climate scenarios with current sowing date (reference) and with new (earlier) sowing dates in the rainy season without irrigation.

Where $\Delta \mathrm{Yield}_{\mathrm{newsowing}}$ is the relative yield change due to earlier sowing in the beginning of the rainy season

$\mathrm{Yield}_{\mathrm{newsowing\ date}}$ is the yield for the new sowing date.

$\mathrm{Yield}_{\mathrm{currentsowingdate}}$ is the yield for the current sowing date.

CHAPTER FOUR

RESULTS

Soil analysis

Data analysis showed a low amount of organic carbon in Bambey both in 2014 and 2015 in the top 50cm of the soils with an average of 0.02% nitrogen content (0.014% to 0.028%). However, phosphorus content was higher in 2014 (28ppm) compared to 2015 (2.62ppm) in which phosphorus was low (Tables 7 and 8). The clay content was less than 5% within a depth of 1 metre resulting in low cation exchange capacity. The percentage of sand reached 90% or more with low water holding capacity. The soil moisture content at wilting point (LL) was 14mm/m and the soil moisture content at field capacity (DUL) was 134.5mm/m that gives a maximum Agricultural Water Reserve (AWR) of 120.5mm/m (Sarr, Ndiendole, Diouf, Diouf and Roy-Macauley, 1999). In Nioro, the soil was higher in organic carbon in the top soil (0.7%) which allowed a higher cation exchange capacity, but the pH was acid. Soil clay content was less than 10%. The phosphorus content was 12.91ppm in 2014 and 4.97ppm in 2015 because of the phosphorus uptake by the previous maize crop.

Table 7: Soil analysis in 2014

localities	horizon	pH	C	N	K	P	CEC	A	L	S	bd
BAMBEY	**0-10**	6.3	0.160	0.015	0.139	45.08	3.39	2.82	1.53	94.95	1.48
	10-20	5.8	0.144	0.024	0.119	40.71	2.67	3.77	1.7	92.7	1.48
	20-30	5.8	0.128	0.024	0.112	39.83	2.90	5.07	1.63	91.8	1.47
	30-40	5.8	0.152	0.020	0.119	36.33	3.36	6.15	1.72	91.15	1.57
	40-50	5.8	0.256	0.039	0.125	26.26	3.59	6.95	1.77	89.85	1.44
	50-60	5.7	0.088	0.015	0.119	24.95	3.36	7.17	1.65	89.7	1.44
	60-70	5.6	0.128	0.015	0.134	20.13	4.33	6.45	2.22	91.5	1.35
	70-80	5.7	0.056	0.010	0.115	18.82	4.79	6.22	2.63	91.05	1.38
	80-90	5.8	0.080	0.015	0.108	18.38	4.45	6.07	2.03	90.35	1.31
	90-100	5.9	0.088	0.015	0.112	18.82	4.41	5.92	1.25	87.6	1.44
NIORO	**0-10**	6.2	0.487	0.049	0.183	37.2	3.51	4.45	4.32	92.8	1.40
	10-20	5.1	0.447	0.029	0.139	23.64	5.30	3.24	9.73	88.65	1.40
	20-30	5.1	0.383	0.024	0.104	16.19	4.76	3.43	10.32	86.45	1.47
	30-40	5.6	0.359	0.020	0.113	10.94	3.31	3.06	9.21	86.6	1.43
	40-50	5.6	0.335	0.015	0.114	10.07	2.67	4.01	12.04	84.25	1.41
	50-60	5.6	0.211	0.010	0.125	7.44	3.59	4.63	13.89	80.7	1.35
	60-70	5.7	0.208	0.015	0.125	6.13	4.05	18.42	3.58	77.55	1.24
	70-80	5.8	0.192	0.015	0.147	5.25	4.51	21.4	4.12	74	1.20
	80-90	5.9	0.207	0.010	0.135	7	4.55	14.82	11.03	73.05	1.17
	90-100	6	0.168	0.029	0.154	5.25	4.88	23.9	4.25	72.5	1.15

Table 8: Soil analysis in 2015

localities	horizon	pH	C	MO	N	K	P	CEC	A	L	S
BAMBEY	**0-10**	7.9	0.156	0.269	0.014	0.012	0.04	8	4	17.135	78.87
	10-20	7.8	0.293	0.504	0.028	0.02	0.04	9	5.75	15.065	79.19
	20-30	7.7	0.215	0.370	0.014	0.016	0.13	9	7	15	78.00
	30-40	6.9	0.312	0.538	0.028	0.02	7.68	10	6.25	19.74	74.01
	40-50	6.6	0.273	0.471	0.028	0.012	6.53	18	9.25	20.72	70.03
	50-60	6.6	0.351	0.605	0.028	0.008	3.33	19	10.25	48.26	41.49
	60-70	6.3	0.234	0.403	0.028	0.04	2.99	20	11	32.425	56.58
	70-80	6.1	0.176	0.303	0.014	0.02	1.79	22	10.5	34.555	54.95
	80-90	6.3	0.195	0.336	0.014	0.016	1.75	20	14.5	27.11	58.39
	90-100	6.2	0.195	0.336	0.014	0.012	1.92	21	15.75	26.205	58.05
NIORO	**0-10**	5.8	0.488	0.840	0.042	0.016	15	24	5.5	25.545	68.96
	10-20	5.0	0.371	0.639	0.028	0.02	10	33	8.5	28.58	62.92
	20-30	4.8	0.234	0.403	0.014	0.02	11	34	10.25	31.705	58.05
	30-40	4.9	0.429	0.740	0.042	0.016	5	34	11	24.915	64.09
	40-50	5.1	0.215	0.370	0.014	0.012	2	31	9.5	29.585	60.92
	50-60	5.0	0.234	0.403	0.028	0.008	2	34	9.25	26.51	64.24
	60-70	5.4	0.244	0.420	0.028	0.04	2	30	12	29.905	58.10
	70-80	5.5	0.254	0.437	0.028	0.02	1	29	19.25	14.11	66.64
	80-90	5.8	0.215	0.370	0.014	0.016	1	27	15	28.36	56.64
	90-100	6.0	0.205	0.353	0.014	0.012	1	26	16.5	27.12	56.38

pH=pH (1:2.5 H_2O), C=Organic carbon (%), N=Total nitrogen (%), P=Available Bray P (mg/kg), K=Available Bray K (meq/100g), MO=organic matter (%) CEC=cation exchange capacity (meq/100g), S=Sand (%), L=Silt (%), A=Clay (%), bd= bulk density

Effects of fertilization rate and water availability on peanut in Senegal

Above ground Biomass (AGB)

The evolution of the above ground biomass was mostly linear from emergence to maturity during the dry season for all the experiments due to the irrigation effect (Figure 9.a,b,c,d) due to the effect of irrigation as peanut is an indeterminate plant (Cattan, 1996). However, during the rainy season, leaf defoliation at maturity had effect to decline the above ground biomass (Figure 9.e,f,g). The evolution of the AGB is faster for the early maturity variety (Fleur11) than the medium maturity variety (73-33) for all experiments and for all seasons. However, greater values were recorded for 73-33 at maturity. During the dry season, the percentage of leaf defoliation was very small due to the effect of irrigation. Therefore, there was no reduction in total above ground biomass at harvest except in Nioro in dry seasons 2014 and 2015 for the variety Fleur11. During the rainy season, a period of rapid growth was observed, followed by a decline towards the maturity because of leaf defoliation which decreased by 30% of the AGB. During the dry season the total AGB produced was higher in Nioro than Bambey. Furthermore, the total AGB produced during the dry season was greater (higher value recorded in Nioro 2014 with 8695kg/ha for Fleur 11 and 10271kg/ha for 73-33) than the total AGB produced during the rainy season (lower value recorded in Bambey 2014 with 3051kg/ha for Fleur 11 and 3264kg/ha for 73-33).

Total AGB is represented in Figure 10 according to the treatment. The effect of fertilizer application rate is represented in Figure 10.c,e,f,g. It showed a slight difference between varieties in all experiments and between fertilizer rate application. However, the difference between fertilizer rate was not linear. For instance, T2 gave the maximum total AGB in Nioro during the dry season 2014 (Figure 10.c) for both varieties, while during the rainy season it gave maximum total AGB for Fleur 11 not for 73-33 (Figure 10.f). Fleur 11 gave the highest total AGB in Sinthiou Malem (Figure 10.g) for all treatments, which was different in Bambey and Nioro (Figure 10.c,e,f).

Evidence was shown for water stress on peanut growth. Total AGB recorded at full irrigation was always greater than total biomass recorded under water stress condition (Figure 10.a,b,d) for both varieties. In Bambey, S2 gave the lower values than S1 (Figure 10.a,b), while the opposite was noted in Nioro (Figure 10.d).

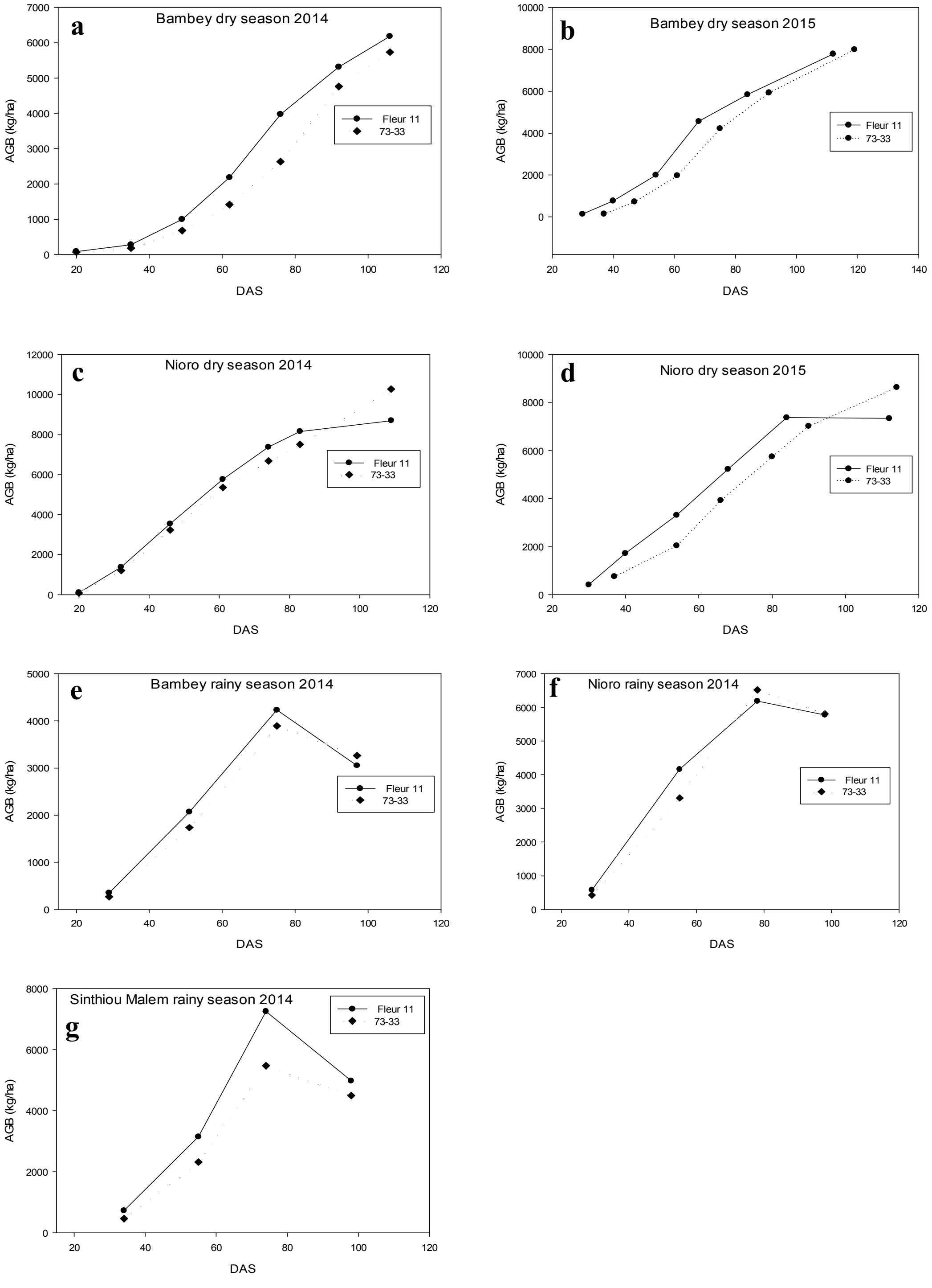

Figure 9: Trend of above ground biomass (AGB)

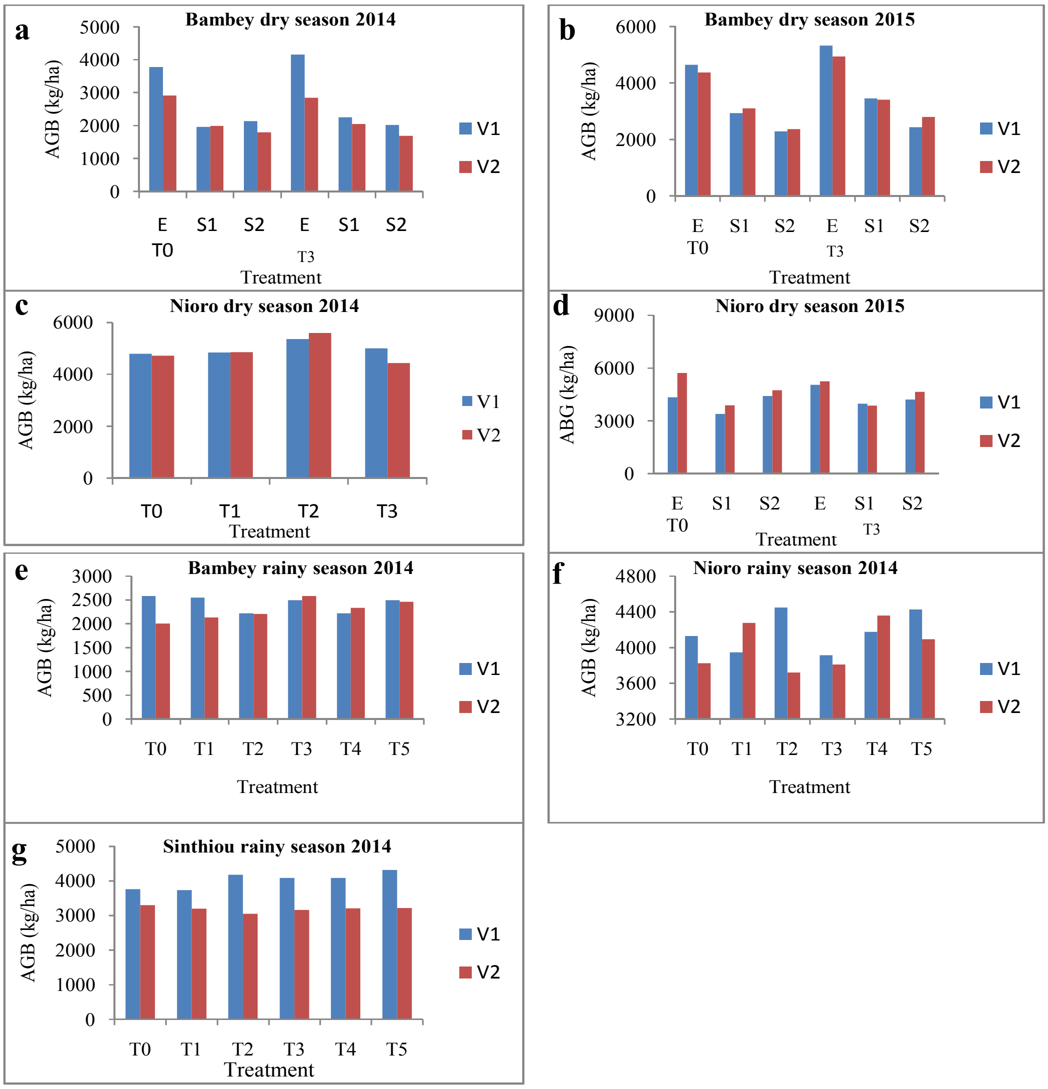

Figure 10: Above ground biomass by treatment

Variety levels: V1 = Fleur 11 and V2 = 73-33

Fertilizer levels: T0, T1, T2, T3, T4, T5

Irrigation levels: E, S1, S2

Leaf area index (LAI)

The two varieties showed similar distribution of LAI. However, 73-33 tended to produce higher LAI at the end of the growing season in both dry and rainy season due to the cycle length except in Bambey during the dry season 2014 (Figure 11.a). The LAI increase was linear during the dry season with a slight decline at maturity (Figure 11,a,b,c,d). However, for the rainy season condition, it increased quickly and declined towards maturity.

This phenomenon of decline was also observed during the dry season when the plants were under water stress treatments (Figure 12.a,b,d). The effect of fertilizer application rate did not show a difference between treatment (Figure 12.c,e,f). There was also no difference between varieties regarding the treatment even if 73-33 gave the highest values of LAI.

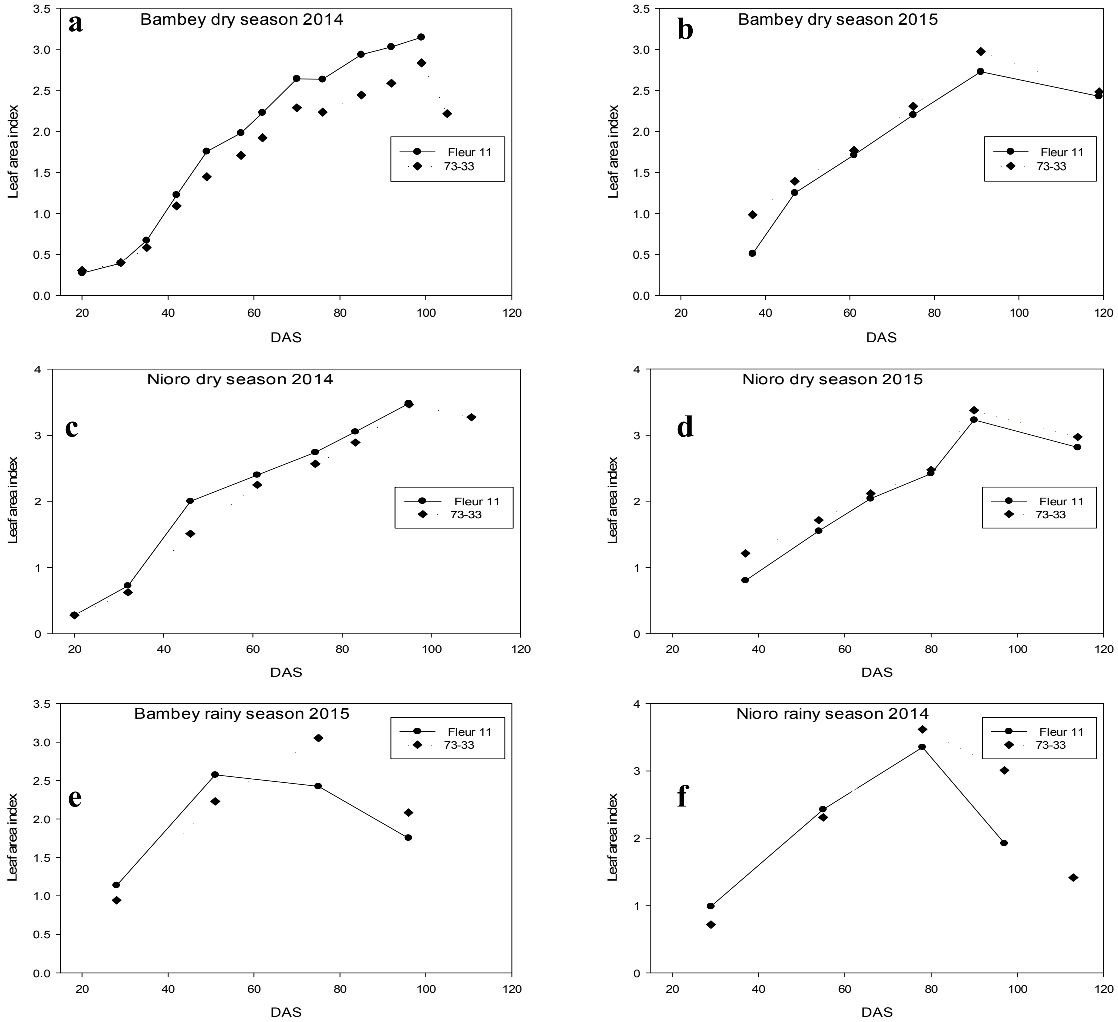

Figure 11: Leaf area index trend under growing season

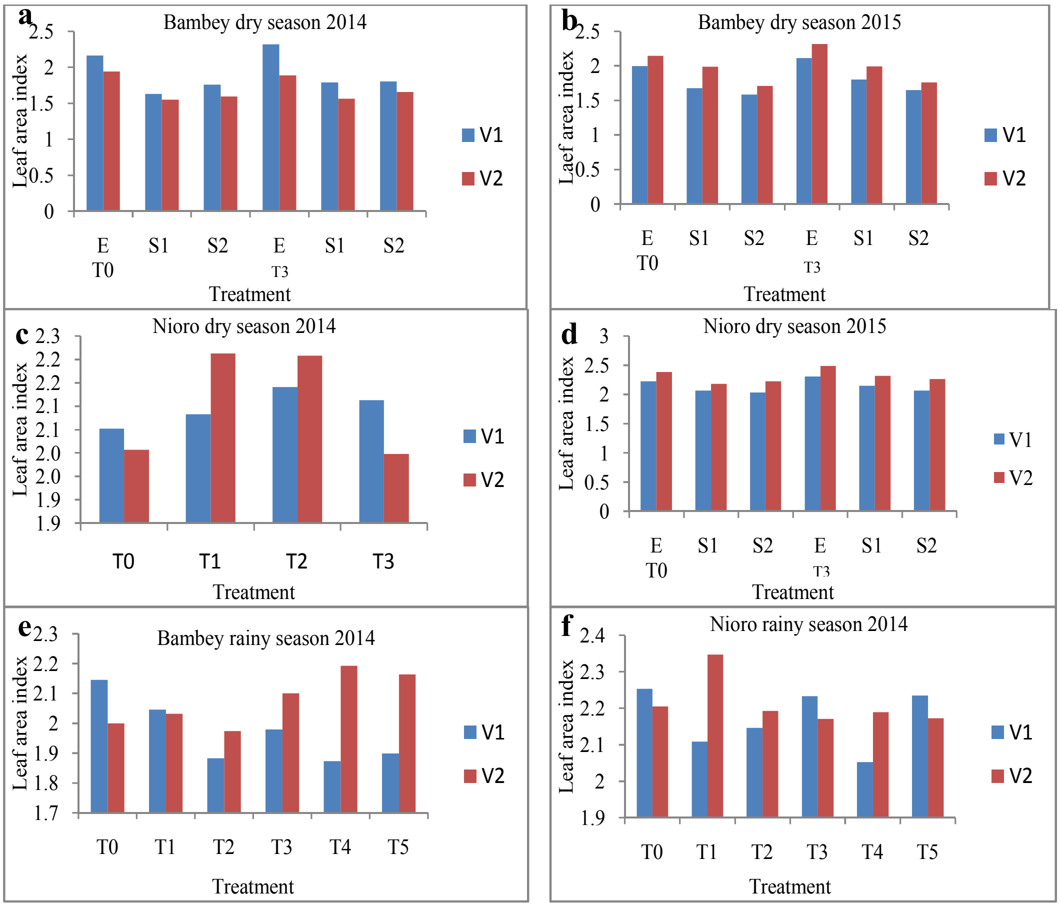

Figure 12: Leaf area index by treatment

Variety levels: V1 = Fleur 11 and V2 = 73-33

Fertilizer levels: T0, T1, T2, T3, T4, T5

Irrigation levels: E, S1, S2

Harvest yield

Table 9 and Table 10 present a summary of the ANOVA results for final biomass and seed yield respectively.

Table 9: Summary of the analysis of variance for final biomass yield for each field experiment

Season	Sites	Irrigation	Fertilizer	Variety	Irrigation Fertilizer	Irrigation Variety	Fertilizer Variety	Irrigation Fertilizer Variety
Dry season	Bambey	S	NS	NS	NS	NS	NS	NS
2014	Nioro		NS	S			NS	
Rainy season	Bambey		NS	S			NS	
2014	Nioro		NS	S			NS	
	Sinthiou		NS	NS			NS	
Dry season	Bambey	S	NS	NS	NS	NS	NS	NS
2015	Nioro	S	NS	S	NS	NS	NS	NS

Table 10: Summary of the analysis of variance for seed yield for each field experiment

Season	Sites	Irrigation	Fertilizer	Variety	Irrigation Fertilizer	Irrigation Variety	Fertilizer Variety	Irrigation Fertilizer Variety
Dry season	Bambey	S	NS	S	NS	S	NS	NS
2014	Nioro		NS	NS			NS	
Rainy season	Bambey		NS	S			NS	
2014	Nioro		NS	S			NS	
	Sinthiou		NS	NS			NS	
Dry season	Bambey	S	NS	NS	NS	NS	NS	NS
2015	Nioro	S	NS	NS	NS	NS	NS	NS

S = significant, **NS** = no significant

Effect of water stress on peanut yield

The results presented in this part regarded experiments conducted in dry season 2014 and 2015 in Bambey and in Nioro 2015. A split split plot design was used for these experiments

Final biomass yield

Final biomass yield was higher in Bambey than Nioro during the dry season in 2015 under full irrigation treatment ET0 and ET1 (Figure 13) for both varieties except for 73-33 under ET0 treatment. In contrast, for the stress treatments S1T0, S1T1, S2T0 and S2T1, final biomass yield was higher in Nioro than in Bambey due to the duration the plants were exposed to drought which was longer in Bambey than in Nioro. The comparison of the two seasons in Bambey showed higher values of biomass for 2015 than the year 2014 under full irrigation and stress conditions, where the temperatures during the growth season were lower in 2015 (Figure 13.a). The treatments were significantly different ($p<0.05$) for the irrigation level (E, S1 and S2) under dry season 2014 and 2015 for both sites (Table 11) with the highest mean values observed in field capacity irrigation (E) followed by the first stress (S1) and then the second stress (S2). No significant difference between fertilizer levels was observed in both Bambey and Nioro, as well as for the interaction between fertilizer levels and varieties. Difference between varieties was observed in Nioro 2015 (Table 9). However, a comparison of the analysis of variance between the two sites in 2015, showed a significant difference between sites, between varieties, between irrigation, between variety and sites and between irrigation and sites (Appendix1).

Table 11: Biomass yield between Bambey and Nioro for the dry season 2015

Treatment	means	Mean separation
E	7252.02	a
S1	5861.459	b
S2	4341.983	c
V2	6124.779	a
V1	5512.196	a
T1	5932.879	a
T0	5704.096	a
E.V2.T1	7565.799	a
E.V1.T1	7444.837	a
E.V2.T0	7240.011	ab
E.V1.T0	6757.433	abc
S1.V2.T1	6212.476	abcd
S1.V2.T0	6133.839	abcd
S1.V1.T1	5798.404	abcde
S1.V1.T0	5301.118	bcde
S2.V2.T0	4879.432	cde
S2.V2.T1	4717.119	de
S2.V1.T0	3912.741	e
S2.V1.T1	3858.641	e

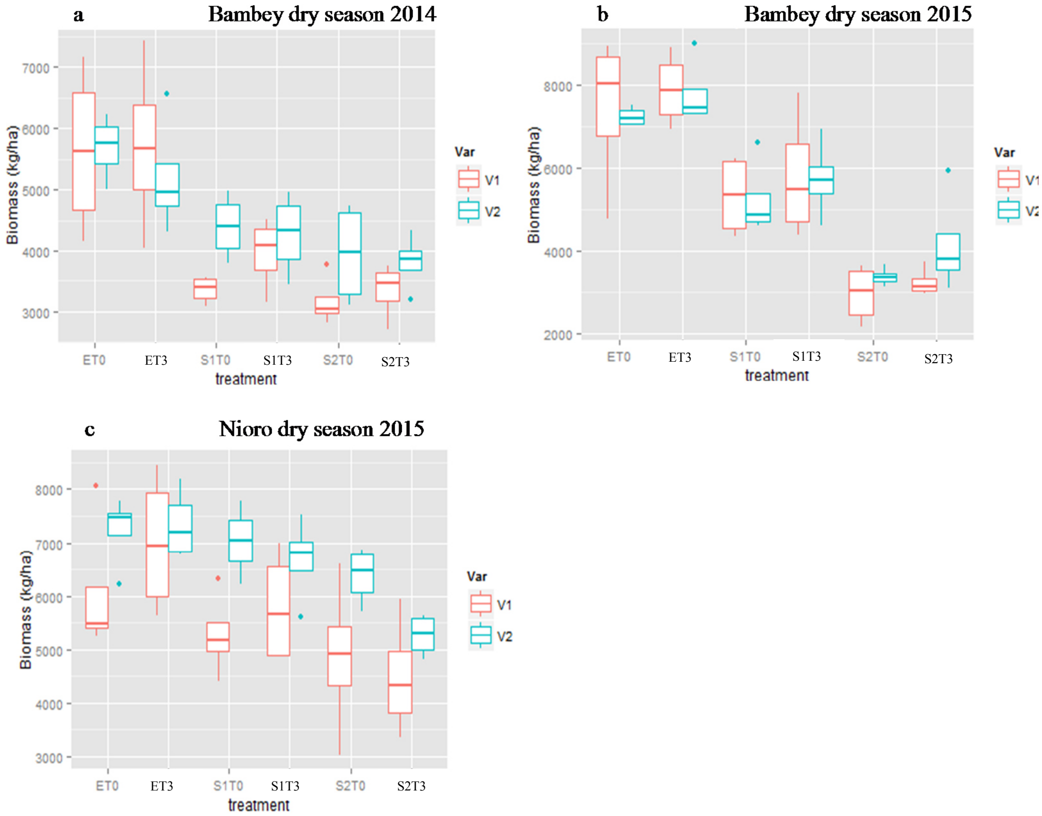

Figure 13: Biomass yield for water stress induction

Variety levels: V1 = Fleur 11 and V2 = 73-33

Fertilizer levels: T0, T3

Irrigation levels: E, S1, S2

Seed yield

Under full irrigation application seed yield varied between 2000kg/ha to 2500kg/ha in both seasons and varieties except for 73-33 in Bambey in 2014 (Figure 14.a). Under stress condition higher values of seed yield were recorded in Nioro 2015 for both stress1 and stress 2 (Figure 14.c). At both sites seed yield was higher under full irrigation followed by stress1 and stress 2 (Figure 14). The analysis of variance in each site showed a significant difference for irrigation in both sites and in both seasons, while, no difference were observed for fertilizer levels. A significant difference was observed between irrigation levels at both sites (Table 12).

The results in Bambey 2014 and 2015 showed higher values recorded in year 2015 under full irrigation and stress1 and stress 2 conditions.

However, a comparison of analysis of variance between the two sites in 2015, showed a significant difference between irrigation, between sites and between site and irrigation (Appendix 2).

Table 12: Seed yield between Bambey and Nioro for dry season 2015

Treatment	means	Mean separation
E	2220.3509	a
S1	1393.4302	b
S2	686.3299	c
V2	1441.339	a
V1	1425.402	a
T1	1459.887	a
T0	1406.854	a
E.V2.T1	2291.5962	a
E.V2.T0	2217.4677	a
E.V1.T1	2191.5989	a
E.V1.T0	2180.7407	a
S1.V1.T1	1477.6161	b
S1.V2.T1	1399.2122	b
S1.V1.T0	1379.741	b
S1.V2.T0	1317.1514	b
S2.V1.T1	715.1678	c
S2.V1.T0	703.1673	c
S2.V2.T1	684.131	c
S2.V2.T0	642.8535	c

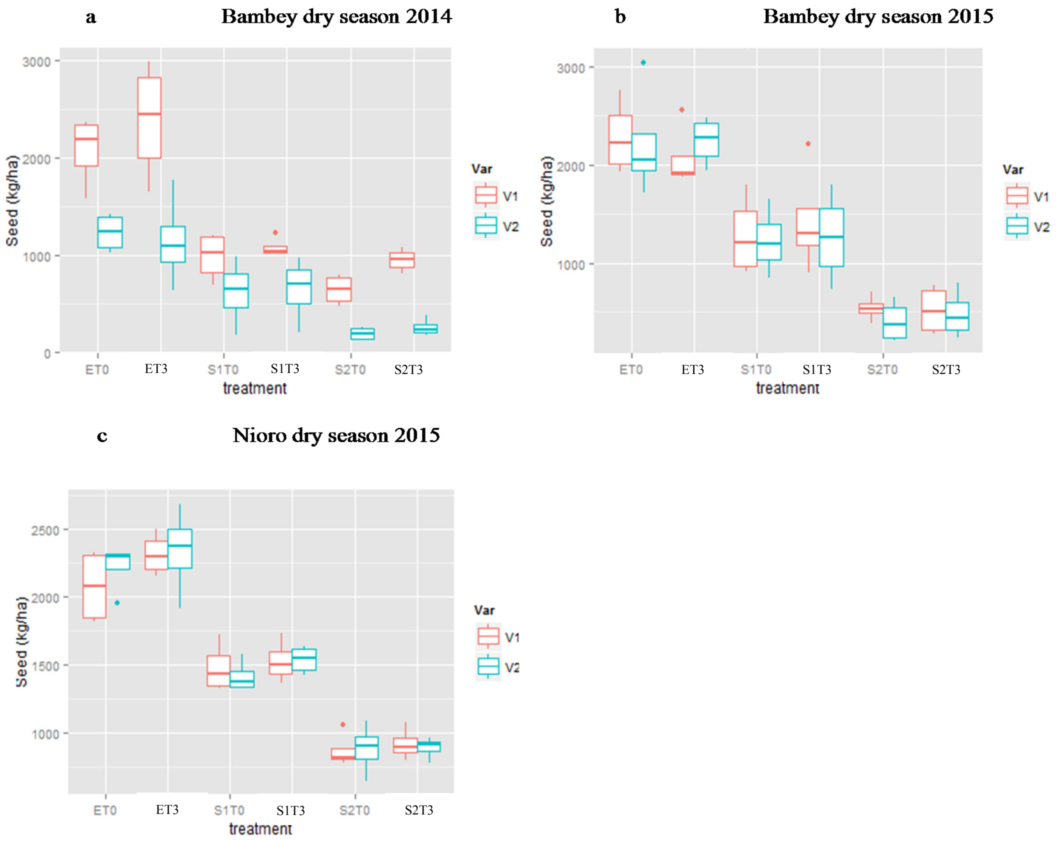

Figure 14: Seed yield for water stress induction

Variety levels: V1 = Fleur 11 and V2 = 73-33

Fertilizer levels: T0, T3

Irrigation levels: E, S1, S2

Effect of fertilizer application rate on peanut yield

In this part, datasets for field experiments conducted during the dry season 2014 in Nioro and the rainy season in Bambey, Nioro and Sinthiou Malem 2014 were used. A randomized complete block design (RCBD) was used with four replications.

Final biomass yield

Final biomass was greater during the dry season (Figure 15.d) than the rainy season (Figure 15.a,b,c). No difference were observed between the fertilizer levels in all sites and in both seasons. However greater values were recorded in treatment with fertilizer application T1 for Fleur 11 and T4 for 73-33 in Bambey (Figure 15.a), T5 for both Fleur 11 and 73-33 in Nioro (Figure 15.b), T5 for both Fleur 11 and 73-33 in Sinthiou Malem (Figure 15.c), T3 for both Fleur 11 and 73-33 in Nioro in dry season 2014 (Figure 15.d). Significant differences between varieties was recorded in Nioro during the dry season 2014 and in Bambey and Nioro during the rainy season 2014, whereas in Sinthiou Malem no difference was observed. However, higher values of biomass were recorded in Sinthiou Malem during the rainy season 2014 with a maximum value for Fleur11, of 4500 kg/ha and 5200 kg/ha for 73-33 compared to Bambey and Nioro (Figure 15. a, b, c). An analysis of variance was made for the interaction between sites (Appendix 3) under rainy season condition. The ANOVA showed a significant site effect on biomass. There was also a significant difference between varieties and sites. However, no significant difference was observed for all treatment at all sites (Table 13).

Table 13: Biomass yield interaction in three different sites in rainy season

Treatment	means	Mean separation
T5	3271.681	a
T4	3241.918	a
T3	3089.3	a
T2	3008.438	a
T0	2855.69	a
T1	2820.053	a
V2	3120.71	a
V1	2974.984	a
T4.V2	3552.902	a
T5.V2	3402.941	a
T2.V1	3145.555	a
T5.V1	3140.422	a
T3.V2	3108.384	a
T3.V1	3070.217	a
T4.V1	2930.935	a
T0.V2	2900.134	a
T1.V2	2888.575	a
T2.V2	2871.322	a
T0.V1	2811.246	a
T1.V1	2751.53	a

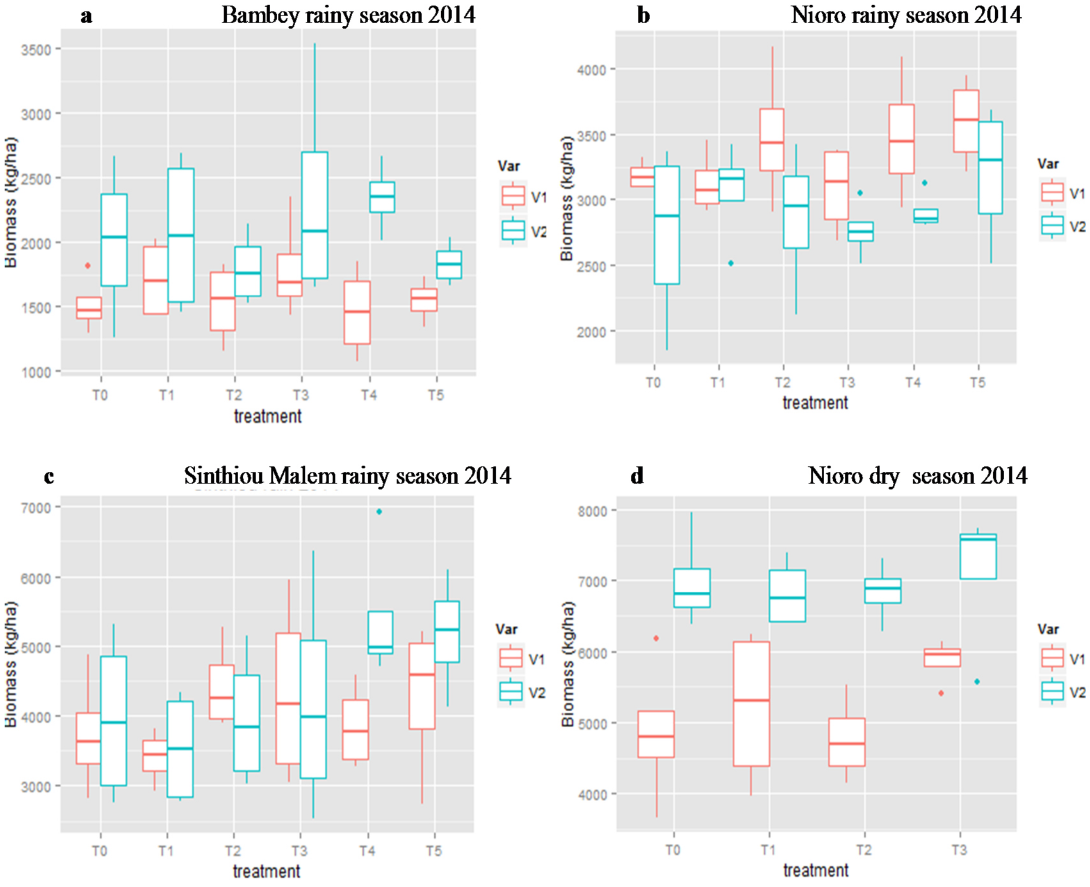

Figure 15: Biomass yield for fertilizer application rate

Seed yield

Seed yield was lower in Bambey followed by Sinthiou Malem and than in Nioro under rainfed condition (Figure 16.a,b,c). The analysis of variance showed significant differences between sites and the interaction between varieties and sites for seed yield while there were no differences for the interaction between variety, fertilizer and site (Appendix 4).

During the rainy season, the variety Fleur 11 gave higher value than 73-33 in all fertilizer levels in Bambey (Figure 16.a), in contrast in Nioro where the variety 73-33 gave higher value than Fleur 11 (Figure 16.b) for all fertilizer levels. While in Sinthiou Malem these difference between variety were not significant (Figure 16.c). In Nioro during the dry season 2014 no significant difference was showed between varieties but the variety Fleur11 gave slightly high yield for all the fertilizer level (Figure 16.d) with a maximum mean value of 2615kg/ha for T3 level.

The fertilizer response was not significant at any sites, as well as the interaction between variety and fertilizer level (Table 14).

Table 14: Seed yield interaction in three different sites in rainy season 2014

Treatment	means	Mean separation
T1	1307.399	a
T3	1305.473	a
T0	1298.857	a
T2	1292.585	a
T5	1250.238	a
T4	1200.473	a
V1	1292.383	a
V2	1259.293	a
T0.V1	1389.322	a
T3.V2	1382.304	a
T1.V2	1337.329	a
T5.V1	1323.744	a
T2.V2	1305.535	a
T2.V1	1279.635	a
T1.V1	1277.469	a
T4.V1	1255.484	a
T3.V1	1228.643	a
T0.V2	1208.393	a
T5.V2	1176.733	a
T4.V2	1145.462	a

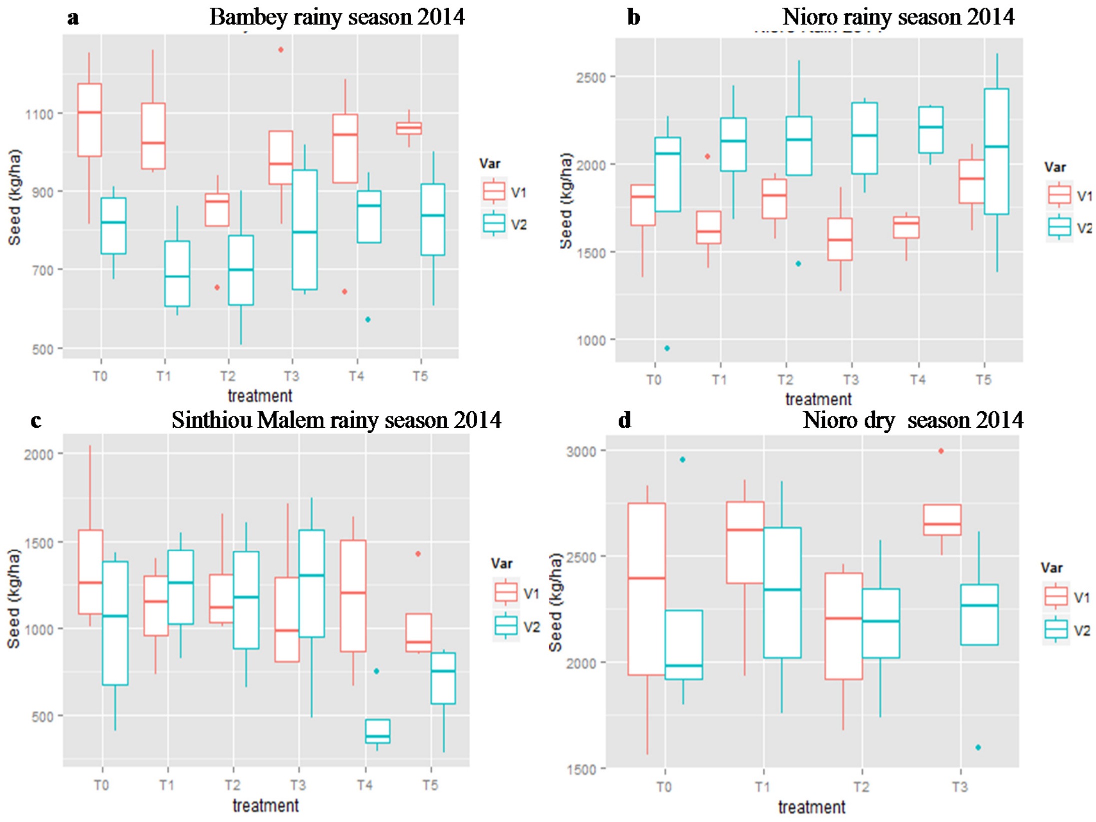

Figure 16: Seed yield for fertilizer application rate

Evaluation of performance of SIMPLACE crop model for peanut in Senegal

Model calibration and evaluation

No heat stress and no drought stress

Data set of the rainy season was used for the model calibration (Appendix 5) and model validation (Appendix 8) under growth conditions without heat stress and negligible drought stress. The model reproduced accurately the above ground biomass (AGB), the leaf area index (LAI) and the seed yield for both varieties in Nioro (Figure 17.a, b, c, d, i, j). In the model validation in the rainy season at Bambey, the model had good agreement with the observed AGB and seed yield for Fleur 11 (Figure 17.k, m) but values for

73-33 in the reproductive phase were overestimated (Figure 17.l, n), due to the length of the cycle and the drought stress occurring at the end of the growth season (Figure 17.o, p). The LAI was slightly overestimated but followed the same tendency between observed and simulated values (Figure 17.s, t). As no heat stress occurred in the rainy season, the seed yield simulated with T_a was the same unlike the seed yield simulated with T_c. This result was not unexpected in the rainy season because the average maximum air temperature was less than 36 °C and little drought stress occurred which mean T_c rarely differed from T_a.

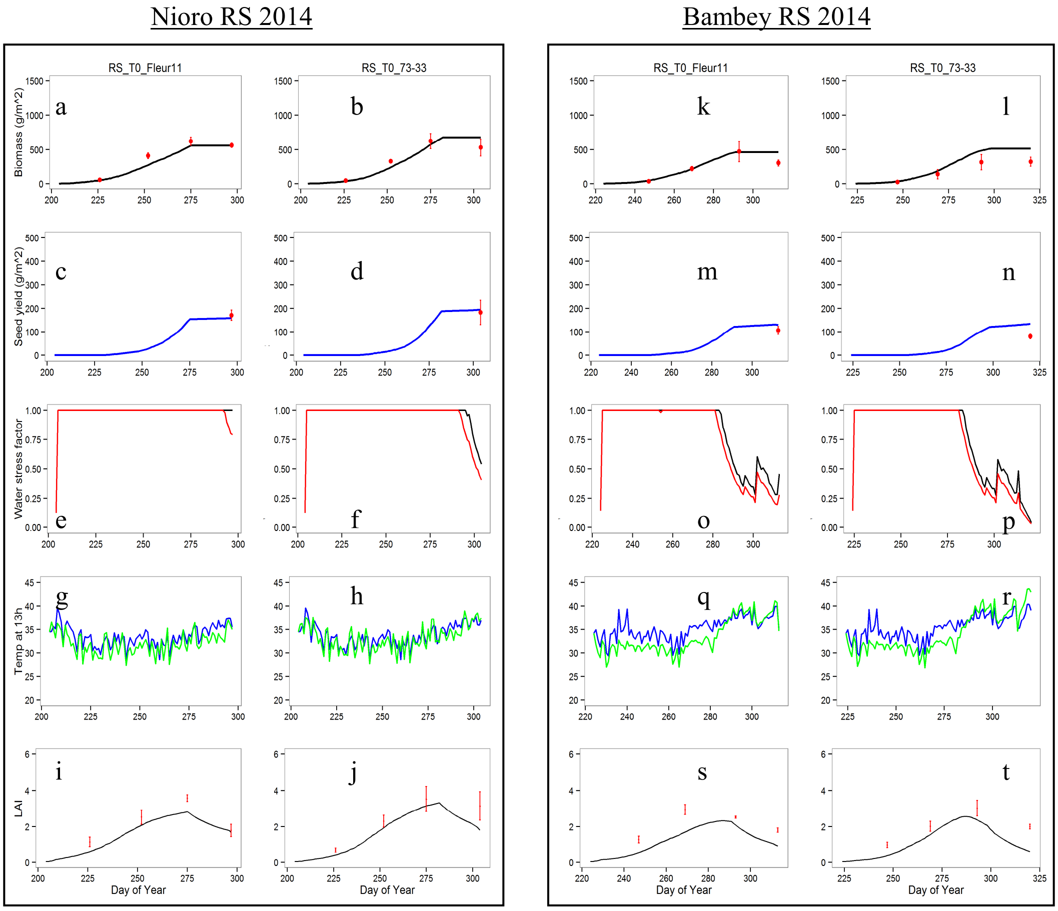

Figure 17: Model calibration and evaluation, no heat stress and no drought stress at Nioro and Bambey using data from rainy season 2014

Simulated (black line) versus observed (red points) values for AGB (a, b ,k ,l) and for LAI (i, j, s,t). Simulated seed yield (black line = yield no heat stress, green = yield with heat stress Tc, blue = yield with heat stress Ta) versus observed values (c, d, m, n). Simulated water stress factor (e, f, o, p) at 13.00 h (red line) and at daily basis (black line) and simulated daily maximum temperature (g, h, q, r) air (blue line) and canopy (green line). The model is calibrated in Nioro rainy season 2014 (Nioro RS 2014) and validated in Bambey rainy season 2014 (Bambey RS 2014), for two varieties (Fleur 11 and 73-33) with RS_T0 (rainy season no fertilizer) with no heat stress and no drought stress.

With heat stress and without drought stress

We present in Figure 18, the results of calibration and validation with heat stress and without drought stress.

Dataset of the dry season 2014 at Nioro were used for calibration (Appendix 6) and at Bambey for validation (Appendix 9). Good agreement was obtained between observed and simulated data for AGB and LAI for both varieties in calibration (Figure 18.a, b, i, j) and validation (Figure 18.k, l, s, t). Likewise, simulated seed yield exhibited good agreement with observed data for calibration of both Fleur 11 and 73-33 (Figure 18.c, d). The same result is noted for fleur11 for evaluation, while the model over estimated yield for 73-33 (Figure 18. m, n). Yield simulated with T_c agreed well with observed data. However, yield simulated with T_a were almost equal to zero. The effect was greater for the medium variety 73-33 than the short variety Fleur11.

It was found that the mean air temperature was around 40°C for both sites whereas mean canopy temperature was less than 35°C (Figure 18. g, h, q, r). No drought stress was observed in Nioro (Figure 18.f,e,) but a little drought stress occurred in Bambey the beginning of the growing season (Figure18.o,p).

Nioro OS 2014

Bambey OS 2014

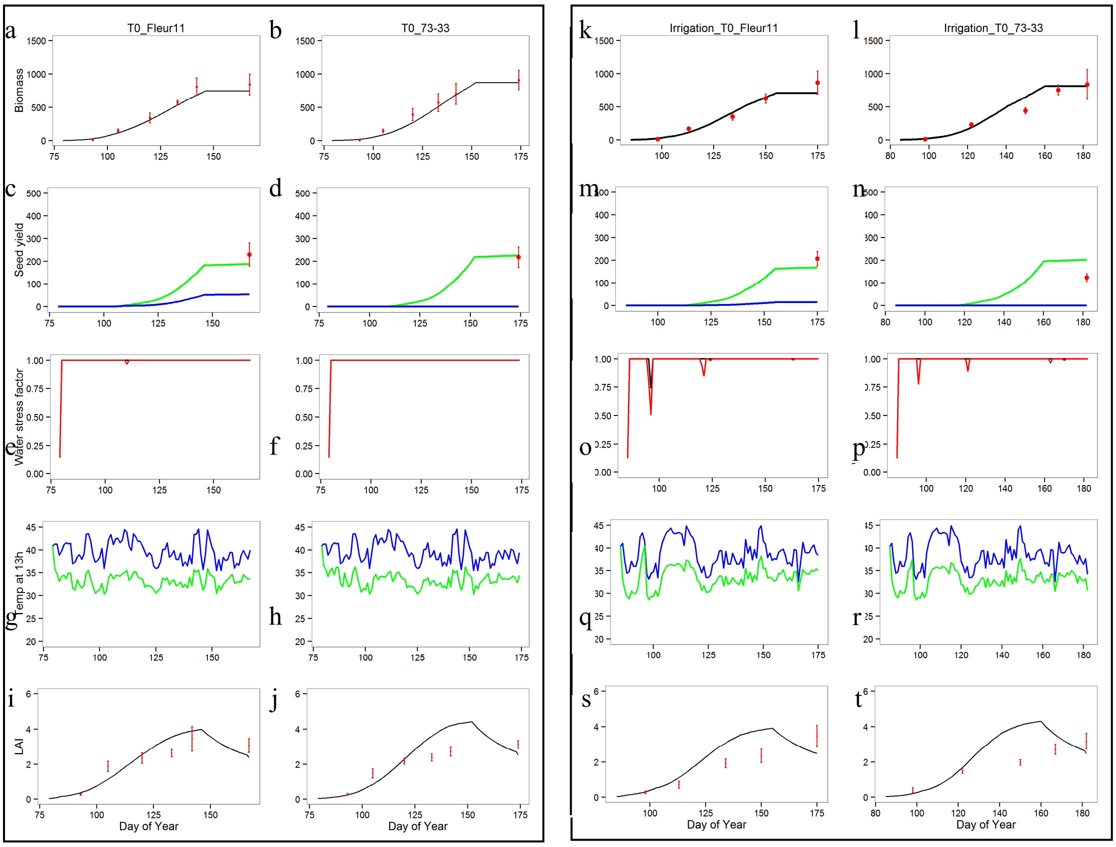

Figure 18: Model calibration and evaluation with heat stress and without drought stress at Nioro and Bambey using data from dry season 2014

Simulated (black line) versus observed (red points) values for AGB (a, b ,k ,l) and for LAI (i, j, s,t). Simulated seed yield (black line = yield no heat stress, green = yield with heat stress Tc, blue = yield with heat stress Ta) versus observed values (c, d, m, n). Simulated water stress factor (e, f, o, p) at 13.00 h (red line) and at daily basis (black line) and simulated daily maximum temperature (g, h, q, r), air (blue line) and canopy (green line).

With combined heat stress and drought stress

Figure 19 presents model calibration and validation for combined heat stress and drought stress. Datasets of the dry season 2015 at Nioro (Appendix7) were used for calibration and at Bambey for validation (Appendix 10). The simulated AGB and LAI values were in good agreement with observation for calibration (Figure 19.a,b,i.j) for both varieties and validation (Figure 19.k,s). The model also accurately simulated the seed yield when water stress occurred during the flowering period (Figure 19.c,m), although, it over estimated seed yield when water stress occurred during seed filling both in calibration and evaluation (Figure 19.d,n). Increased T_c was simulated during water stress induction, with the result of T_c being greater than or equal to T_a (Figure 19.g, h, o, p).

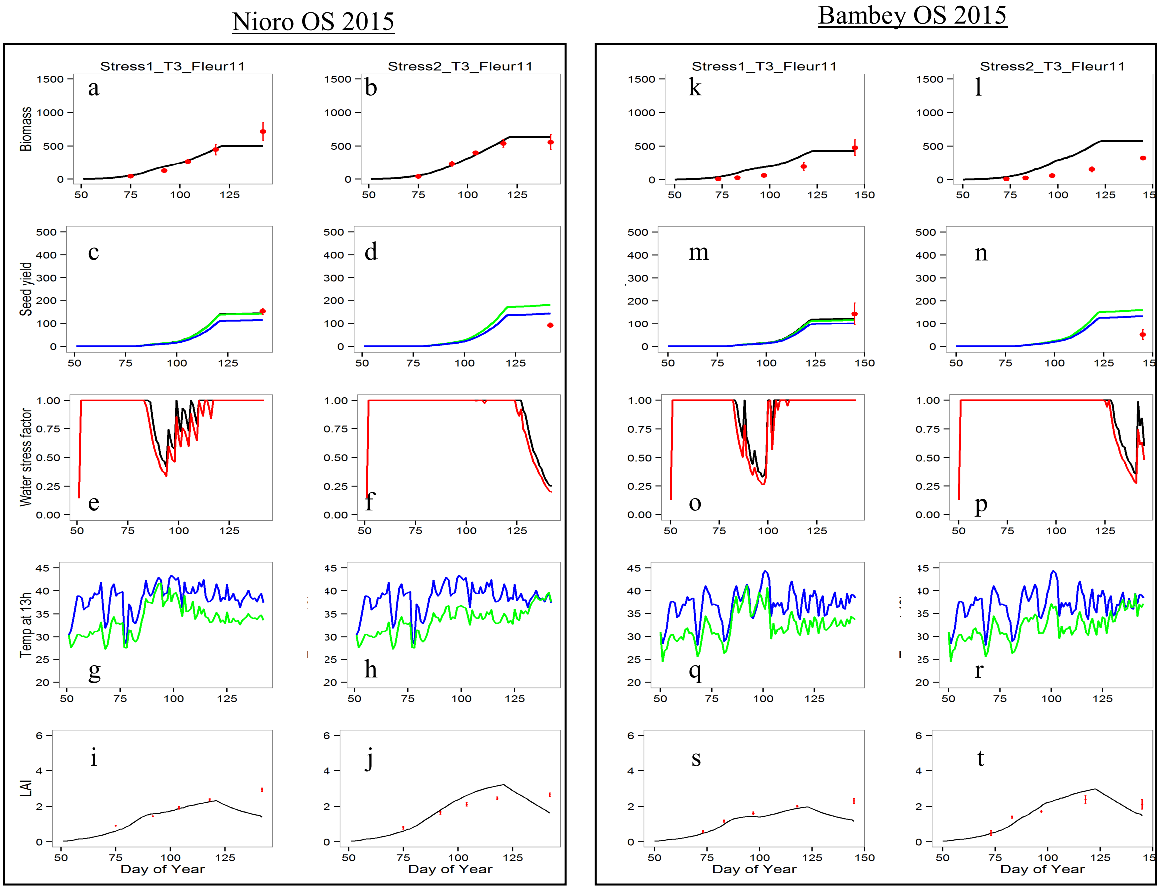

Figure 19: Model calibration and evaluation with combined heat stress and drought stress at Nioro and Bambey using data from dry season 2015

Simulated (black line) versus observed (red points) values for AGB (a, b ,k ,l) and for LAI (i, j, s,t). Simulated seed yield (black line = yield no heat stress, green = yield with heat stress Tc, blue = yield with heat stress Ta) versus observed values (c, d, m, n). Simulated water stress factor (e, f, o, p) at 14.00 h (red line) and at daily basis (black line) and simulated daily maximum temperature (g, h, q, r), air (blue line) and canopy (green line). The model was calibrated in Nioro dry season 2015 (Nioro OS 2015) and validated in Bambey dry season 2015 (Bambey OS 2015), for two varieties (Fleur 11 and 73-33) with heat stress and drought stress.

Evaluation of model performance

Model performance for simulating above ground biomass and leaf area index

The evaluation of the performance of the model was based on the coefficient of determination R^2 and the root mean square error (RMSE).

Figure 20 presents model performance for simulating above ground biomass (AGB) and leaf area index (LAI).

The model reproduced accurately the above ground biomass for both Fleur 11 and 73-33 with an $R^2 = 0.7$ for calibration and evaluation (Figure 20. a, c). The square root of the variance of the residuals (RMSE) is lower for calibration than for evaluation, therefore, the model prediction was more accurate for calibration than for validation dataset. The model performed quite well for the leaf area index with an $R^2 = 0.3$ for calibration and validation for both varieties. In contrast to the AGB, the validation of LAI performed better than the calibration data based on the RMSE (Figure 20. b, d). The Fleur 11 variety gave better result than the 73-33 variety.

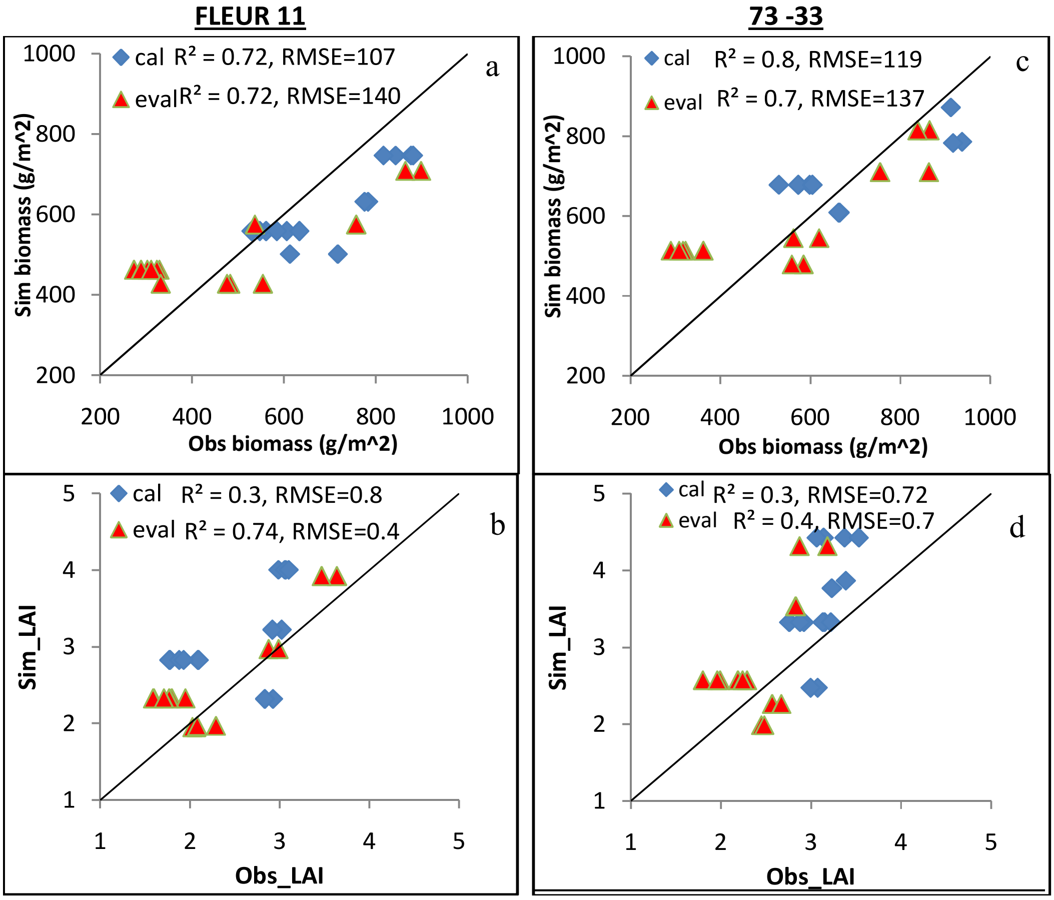

Figure 20: Model performance for simulating above ground biomass (a, c) and leaf area index (b, d)

Calibration: blue points; validation: red points. The two varieties are Fleur 11 and 73-33. The black line is 1:1 line for visualization of goodness of fit.

Model performance for simulating seed yield

Model performance for simulating seed yield is presented in Figure 21. The analysis of the yield response was done in three steps: (i) seed yield with no heat stress (No_HS), (ii) seed yield with heat stress using simulated canopy temperature (HS_Tc) (iii) and the seed yield with heat stress using measured air temperature (HS_Tair) (Figure 21). The model showed a good correlation between observed and simulated values for model No_HS and HS_Tc for both varieties (Figure 21. a, b, d, e). However, under HS_Tair, a significant variation between observed and simulated values was noted (Figure 21. c, f). The result demonstrated the importance of using canopy temperature to estimate heat stress impacts on seed yield.

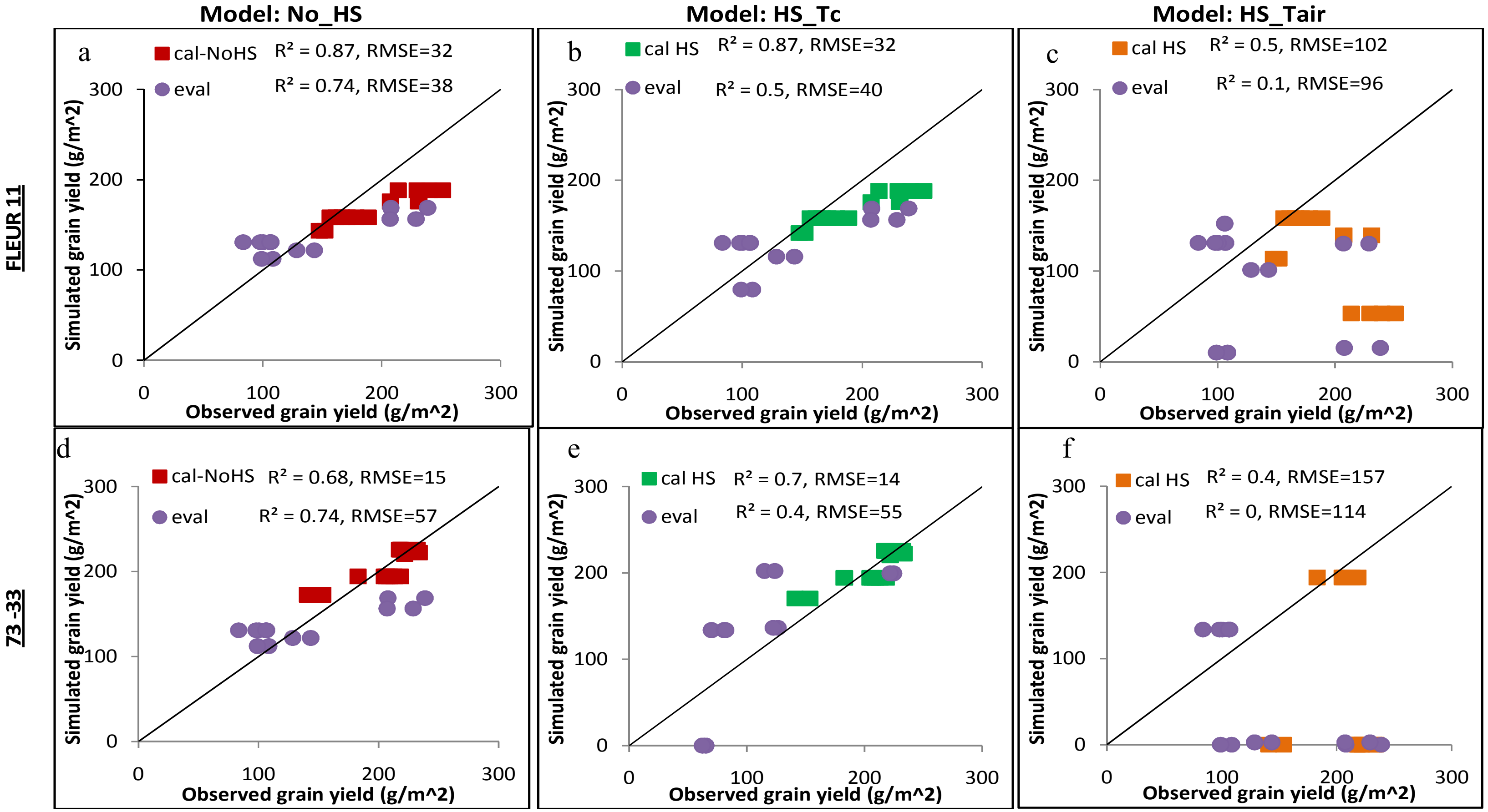

Figure 21: Model performance for simulating seed yield

NoHS: calibration under no heat stress, red points (a, d); HS_Tc. calibration yield with heat stress using canopy temperature: green points (b, e); HS_Tair, calibration with heat stress using air temperature: orange points (c, f) and for validation: purple points. The black line is 1:1 line for visualization of goodness of fit.

Climate impact analysis and adaptation strategies to climate change on peanut in Senegal

Climate data analysis

Standard precipitation index (SPI) and temperature anomalies for observation

The SPI in Bambey and in Nioro showed an irregular variation of precipitation from 1983 to 2014 (Figure 22.a.b). However, it can be subdivided into two major parts in Bambey where dry years were noted from 1983 to 2004 and wet years from 2005 to 2013. In Nioro, the SPI could be subdivided into four different parts: dry years from 1983 to 1986 and 1991 to 2000 and wet years from 1987 to 1990 and from 2001 to 2013.

The inter-annual variation of the temperature anomalies in Bambey and in Nioro is presented in Figure 22.c.d. At both sites, temperature increased over the past decade (2000-2013). On the contrary, from 1984 to 1996, temperature decreased in both sites and was more pronounced in Nioro than in Bambey.

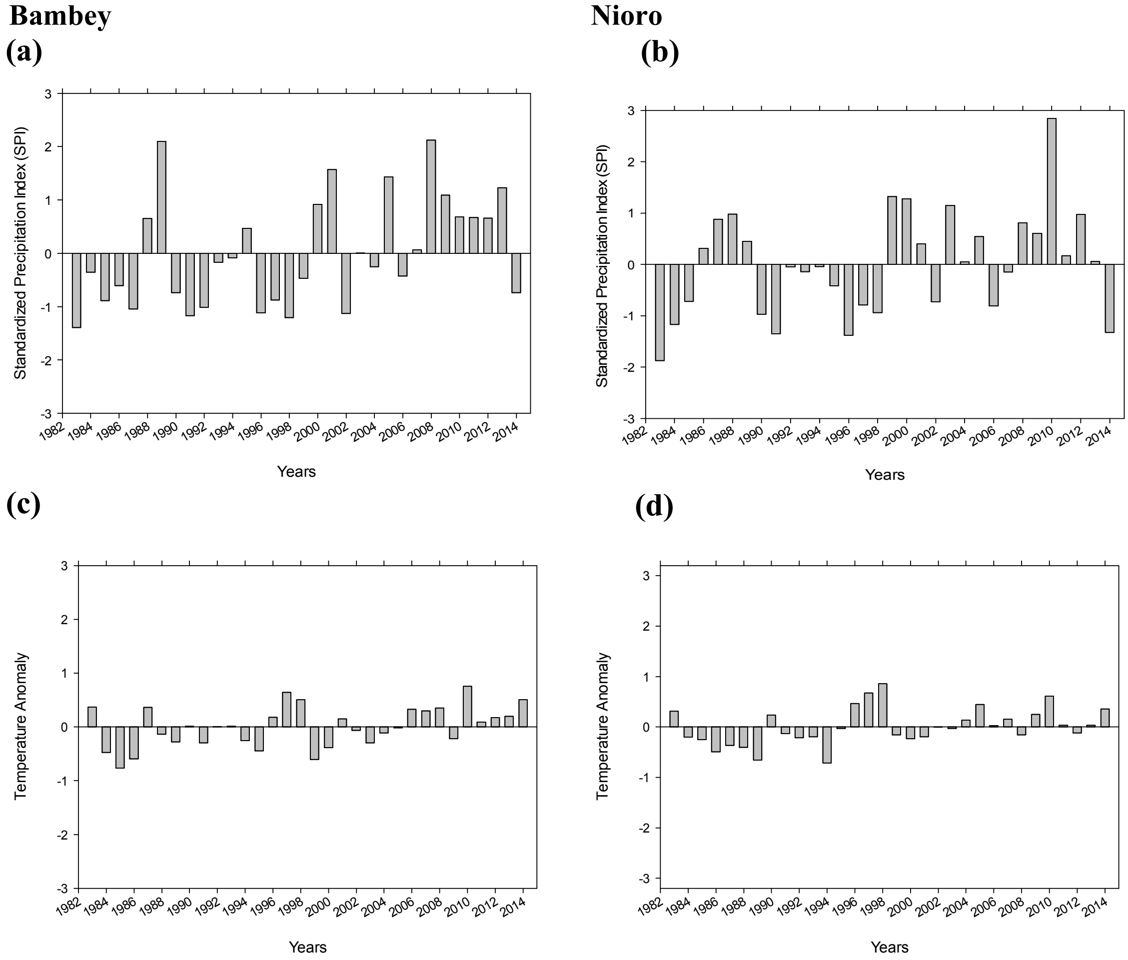

Figure 22: SPI and temperature anomalies for Bambey and Nioro

Source: CNRA Bambey and ANACIM

Simulation of inter-annual variation of precipitation and temperature

The inter-annual variation of precipitation in both sites is presented in Figure 23.a.c. The variation was slightly clear but in both sites, a decrease of precipitation was noted over years. The period 2051-2100 is more affected by decreasing precipitation than the period 2011-2050 compared to the baseline 1981-2010, even though there was clear increase of temperature at both sites. But the difference between the RCP4.5 and RCP8.5 became more clearer from 2051 where RCP 8.5 was always above RCP4.5 (Figure 23.b,d).

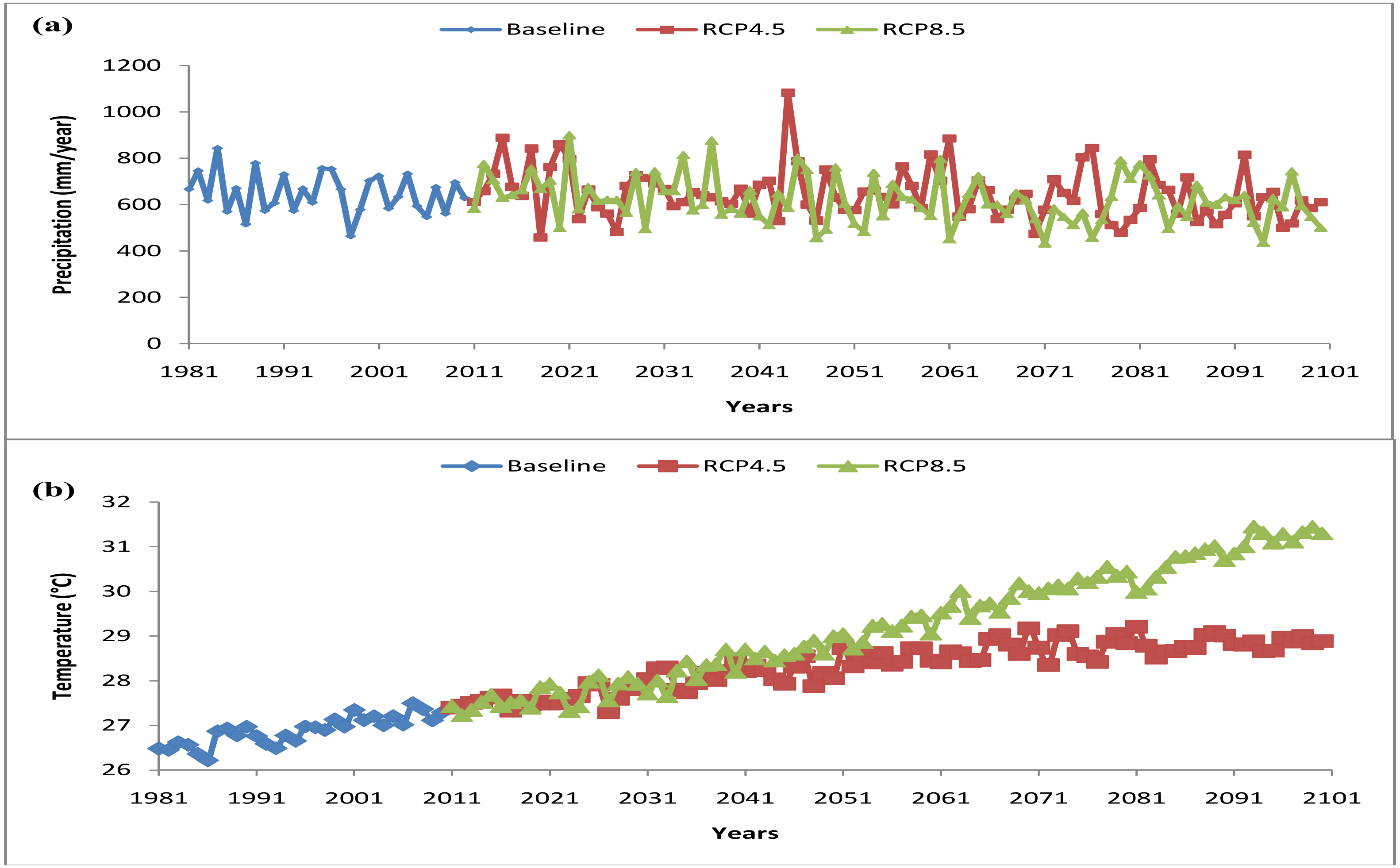

Figure 23: Inter-annual variation of precipitation and temperature simulated for Bambey (a,b)

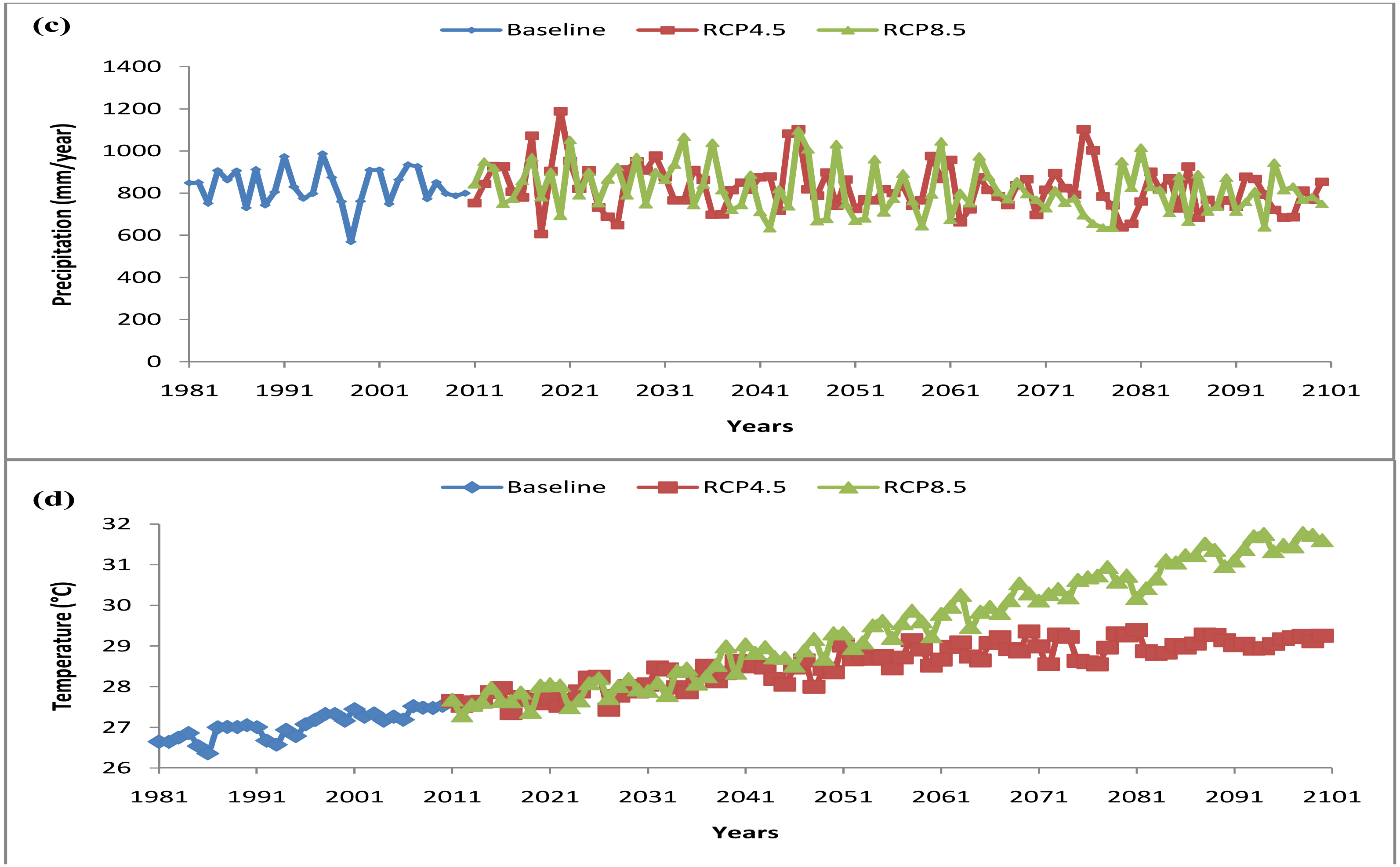

Figure 24: Inter-annual variation of precipitation and temperature simulated for Nioro (c,d)

Climate change analysis

Figure 25 presents the uncorrected and bias-corrected precipitation for the two sites Bambey and Nioro for the four RCMs. A decrease of precipitation for the DMI-HIRHAM5 and MPI-CLMRCMs was observed at the two sites for both scenarios (RCP 4.5 and RCP 8.5) compared to the baseline (1981-2010). In contrast, SMHI-RCA, precipitation increased at both sites, whereas in the case of KNMI-RACMO22T, precipitation increased for Nioro for both RCPs and in Bambey, it also increased for the RCP 8.5 and decreased for the RCP 4.5 (Figure 25a). However, all models predicted higher rainfall in Nioro than in Bambey. These results corroborate the well-known gradient of rainfall in the study area for both corrected and uncorrected data.

The RCMs temperature output are shown in Figure 26. All four RCMs showed an increase of temperature for the scenario period for RCP4.5 and RCP8.5 compared to the baseline period.

The RCP4.5 scenario showed a rise of mean temperature of 1°C whereas RCP8.5 showed a rise of 1.2°C between (1981-2010) and (2016-2045) in both sites after bias correction of regional climate model simulations. The higher values of temperature are recorded in Nioro (Figure 26.d).

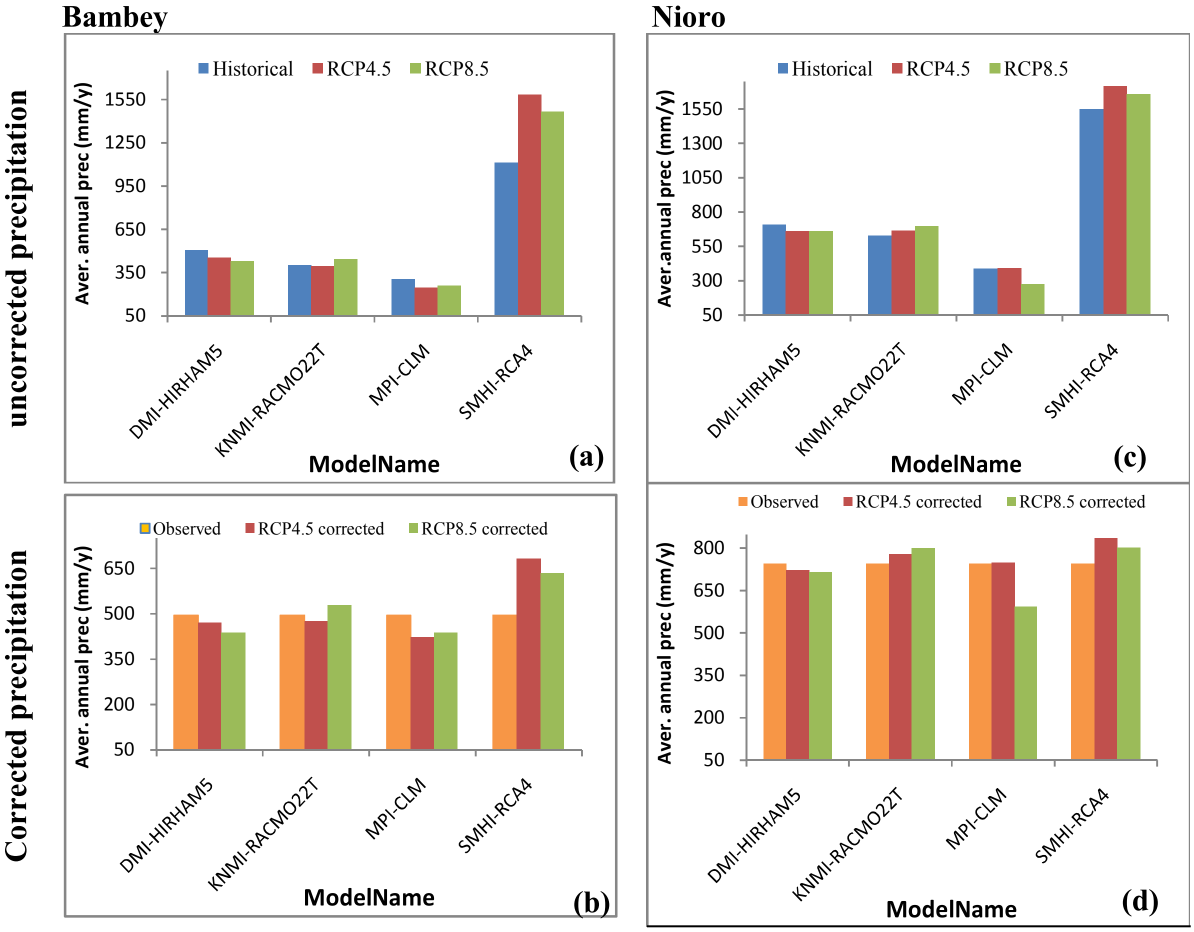

Figure 25: Uncorrected and corrected precipitation for Bambey and Nioro

Four RCMs for the RCP4.5 (red colour) and RCP8.5 (green colour) scenarios, historical (blue colour) and observed (orange colour)

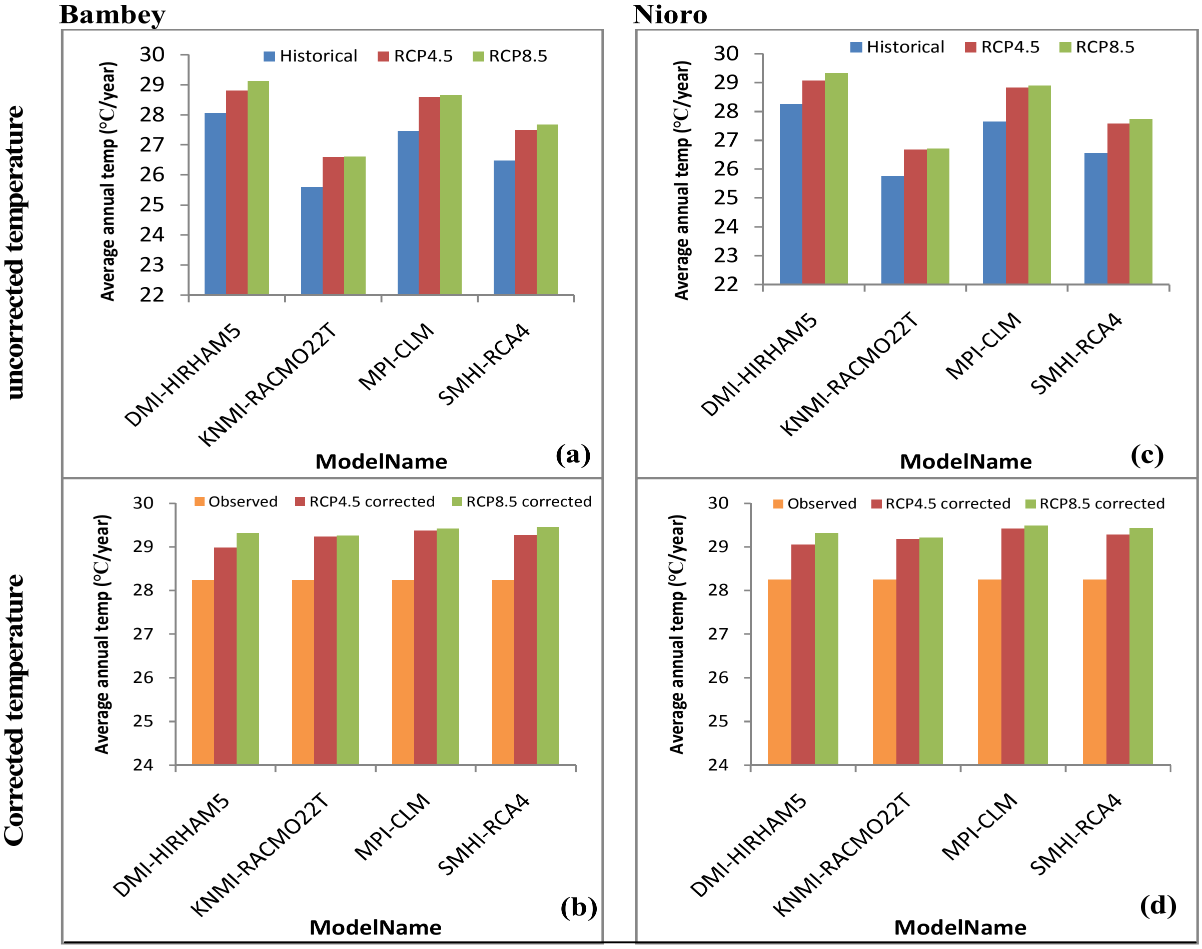

Figure 26: Uncorrected and corrected temperature for Bambey and Nioro

Four RCMs for the RCP4.5 (red colour) and RCP8.5 (green colour) scenarios, historical (blue colour) and observed (orange colour)

The corrected precipitation and temperature were used in the SIMPLACE crop model to simulate peanut yield in order to determine the relative change yield under projected climate change conditions.

Yield changes under projected climate change conditions

Relative changes in biomass yield

Biomass yield under dry season condition with irrigation

The Relative changes in biomass yield in the dry season for the four RCMs at both sites is presented in Figure 27. The relative biomass change was determined by Eq.16 with elevated ambient CO_2 and no change in CO_2 concentration. It was observed at both sites, that there was a positive relative change in biomass with elevated CO_2 while there was a decrease in instances where the CO_2 concentration remained at the same level as the current climate. The negative change without CO_2 elevated was greater under the RCP8.5 than RCP4.5 scenario at both sites, whereas the positive increase under elevated CO_2 is greater for RCP4.5 than for RCP8.5 scenario for the RCMs DMI-HIRHAM5 in Bambey and KNMI-RACMO22T in both sites (Figure 27b,d). It was found that the positive effect in Nioro (Figure 27.d) under the RCP 8.5 is larger than the increase in biomass with RCP 8.5 in Bambey (Figure 27b). For RCP 4.5, the same change was noted for KNMI-RACMO22T.

Biomass decreased by 7.9% in both Bambey and Nioro for RCP 4.5 and by 11.5% in Bambey for RCP8.5 and 10% in Nioro for RCP8.5 across the four RCMs in ambient current CO_2. However, in ambient CO_2 elevation, increase of biomass by 4.6% and 6% in Bambey were noted for RCP4.5 and RCP8.5 respectively and by 5.4% and 8.8% in Nioro for RCP4.5 and RCP8.5 respectively.

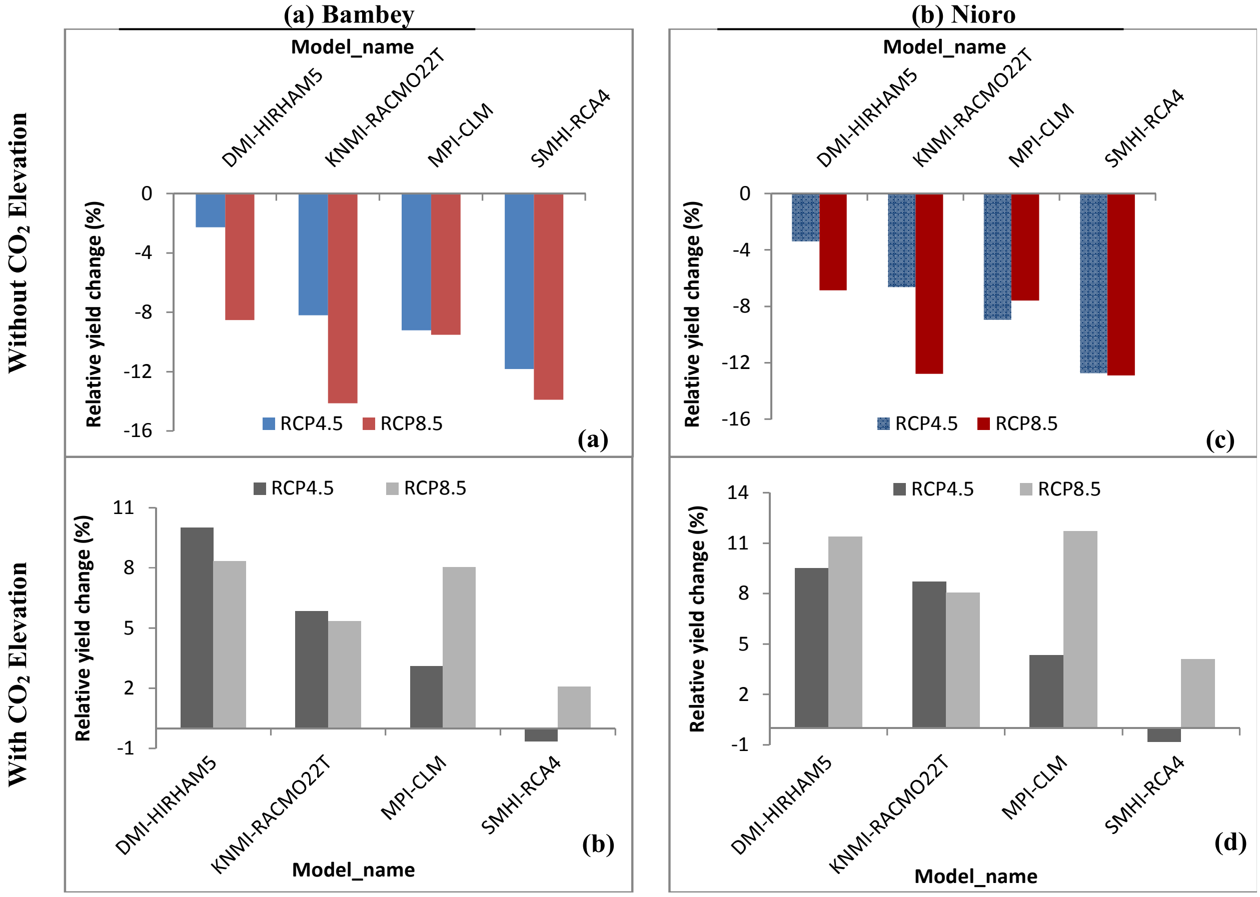

Figure 27: Relative biomass yield change for Bambey and Nioro under dry season condition with irrigation

Four RCMs for RCP4.5 (blue colour) and RCP8.5 (red colour) scenarios in no CO_2 elevation and for RCP4.5 (black colour) and RCP8.5 (grey colour) scenarios in CO_2 elevation in dry season.

Biomass yield under rainy season condition with irrigation

Figure 28 presents the relative changes in biomass yield in rainy season. Negative changes were shown for the four RCMs when CO_2 concentration remain same as for the baseline climate. Positive changes occurred where CO_2 increased as predicted in the future. The negative effect of climate change under ambient CO_2 is higher for the RCP4.5 scenario for RCMs DMI_HIRHAM5 and KNMI-RACMO22T than the RCP8.5 whereas the opposite effect showed for the two other RCMs in Bambey (Figure 28.a). In Nioro, the negative effect was higher for the RCP 4.5 in RCMs, DMI_HIRHAM5 and KNMI-RACMO22T than the RCP8.5, whereas in MPI-CLM and SMHI-RCA4, the negative effect was higher for the RCP 8.5 than the RCP 4.5 (Figure 28.c). In the case where there was CO_2 elevation, the positive effect for RCP8.5 was higher than RCP4.5 for all the RCMs and for both sites (Figure 28.b,d).

An average across the four RCMs indicated a decrease of biomass in Bambey by 11.9% for RCP4.5 and 13% for RCP8.5, while in Nioro, it decreased by 10.4% for both RCPs. However, with ambient CO_2 elevation, biomass increased by 3.4% and 8.9% in Bambey for RCP4.5 and RCP8.5 respectively and by 4.8% for RCP4.5 and 11.8% for RCP8.5 in Nioro.

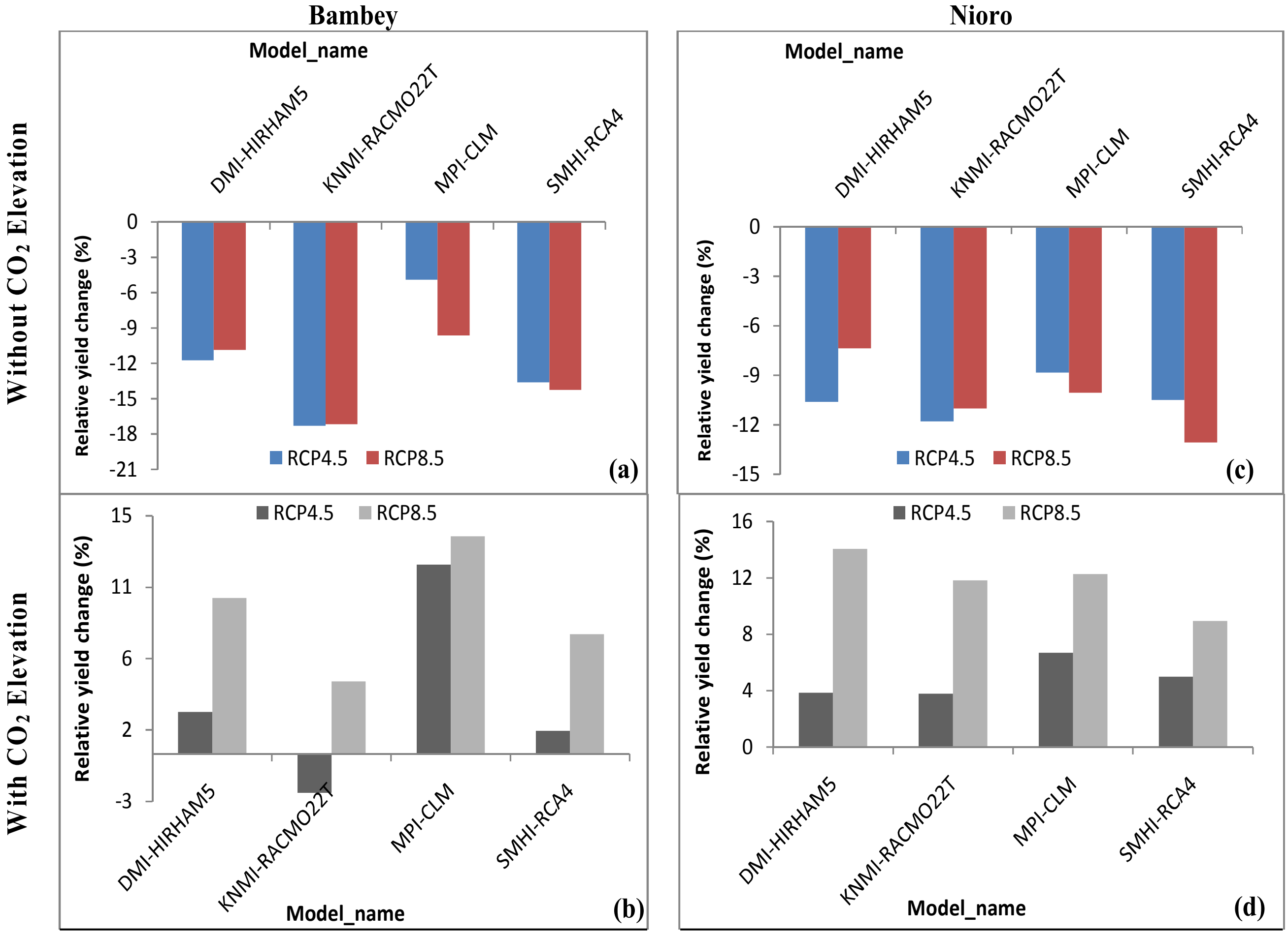

Figure 28: Relative biomass yield change for Bambey and Nioro under rainy season condition with irrigation

Four RCMs for the RCP4.5 (blue colour) and RCP8.5 (red colour) scenarios in no CO_2 elevation and for RCP4.5 (black colour) and RCP8.5 (grey colour) in CO_2 elevation in rainy season with irrigation

Biomass yield under rainy season condition without irrigation

The relative changes biomass yield in the rainy season without irrigation is presented in Figure 29. Biomass decreased by 7.5% and 9.5% in Bambey for RCP4.5 and RCP8.5 respectively and by 14.4% and 17% in Nioro for RCP4.5 and RCP8.5 respectively across the four RCMs in ambient current CO_2 (Figure 29 a.c). In ambient CO_2 elevation, biomass increased by 8% and 12.4% in Bambey for RCP4.5 and RCP8.5 respectively. In Nioro, it increased by 0.7% for RCP4.5 and 4.2% for RCP8.5.

In both Bambey and Nioro, there is an increase in yield in elevated CO_2 conditions. It was higher for the RCP8.5 than the RCP4.5 except the DMI_HIRHAM5 where RCP4.5 is greater than the RCP8.5 in Bambey (Figure 29 b). In Nioro, the RCP 8.5 indicated a greater relative changes in yield than the RCP4.5 for RCMs DMI_HIRHAM5, KNMI-RACMO22T and SMHI-RCA4. The opposite rather occurred for the RCM, MPI-CLM (Figure 29 d).

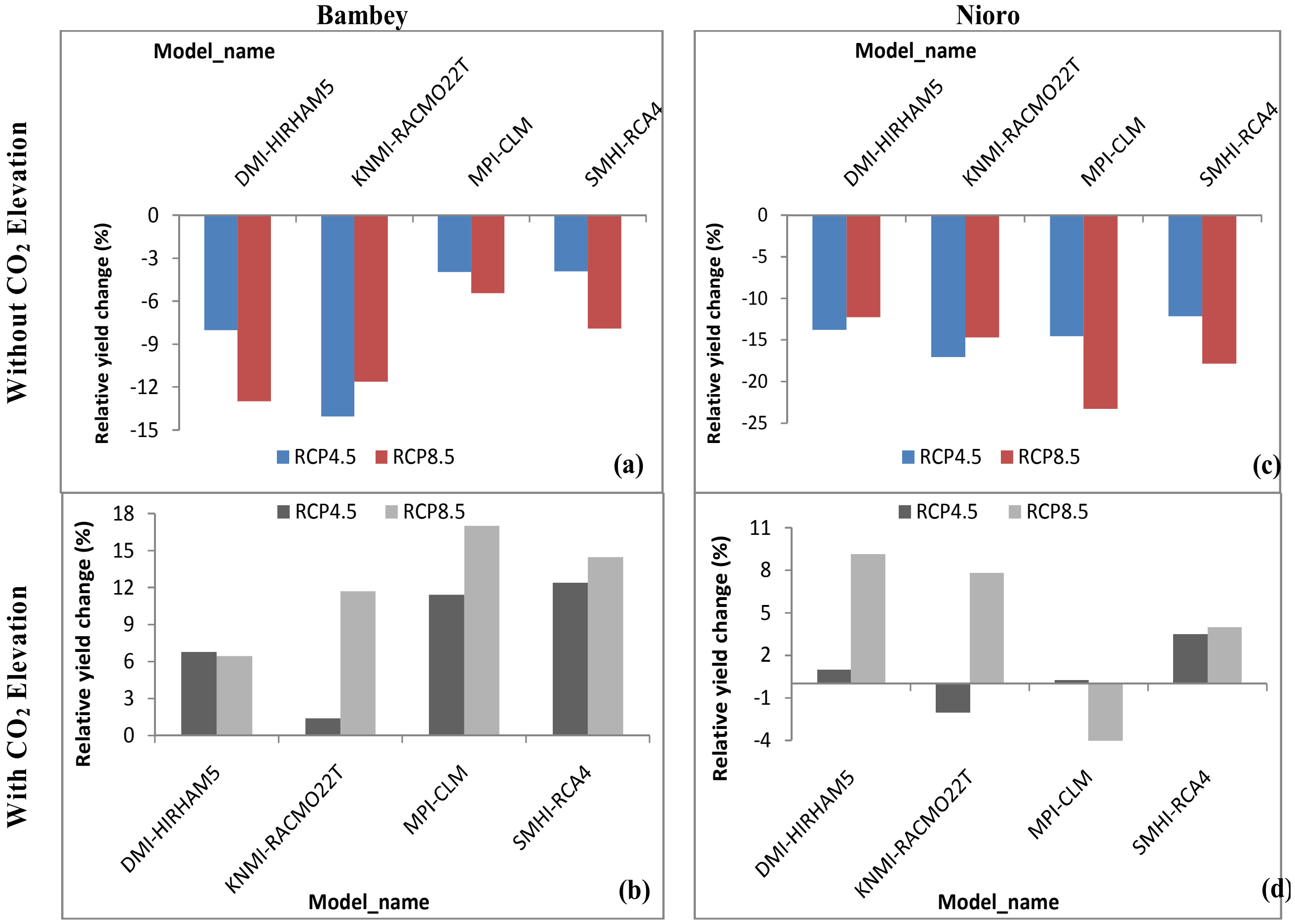

Figure 29: Relative biomass yield change for Bambey and Nioro under rainy season condition without irrigation

Four RCMs for the RCP4.5 (blue colour) and RCP8.5 (red colour) scenarios in no CO_2 elevation and for RCP4.5 (black colour) and RCP8.5 (grey colour) in CO_2 elevation in rainy season in no irrigation

Relative seed change yield

Seed yield under the dry season

The effects of climate change on peanut under ambient CO_2 concentration at both sites had negative impacts on both canopy and air temperature (Figure 30). The negative effects were larger when air temperature was used instead of canopy temperature at both sites. Yield losses were greater in Nioro site which ranged from -7.2% for RCP4.5 to -42.1% for RCP8.5 across all RCMs for canopy temperature and from -9.8% for RCP4.5 to -55.8% for RCP8.5 for air temperature (Figure 30.c). In Bambey however, losses ranged from -6.2% for RCP4.5 to -16.2% for RCP8.5 across all RCMs for canopy temperature and from -10.2% for RCP4.5 to -27% for RCP8.5 for air temperature (Figure 30.a). The RCP4.5 gives less yield losses compared with the RCP8.5.

All RCMs projected a negative effect on yield for air temperature by -6.6% for RCP4.5 and -13.7% for RCP8.5 with elevated CO_2 concentration in Bambey. In Nioro, yield losses for air temperature range from -34.2% for RCP4.5 and -46.9% for RCP8.5 (Figure 30.b.d).

Positive effects on relative changes in seed yield for canopy temperature were noted at both sites with 5.2% and 5.6% for RCP4.5 and RCP8.5 in Bambey, and 5.1% for RCP4.5 and 7.2% for RCP8.5 in Nioro.

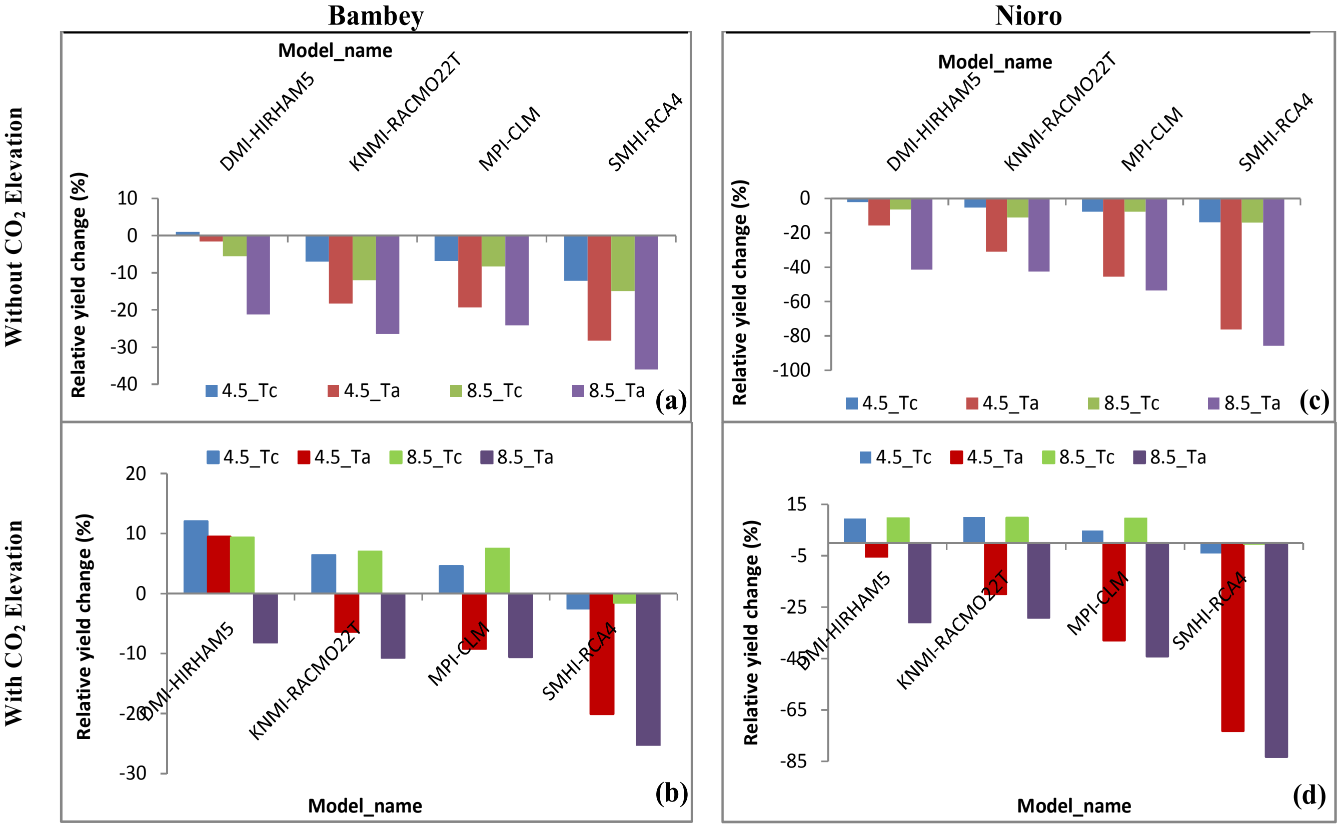

Figure 30: Relative seeds yield change for Bambey and Nioro under the dry season

Four RCMs for the RCP4.5 (4.5) and RCP8.5 (8.5) scenarios, yield with canopy temperature (Tc), yield with air temperature (Ta), in no CO2 elevation and CO2 elevation in dry season

Seed yield with irrigation in the rainy season

Figure 31 shows the relative changes in seed yield with irrigation for rainy season conditions. It indicated a negative impact on yield at both sites under current CO_2 concentrations for all the models (Figure 31 a. c.). An average across all RCMs showed a decrease by 12.% for RCP4.5 for both canopy and air temperature and by 12.6% and 12.7% for RCP8.5 for canopy and air temperature respectively in Bambey. In Nioro, it decreased by 10.9% and 11% for RCP4.5 for canopy and air temperature respectively but by 11.1% for RCP8.5 for both canopy and air temperatures.

In contrast, under subsequent elevated CO_2 concentration, the simulated results showed a positive impacts of climate change on yield at both sites (Figure 31 b. d.) and for all the models excepted in Bambey for RCP4.5 for KNMI-RACMO22T. In Bambey, an increase by 3.6% to 3.5% for RCP4.5 and by 9.8% to 9.7% for RCP8.5 for canopy and air temperature respectively. While in Nioro, it shows an increase by 4.8% for RCP4.5 and by 11.6% for RCP8.5 for both canopy and air temperatures.

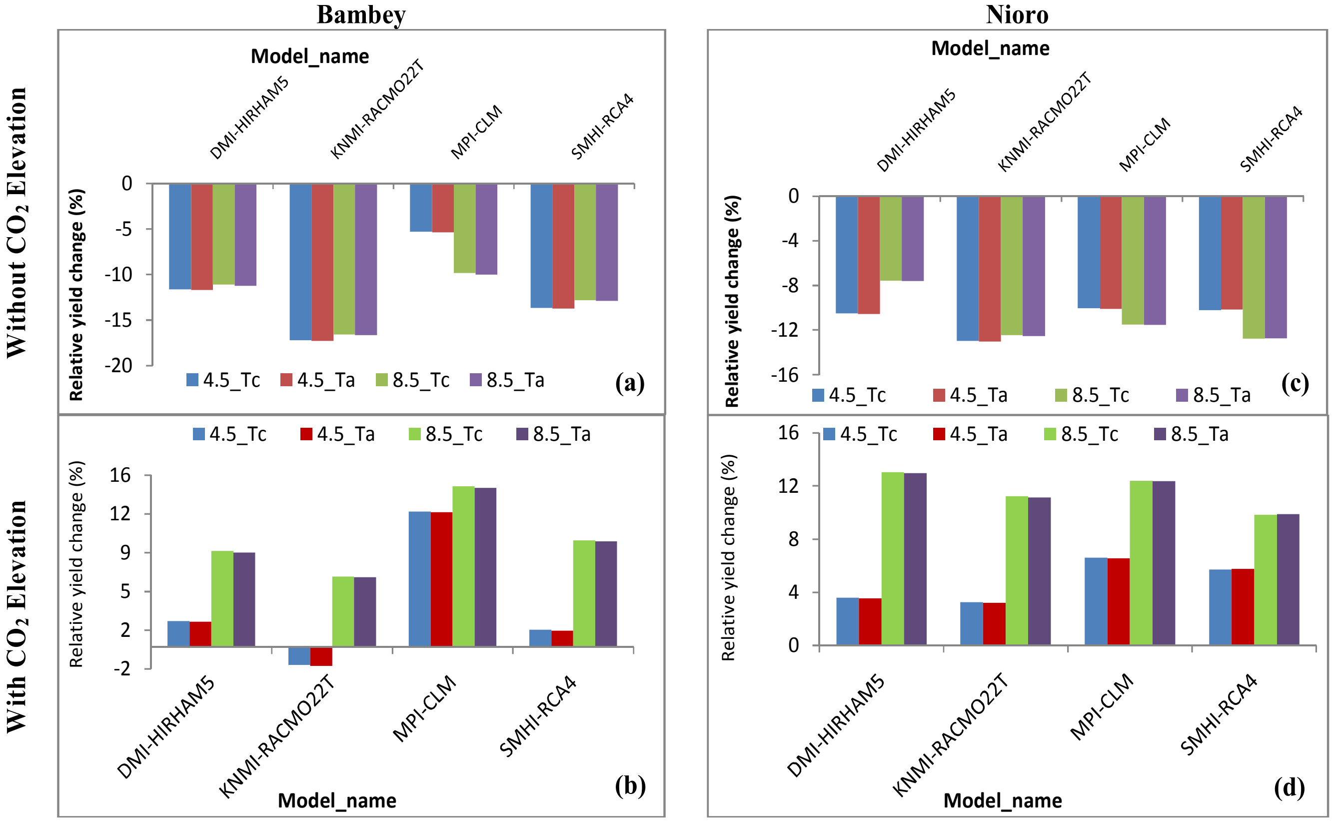

Figure 31: Relative seeds yield change for Bambey and Nioro with irrigation in the rainy season

Four RCMs for the RCP4.5 (4.5) and RCP8.5 (8.5) scenarios, yield with canopy temperature (Tc), yield with air temperature (Ta), in no CO_2 elevation and CO_2 elevation in rainy season in irrigation condition

Seed yield without irrigation under rainy season

The relative changes in seed yield under rainy season conditions without irrigation was shown in Figure 32. The effects of CO_2 variation on peanut in Bambey had negative impacts for both canopy and air temperature for all models under ambient CO_2 by -6.3% for RCP4.5 and -9% for RCP8.5 and a positive impacts under future elevated CO_2 by 9.5 % for RCP4.5 and 13.2% for RCP8.5 in both canopy and air temperature (Figure 32.a. b).

In Nioro, it showed a negative impacts of climate change on yield for the current CO_2 (without CO_2 elevation) for all the models by -15.2% for RCP4.5 and -17.8% for RCP8.5 in both canopy and air temperatures (Figure 32.c). In contrast, for the elevated CO_2 concentration change it showed a positive effect of climate change on peanut yield across all the RCMs by 0.5% for RCP4.5 and 4.5% for RCP8.5 in both canopy and air temperatures (Figure 32.d). However, a decrease in yield was shown by the RCMs KNMI-RACMO22T for RCP4.5 and MPI-CLM for both RCPs.

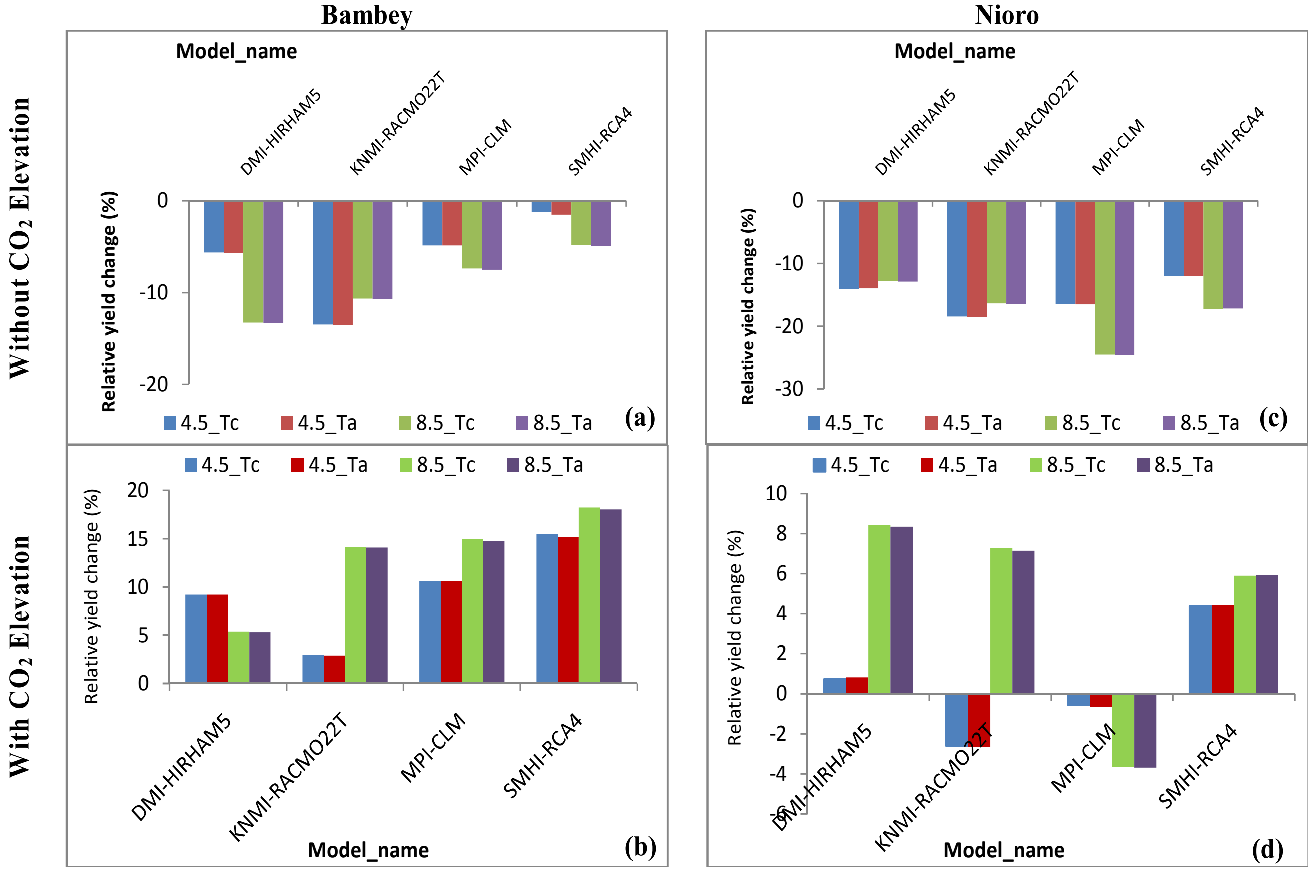

Figure 32: Relative seeds yield change for Bambey and Nioro without irrigation under rainy season

Four RCMs for the RCP4.5 (4.5) and RCP8.5 (8.5) scenarios, yield with canopy temperature (Tc), yield with air temperature (Ta), in no CO_2 elevation and CO_2 elevation in rainy season in no irrigation condition

Seed yield without irrigation under rainy season condition according to the sowing date

The relative changes in yield seed under rainy season conditions without irrigation are presented in Figure 33. In general, in both sites the early sowing date gave less yield than the current sowing date without CO_2 elevation and with CO_2 elevation. However, the model DMI-HIRHAM5 showed a positive effect in yield change the early sowing date in Bambey for both scenarios independently of the CO_2 amount variation (Figure 33.a.b). Under current ambient CO_2 relative changes in yield in Bambey decreased by 7.4% to 7% for RCP4.5 and 3.8% to 3.4% for RCP8.5 in canopy and air temperature respectively. In Nioro it decreased by 10.2% for RCP4.5 and by 6.5% for RCP8.5 for both canopy and air temperature respectively (Figure 33.a.c). Under future elevated CO_2, relative changes in yield decreased by 5.9% to 5.5% for RCP4.5 and by 2.5% to 2.1% for RCP8.5 in canopy and air temperature in Bambey. In the case of Nioro it decreased by 10.1 for RCP4.5 and 6.5 for RCP8.5 for canopy and air temperature (Figure 33.b.d).

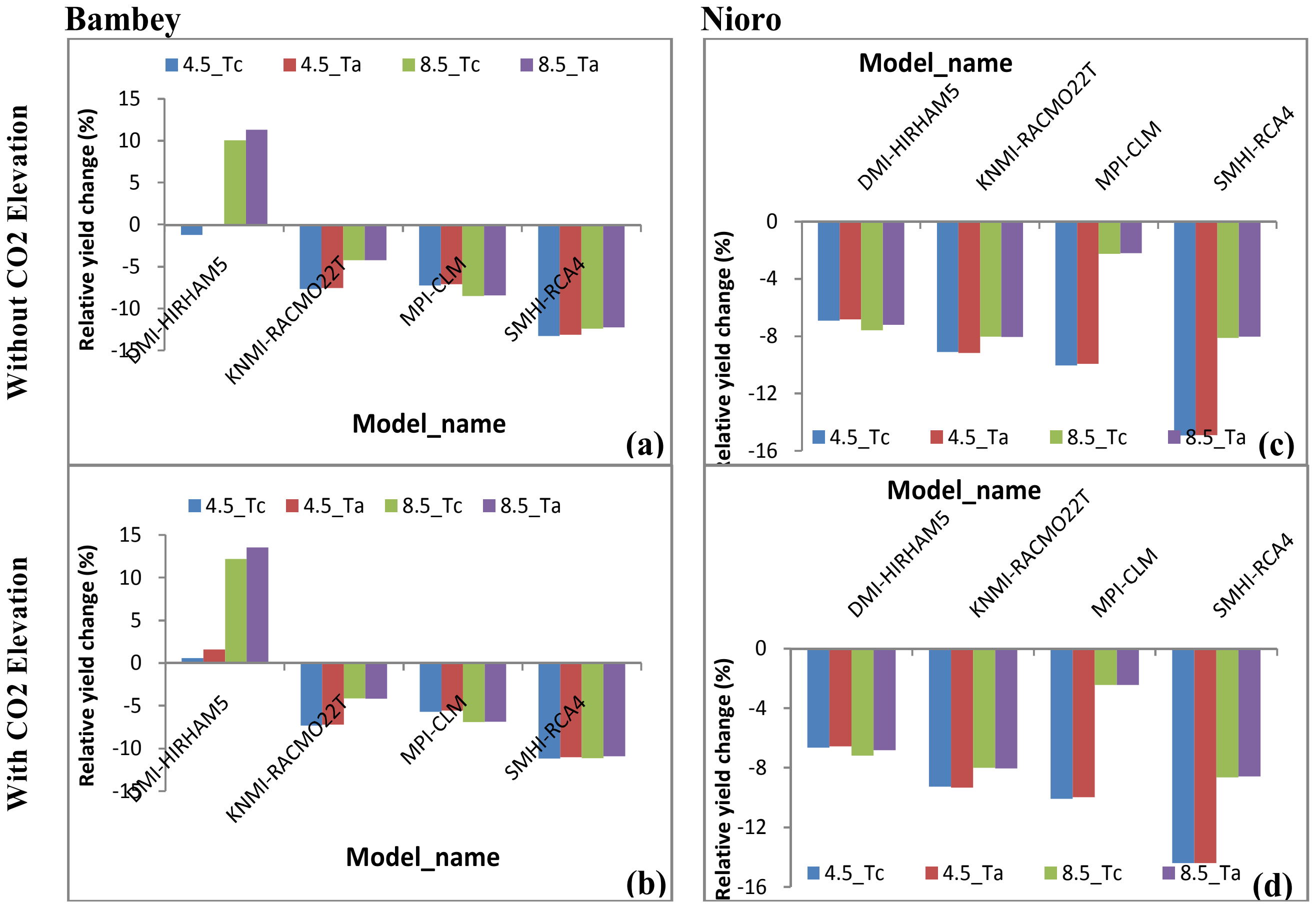

Figure 33: Relative seeds yield change according to the sowing date

Bambey (difference between current sowing date: 08/06/year and change sowing date 07/15/year) and Nioro (difference between current sowing date:07/16/year and change sowing date 07/01/year) for four RCMs for the RCP4.5 (4.5) and RCP8.5 (8.5) scenarios, yield with canopy temperature (Tc), yield with air temperature (Ta), in no CO_2 elevation and CO_2 elevation in rainy season under no irrigation condition

CHAPTER FIVE

DISCUSSION

Soils properties

Data analysis showed low content of organic carbon in Bambey in the top 50cm which could be attributed to the low contain of cro residues and the high level of soil degradation which was already shown by (Diouf, 2000). While in Nioro the higher value of organic carbon could be explained by the effect of soil residues because of fallowing. The low content of organic carbon, in Bambey is associated also to a low clay contain (5.65 %) which explains the low cation-exchange capacity (CEC). The higher percentage of sand in Bambey explained the low capacity of soil to retain water. In contrast, in Nioro the medium clay contain (10.1%) in the top soil explained the higher values of CEC.

The low pH value recorded in both sites explained the low amount of base cations due to leaching. The low values of pH were reported by (Sarr et al., 1999) for the soil in Bambey. The low total soil nitrogen content (0.02%) in Bambey was as a result of the low soil organic matter (SOC), which was due to the lack of crop residues. The phosphorus content was high in both sites. It could be attributed in Bambey 2014 to the phosphorus uptake by the previous millet crop in rainy season 2013 and previous maize crop in rainy season 2014 in Nioro 2015 which values were above the threshold of phosphorus deficiencies (Diouf, 2000).

Effect of water stress on peanut development, growth and yield

The decline in peanut production through recent decades (DAPSA., 2014) was mostly explained by lack of input, soil degradation and limited water availability (Montfort, 2005).

The two varieties grown during the field experiments are drought tolerant and they are part of the high yielding varieties mostly grown in the country.

The substantial reduction of biomass yield, pod yield and seed yield were recorded in all the stress induction treatments in two different reproductive stages of the growth of peanut. Drought stress is known to substantially reduce peanut yield when it occurred at a reproductive stage (Annerose, 1990; Cecilia, Ayman, Jakarat, Ian and Gerrit, 2013; Pandey, Shekh, Vadodaria and and Bhat, 2001; Reddy, Reddy, Praveen Rao and Sarma, 1996; Wright, Hubick and Farquhar, 1991; Wright and Rao, 1994; Yao, Luo and Yang, 1982). These are in agreement with results obtained by Annerose (1985) which showed that biomass and pod yield is linear according to the quantity of water received.

The yield obtained at field capacity for the two varieties showed a good production of above ground biomass, pod and seed yield with an average of 6500 kg/ha, 3500kg/ha and 2000kg/ha respectively. However, the variety Fleur11 produced more above ground biomass than the variety 73-33 in Bambey whereas the varieties 73-33 produced a quantity of above ground biomass greater than Fleur 11 in Nioro. It could be explained by the fact that the Fleur 11, which is early maturing, adapted more in Bambey than in Nioro.

However, under rainfed condition, these differences could be attributed to the higher amount of water received in Nioro than in Bambey which allow medium cycle varieties (73-33) to complete their growth.

In dry season under irrigation, the highest biomass yield was observed at the full irrigation treatments followed by first stress treatments and then the second stress treatments in Bambey. In Nioro, biomass yield was also higher in full irrigation treatments followed by the first stress application with a slight difference between the two stressors. The difference was attributed to the duration of stress on plants which was longer in Bambey (25days) than in Nioro (20days).

Pod yield and seed yield observed are also lowest when stress was imposed at maturation stage than at flowering stage with a reduction of seed yield by 50% and 33% (Figure 14.a.b.c) respectively. These differences might have occurred due to the fact that after re-watering plants during the first stress, peanut still produced flower and was able to recover and produce yield. Similar observations were reported for Bambara groundnut in Botswana by (Vurayai, Emongor and Moseki, 2011). The amount of yield losses is a function of number of days stress was imposed and the period of stress application.

Vaghasia, Jadav, Jivani and Kachhadiya (2010) established that the stress at flowering stage (25-47 days after sowing) and pod development stage (50-72 days after sowing) gave 18.45% and 30.63% reduction in pod yield than no water stress treatment, respectively. In irrigation deficit, seed yield decreased by 28% at late vegetative and early flowering, by 36% at late flowering and early pegging, and by 41% at pegging and pod formation growth stages, compared with full irrigation treatment (Kheira, 2009). The reduction of yield for peanut due to water stress is known to occur during the pod filling stage (Rao, Narasimha and Umamaheswara, 1974; Vaghasia et al., 2010; Vurayai et al., 2011) which was confirmed in this study at both sites and both varieties. However, the water stress management can depend on the variety cycle. In this study the reduction of the pod and seed yield is less with Fleur 11 variety than the 73-33 variety. It can be explained by the fact that the Fleur11 variety achieved the physiological maturity faster than the 73-33 variety and therefore, water deficit reduced pod and seed yield by causing smaller and younger pods to terminate the growth and eventually by reducing the growth rate of old pod. These results corroborated that reported by Rao et al. (1985) in their study in India.

The stress induction on the flowering stage and the pod filling stage was justified by the fact that peanut was most sensitive for these periods to water stress (Billaz and Ochs, 1961; Black, Tang, Ong, Solon and Simmonds, 1985; Nageswara Rao, Singh, Sivakumar, Srivastava and Williams, 1985; Patel and Golakiya, 1991; Reddy, Reddy and Anbumozhi, 2003; Stirling et al., 1989) where the greatest reduction in kernel yield occurred when stress was imposed during the seed filling phase.

Most of the flowers did not form pegs during the stress at the flowering period (30-45 days after sowing) but flowers produced after re-watering compensated for this loss (Gowda and Hegde, 1986). It confirms the greater yield obtained during the flowering period compared to the yield obtained during the maturity period in the experimental sites under irrigated conditions.

It is observed a slight of increased above ground biomass, pod and seed yield when fertilizer was applied but no significant difference was observed between fertilizer levels application. There was also no significant interaction between fertilizer and irrigation. The lowest difference may be explained by the lowest quantity of NPK applied which contained 9kg/ha of nitrogen 14 kg/ha of phosphorus and 9kg/ha of potassium.

The effect of fertilizer application rate is discussed in detail in the following paragraph with main datasets under rainfed condition.

Peanut response to NPK fertilizer was studied in Nioro during the dry season 2014 and in Bambey, Nioro and Sinthiou Malem during the rainy season 2014. In Sinthiou Malem, low harvest yield could be attributed to the dry spell that occurred earlier in October when plants were at maturity stage (seed filling) while in Bambey the low harvest could be explained by the low quantity of water received during the rainy season 2014 (407mm).

There were no significant fertilizer responses at all sites. However, the plot with fertilizer application resulted in the greatest biomass yield, pod yield and seed yield. These results showed that the quantity of fertilizer used was not in the optimum dose to determine a difference between fertilizer level on one hand and on other hand, the initial soil properties contained considerable quantity of nutrients. This may be because the experiments were conducted at field research stations which receive ample amount of fertilizer. However, the quantity of nitrogen used was sufficient (9kg/ha) because of the capacity of peanut to fix nitrogen. Campbell et al. (1980) showed that there was no significant difference in kernel yield from plots that received 10, 50 and

100kg/ha of nitrogen, therefore, it is an economic disadvantage to increase N levels beyond 10kg/h. In addition, organic amendments increased microbial population and resulted in a positive correlation between population of symbiotic bacteria and nitrogen fixation. Similar observations were reported by (Lee, Park, Kim, Shim, Chae et al., 2004; Limtong and Piriyaprin, 2006). This could also be explained by the higher nitrogen contain in Bambey and Nioro which received 5750 kg/ha of cow manure incorporated in the soil before sowing in the year 2014.

The quantity of phosphorus used was too low to give a response on peanut growth where the appropriate application rate for peanut is 60 kg P_2O_5/ha for poor alluvial soils and 90 kg P_2O_5/ha for sandy soils (Ha, 2003; Mirvat, Magda and Tawfik, 2006; Ogeh and Oyibo, 2015). Naab et al. (2009) demonstrated positive effects of phosphorus application from 30kg/ha on biomass and seed yield but no difference was found between 30kgP/ha and 60kgP/ha application and between 60kgP/ha and 90kgP/ha application on farm experiments in Ghana.

Modelling heat and drought stress on peanut

Simulated heat stress during the dry season was the result of the average maximum air temperature which was always greater than 38°C. Crop temperatures above 35°C are known to significantly reduce total dry matter production and the partitioning of dry matter to pods and seeds (Prasad, 1999). The greatest sensitivity to hot days (38°C) occurred from 6 days before to 15 days after flowering (Prasad, Craufurd, Summerfield and Wheeler, 1998). It explained the yield reduction recorded with air temperature during the dry season. Some scholars Singh et al. (2014) demonstrated that high temperatures affect growth and development of crops, thus influencing potential yields in West Africa.

In the rainy season, yield decline mostly affected this area by drought stress due to the early cessation of rainfall. Data presented in Figure17 (k, l). showed a low above ground biomass (<500g/m^2) and seed yield (<100g/m^2) in Bambey which were related to the late start and early cessation of rainfall during the rainy season 2014. In most cases in this area, long dry spells during the rainy season (e.g. early in the season, at flowering period and later during the seed filling) caused a decrease in peanut seed yields, irrespective at the fertilizer rate and density of sowing (Salack, Muller, Gaye, Hourdin and Cisse, 2012a). However, in Nioro the dry spell during the early season was compensated by irrigation which was to the benefit of the plant. High above ground biomass (>500g/m^2) and seed yield (>150g/m^2) for both varieties and for all the treatment were observed in this site during the rainy season.

During the rainy season maximum air temperature was almost less than 35°C. This was due to fact that, the cooling of the atmosphere is related to high evaporative cooling and decrease of sensible heat (Jain and Tiwari, 2002). However, heat stress is still possible under these conditions if the soil is dry and the plant has low transpiration rate in which case the plant can heat up as much as 6°C above the air temperature (Siebert et al., 2014).

In the dry season, peanut grew under irrigated conditions and yield reductions were mainly due to high temperatures. In this area the projected climate changes in the near future will further intensify the problems of heat and drought stress on peanut, thus further limiting its production potential (Singh et al., 2014).

The effects observed under heat stress conditions for AGB, LAI and seed yield were strongly related to combined heat and water stress. The effect of drought stress is known to reduce substantially above ground biomass (Annerose, 1990), pod and kernel yield (Cecilia et al., 2013; Wright et al., 1991; Yao et al., 1982). Meanwhile, many studies have shown the negative effect of higher temperature on reducing flower production and fruit-set on peanut (Prasad et al., 1999b; Prasad et al., 2001), and reduction of seed yield (Prasad, Boote, Hartwell and Thomas, 2003).

In this study, the model simulated an interaction between heat stress and water availability. Previous studies have shown that there are strong interactions between heat and drought stress (Siebert et al., 2014) due to the cooling effect of transpiring leaves. Pinto and Reynolds (2015) showed that heat and drought are both challenging targets separately, and are expected to increasingly occur together. Low biomass and seed yield recorded in both sites (Figure 19) could be explained by the simultaneous effect of drought and heat stress. The combined effect of drought and heat stress was clearly reducing peanut yield but how a single stress affected this reduction of yield need more investigation. Moreover, drought and heat represent two related but distinct constraints on grain production (Lobell, Hammer, Chenu, Zheng, McLean et al., 2015). Furthermore, Kaushal, Bhandari, Siddique, Nayyar and Tejada Moral (2016) has demonstrated with wheat that drought and heat stress in combination have more detrimental effects on plant growth and development as observed at grain filling.

The seed yield simulated with canopy temperature were compared to the seed yield simulated using air temperature. The yields simulated with canopy temperature were always higher than the yield simulated with air temperature under heat stress condition. The result could be attributed to the fact that in under irrigated conditions in hot and arid conditions, plants experience substantial cooling of up to 10°C (Kimball, White, Ottman, Wall, Bernacchi et al., 2015; Webber et al., 2016). Therefore, if canopy temperature is not considered, heat stress effects will be greatly overestimated, as the air will be hotter than the crop. This results has previously been demonstrated for wheat (Webber et al., 2016) where it was suggested to used Tc rather than Ta in simulating heat stress.

SIMPLACE crop model was able to simulate biomass and leaf area index as observed in Figure 20. However, the model performance was better for biomass than LAI which could be explained by the difficulty for calibrating and validating LAI on peanut which is also related to the leaf defoliation and percentage of leaf area diseased that is not simulated by the model. The model performance on seed yield showed good agreement between observed and simulated data when yield was simulated in no heat stress condition and on heat stress condition with canopy temperature (Figure 21.a.b.d.e). While low performance in heat stress condition with air temperature could be attributed to uncertainties of model to take into account the effect of heat on simulated yield. Recent studies have demonstrated that for accurate evaluation of the heat stress on crop, canopy temperature should be used to reduce uncertainty in assessing heat stress impact (Rezaei et al., 2015; Siebert et al., 2014), rather than to air temperature, (Webber et al., 2016; Webber, Martre, Asseng, Kimball, White et al., 2015a).

Climate change impact analysis

Bias correction of precipitation and temperature

The investigated sites are likely to experience a decrease in precipitation in coming decades (Figure 23.a and 24.c). However, the climate change signal is not identical for all models; while some of them project an increase of precipitation, others exhibit a decrease (Figure 25). The divergence of the climate change signal is mainly due to the difference of the RCMs physical parameterizations and the boundaries conditions. The effects of the radiative-forcing scenarios used will have more impacts on the long term future. By contrast, the near future will be more affected by the natural variability of the climate (Mbaye, 2015). These mean that in climate change impact analysis, the change of precipitation depends on the RCMs used and also the considered time slices. The decrease of precipitation might be due to a reinforcement of the warm and dry air advection from the Sahara that reduces convection which brings precipitation (Mbaye et al., 2015). In addition, lower evaporative cooling and cloudiness as a result of drier conditions and large warming (Diallo, Sylla, Giorgi, Gaye and Camara, 2012) also accounted for the decrease in precipitation.

Moreover, the climate change signal for temperature is clear (Figure 23.b and 24.d). The four RCMs projected an increase in temperature from 1°C for RCP4.5 to 1.2°C for RCP8.5 at both sites (Figure 26.b.d) regarding the condition considered. The effect on increase in temperature was mainly attributed to increase in greenhouse gases emissions due to human activities.

The future precipitation and temperature series used in the model to assess the impact of climate change were conducted through the delta change method approach. The correction of RCMs output minimized the gap between models simulation and observed data. (Figure 25.b.d)

Impact of climate change on peanut

Biomass yield

Changes in precipitation and temperature are the two major climate parameters that affect crop yield. At both sites decrease in biomass and seed yield for the two RCPs could be attributed to decrease in rainfall associated with an increase in temperature under ambient current CO_2 concentration. However, temperature rise will likely be accompanied by an increase in atmospheric carbon dioxide concentration CO_2. C3 plants such as peanut are more responsive to increased CO_2 levels than C4 plants. Elevated CO_2 from 369ppm to 439ppm for RCP4.5 and 469ppm for RCP8.5 increased relative changes in biomass yield in both seasons and at both sites with four RCMs. These observations are supported by the findings of Bannayan, Soler, Guerra and Hoogenboom (2009); (Heinemann, de HN Maia, Dourado-Neto, Ingram and Hoogenboom, 2006; Kim, Lieffering, Kobayashi, Okada and Miura, 2003) which found an increase in biomass yield on crop in increased CO_2 concentration. The greater positive effect was found during the rainy season than the dry season and Bambey recorded maximum value up to 12% for

RCP4.5 to 16% for RCP8.5 (Figure 28) for MPI-CLM model. In Nioro it was found a maximum value of 14% for RCP8.5 in rainy season and 9% for RCP4.5 in dry season. The results showed that an increase in CO_2 is expressed by an increase in peanut biomass yield. This increase of biomass could be explained by correction of radiation use efficiency (RUE) as a function of atmospheric CO_2 concentration setup to 1.11 when CO_2 increases from 369ppm to 469ppm Moreover, the positive effect of increased CO_2 was influenced by the variation of temperature which gave less yield where temperature increased. In soybean Heinemann et al. (2006) found that for aboveground biomass, an increase in the CO_2 level caused a more vigorous growth at lower temperatures.

The negative effect on biomass change in yield at both sites was more pronounced in the rainy season than the dry season than. Thus, in the dry season, the negative effect of increase temperature was compensated by the positive effect of increased CO_2 and irrigation (Figure 27 .a. c). High biomass yield during the rainy season was as a result of the application of irrigation combined with an increase of CO_2. While in no irrigation condition, low increase in biomass only resulted in the effect of increased CO_2.

Seed yield

Increased temperature had negative effect on seed yield which was expressed by the reduction of seed yield, usually explained by a reduced seed number (Ketring, 1984; Prasad et al., 1998). However, SIMPLACE is not explicitly simulating seed number.

It was found that the relative change in yield was strongly related to the intensity of the warming. In the Sahel where peanut is mostly grown at temperature above optimum (>35°C), elevated CO_2 could possibly have negative effects on yield as the reduced stomatal conductance may lead to high plant temperatures despite greater photosynthesis and vegetative growth. This is not explicitly modelled in the current version of SIMPLACE but should be considered in future assessments, since it could be important in the consideration of the effects of heat stress.

High temperature will increase water losses through evaporation which will reduce soil moisture and this may have negative effects on potential yield. Sultan et al. (2013) showed that high temperature cannot be counteracted by any rainfall change when warming exceeds +2°C. An increase in temperature without CO_2 elevation, shortens the length of the growing season and increases the vulnerability of peanut on heat and drought stress.

During the dry season where maximum mean temperature was above 35°C, relative change in yield with canopy temperature was always more positive than the relative change in yield with air temperature (Figure 30). In contrast, during the rainy season where maximum mean temperature was below 35°C, the relative yield change with canopy temperature was almost equal to the relative yield with air temperature (Figure 31 and 32). This was because under drought conditions, the plant might actually be hotter than the air.

These results were supported in many studies which suggested the use of canopy temperature instead of air temperature in modelling studies to account uncertainty in assessing the impacts of heat (Rezaei et al., 2015; Siebert et al., 2014; Webber et al., 2015a).

In irrigation conditions with current ambient CO_2, climate change will have negative impact on seed yield whereas, in elevated CO_2, the impact will be positive when considering canopy temperature and negative when considering air temperature because of the higher temperature greater than the optimum peanut required.

In rainfed conditions a positive effects on seed yield was recorded in CO_2 elevation at both sites whatever temperature considered with and without irrigation. These results corroborated the positive effect of CO_2 in optimum temperature. Burkey et al. (2007) showed that, elevated CO_2 had a positive effect on yield parameters in general.

Testing new sowing date and new short varieties

To deal with climate change adaptation, most of the studies were widely based on modelling technologies (Crane, Roncoli and Hoogenboom, 2011). In this study, two adaptation strategies were investigated (i) new sowing dates and (ii) varieties with new cycle length. It was found that under climate change conditions, shifting the sowing date 15 days earlier negatively affected the relative yield change at both sites and for all RCMs independently of CO_2 variation except DMI-HIRHAM5 which predicted positive effect in Bambey. For legumes it was found that sowing date was an important factor influencing soybean (Egli and Bruening, 1992). This negative effect on yield of early sowing date can be explained by the shifting rainy season with a late start or by dry spell in the beginning of the season.

Therefore, future studies should investigate a larger range of sowing dates.

Table 15: Relative yield change in Bambey and Nioro with new variety

Model_Name	CO_2	Bambey				Nioro			
		Canopy temperature		Air temperature		Canopy temperature		Air temperature	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
DMI-HIRHAM5	369	9.5	11.6	9.3	11.5	-6	-4.1	-5.8	-3.8
KNMI-RACMO22T	369	2.8	7.5	2.8	7.4	-5.3	-3	-5.3	-3
MPI-CLM	369	13	9.7	13	9.6	-8.2	-12.9	-8.2	-12.9
SMHI-RCA4	369	9.6	6.1	8.8	5.3	-5.6	-4.1	-5.6	-4
DMI-HIRHAM5	439 or 469	37.7	39.6	37.4	39.4	18.1	20.2	18.3	20.7
KNMI-RACMO22T	439 or 469	31.8	37.5	31.7	37.3	21.5	24.3	21.5	24.3
MPI-CLM	439 or 469	43.2	39.6	43.5	39.5	17.1	10.8	17.1	10.7
SMHI-RCA4	439 or 469	40.3	35.2	39.2	34.1	20.8	22.2	20.8	22.3

The relative changes in yield between the new variety of 85 days to the standard variety of 90 days showed an increase in Bambey in both CO_2 conditions, while in Nioro it showed a decrease in ambient current CO_2 and an increase in elevated CO_2 compared to the standard variety. These results were obtained by changing the thermal time from anthesis to maturity. The study also revealed that the short varieties adapted more in Bambey than in Nioro. This can be explained by the fact that the length of the rainy season is shortened in Bambey than in Nioro. Therefore, a variation of relative change yield (Table15) will be more effective in term of shortening the cycle of crop.

CHAPTER SIX

CONCLUSIONS AND OUTLOOKS

Conclusions

Given the importance of peanut production to the economy of Senegal and the role of agriculture in providing livelihoods to a large part of the national population, ensuring its increased productivity under climate change is a priority. This study combined experimental trials, model evaluation and climate change scenario analysis to firstly understand potential climate change impacts on peanut yield and further investigate potential adaptations. This chapter presents the conclusions that were arrived at in line with results.

- In the field experiments carried out in three different agroclimatic zones in Senegal, results of assessing the effect of water stress on peanut and the fertilizer response indicated that the reduction of peanut yield was highly associated to water stress than to fertilizer application for the range of conditions considered. Therefore, addressing the issues of water stress is pivotal in increasing the yield of peanuts as opposed to fertilizer application. Furthermore, the quantity of fertilizer applied was insufficient to show a difference between the fertilizer levels and the interaction between irrigation and fertilizer during the two growth seasons. Thus, adequate fertilizer application at the right dose and time could influence the performance of the peanut.
- This study presents the first use of SIMPLACE<Lintul5,DRUNIR,CanopyT ,HourlyHeat>for peanut. The model framework was selected to allow

flexibility in simulating the effects of elevated CO_2, heat and drought stress as well as the interaction between water status and high temperatures. As a result, it is possible to understand how the different climatic factors individually and in combination are likely to affect peanut growth. It was validated successfully in tropical zone in Senegal. The model showed good agreement with observed data for above ground biomass, leaf area index and seed yield under no drought and no heat stress conditions for peanut in Senegal. However, the model overestimated seed yield when water stress occurred at seed filling but performed perfectly when the latter occurred at flowering period. The adoption of the Monin-Obukhov Similarity Theory method for calculation of canopy temperature used in the model was beneficial for the simulation of the seed yield when heat stress occurred. It was shown that the model performed much better when using canopy temperature than air temperature for the simulation of seed yield. Despite that fact, this is the only model currently applied in the region to consider joint heat and drought stress which could be improved in a number of aspects for future studies. Such areas of consideration should include taking into account the effect of elevated CO_2 on reducing stomatal conductance and therefore possibly increasing heat stress. Further, the model has not been applied before with an indeterminate crop and as such, it needs improvement to account for water stress during late seed filling. Finally, canopy temperature measurements in the field are needed to further improve the model for other crops and differentiate between varieties.

- The potential impact of climate change on peanut in Senegal was assessed using the process-based crop model, SIMPLACE<Lintul5,DRUNIR, CanopyT,HourlyHeat>. Bias corrected climate simulations from four RCMs demonstrate that climate change may positively affect peanut yield due to elevated CO_2 both in Bambey and Nioro under both irrigated and rainfed conditions. The negative impact of climate change was greater in the rainy season than the dry season for biomass yield. While, the negative effect of relative changes in seed yield was higher in dry season than in rainy season at both sites.
- Results indicated that the elevated CO_2 associated with climate change is likely to positively impact peanut yields at both locations. However, interactions between heat stress, drought and elevated CO_2 are still highly uncertain and need consideration in modelling assessments. Further to that, the adaptation strategies, including irrigation, under climate change conditions in the region showed a positive response to higher CO_2 in short varieties in Nioro and in Bambey. While the current sowing dates in both sites are suggested as sowing date in future climate change.

Outlooks

Based on the findings of the study, the following recommendations are offered:

- The response of fertilizer in the three sites did not significantly different between fertilizer levels when fertilizer is applied just after sowing. Therefore, further investigations have to be made to test higher single dose of nitrogen or phosphorus in split applications. After successful results are obtained, in an ideal field based situation they can be evaluated under limited water conditions. This investigation could further be conducted in field based conditions where limited soil nutrients occur.
- Further research on SIMPLACE<Lintul5,DRUNIR,CanopyT, HourlyHeat> crop model parameterization for more soils details inputs such us soil type, pH, soil holding, soil residues, soil organic carbon which have an influence on crop development and growth are useful to better improve the model on simulating yield for different soil improvement and conservation strategies. Furthermore, output data on pod yield, pod number and seed number could be simulated to improve heat stress assessments.
- The research presented in this study has focused on the evaluation of canopy temperature versus air temperature to account for the interaction of heat stress and crop water status. However, no canopy temperature observations were available. Further studies have already indicated that canopy temperature should be used instead of air temperature to

accurately account for heat stress impacts yield. However, little evidence of this exists in environmental or production conditions similar to Senegal. Given the potential negative impacts of heat stress under drought conditions, further evaluation of the canopy temperature simulations with observations is seen as critical.

- Datasets with controlled heating in tropical zones for understanding the mechanisms of crop heat stress in general, and specifically for calibration of heat responses are important for model development. Therefore, experiments are now needed to identify the effects and model parameters (e.g. maximum daily air temperature and sensitive period) of heat stress.
- This research shows a positive impact of climate change on peanut yield in Senegal for the scenario period. However, further investigation on the interaction between temperature, rainfall and CO_2 variation need to be establish in future firstly in controlled environments and secondly in farming system conditions, as elevated CO_2 is likely to cause plants to experience more heat stress.

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APPENDICES

Appendix 1: *Anova for final biomass yield between Bambey and Nioro for the dry season 2015*

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	
Variety	1	9006201	9006201	9.169	0.00341	**
Fertilizer	1	1256208	1256208	1.279	0.26184	
Irrigation	2	135581676	67790838	69.019	< 2e-16	***
Site	1	8584792	8584792	8.74	4.21E-03	**
Variety:Fertilizer	1	526263	526263	0.536	0.46656	
Variety:Irrigation	2	1493782	746891	0.76	0.47119	
Fertilizer:Irrigation	2	1553950	776975	0.791	0.45727	
Variety:Site	1	5154473	5154473	5.248	0.0249	*
Fertilzer:Site	1	1869507	1869507	1.903	0.17197	
Irrigation:Site	2	25136656	12568328	12.796	1.76E-05	***
Var:Fert:Irri	2	109224	54612	0.056	0.94596	
Var:Fert:Site	1	1515597	1515597	1.543	0.21819	
Var:Irri:Site	2	834412	417206	0.425	0.65555	
Fert:Irri:Site	2	1710738	855369	0.871	0.42295	
Var:Fert:Irri:Site	2	44165	22083	0.022	0.97777	
Residuals	72	70718621	982203			

Appendix 2: *Anova for seed yield between Bambey and Nioro for dry season 2015*

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Variety	1	6095	6095	0.072	0.788734
Fertilizer	1	67501	67501	0.801	0.373759
Irrigation	2	37728097	18864049	223.866	< 2e-16 ***
Site	1	1007315	1007315	11.954	0.000919 ***
Variety:Fertilizer	1	3925	3925	0.047	0.82973
Variety:Irrigation	2	87740	43870	0.521	0.596372
Fertilizer:Irrigation	2	17375	8688	0.103	0.90217
Variety:Site	1	26424	26424	0.314	0.577228
Fertilzer:Site	1	46463	46463	0.551	0.460163
Irrigation:Site	2	562212	281106	3.336	0.041157 *
Var:Fert:Irri	2	6295	3148	0.037	0.963353
Var:Fert:Site	1	16948	16948	0.201	0.655155
Var:Irri:Site	2	3552	1776	0.021	0.97915
Fert:Irri:Site	2	102179	51090	0.606	0.548126
Var:Fert:Irri:Site	2	78252	39126	0.464	0.630431
Residuals	72	6067065	84265		

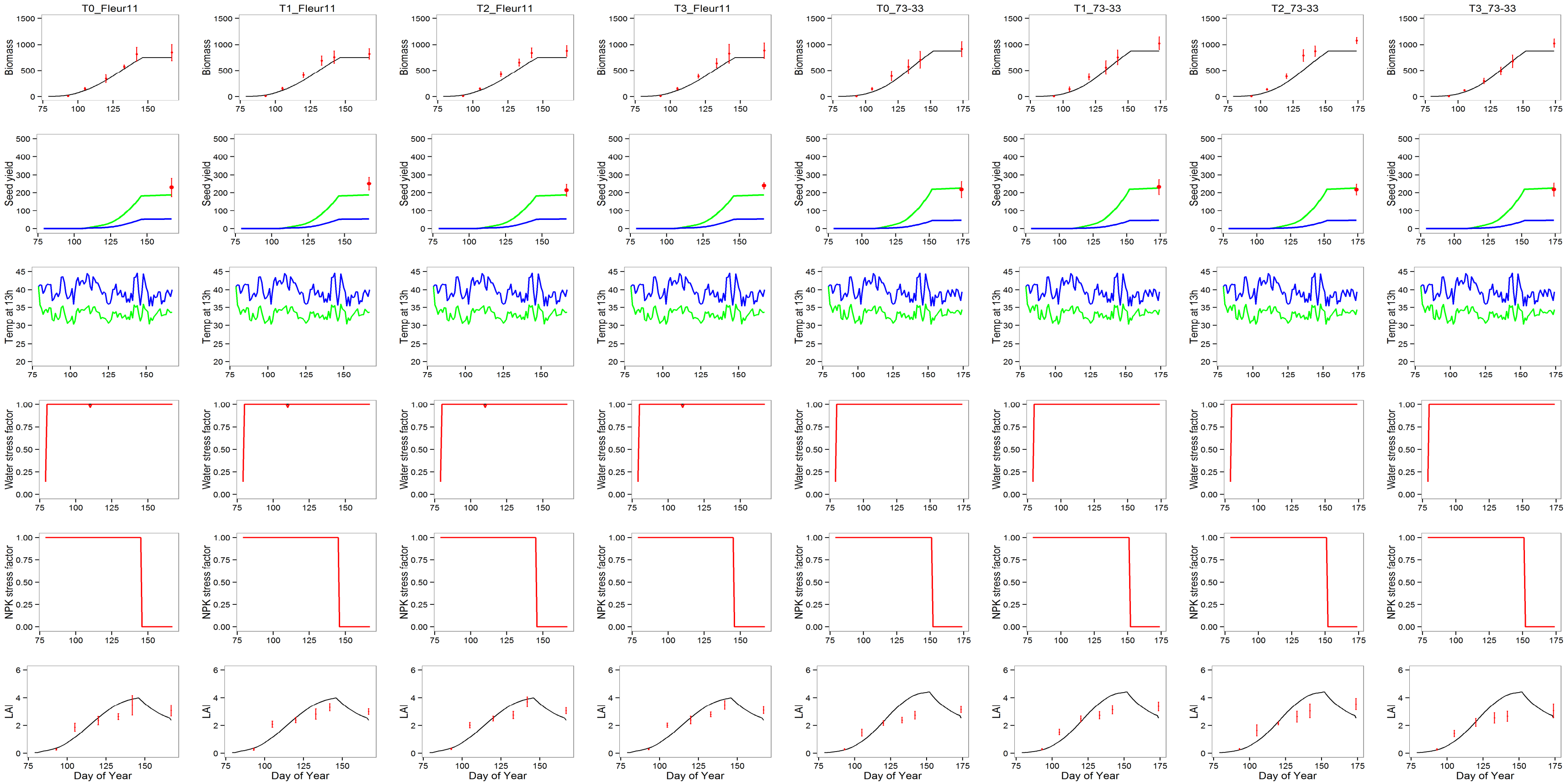
Appendix 3: *Anova for final biomass yield interaction in three different sites in rainy season*

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Variety	1	764491	764491	1.634	0.20389
Fertilizer	5	4316427	863285	1.845	0.1101
Site	2	134453126	67226563	143.68	< 2e-16***
Variety: Fertilizer	5	2590121	518024	1.107	0.36091
Variety:Site	2	5464224	2732112	5.839	0.00391**
Fertilizer:Site	10	6681037	668104	1.428	0.17767
Variety:Fertilizer:Site	10	3699469	369947	0.791	0.63768
Residuals	108	50530028	467871		

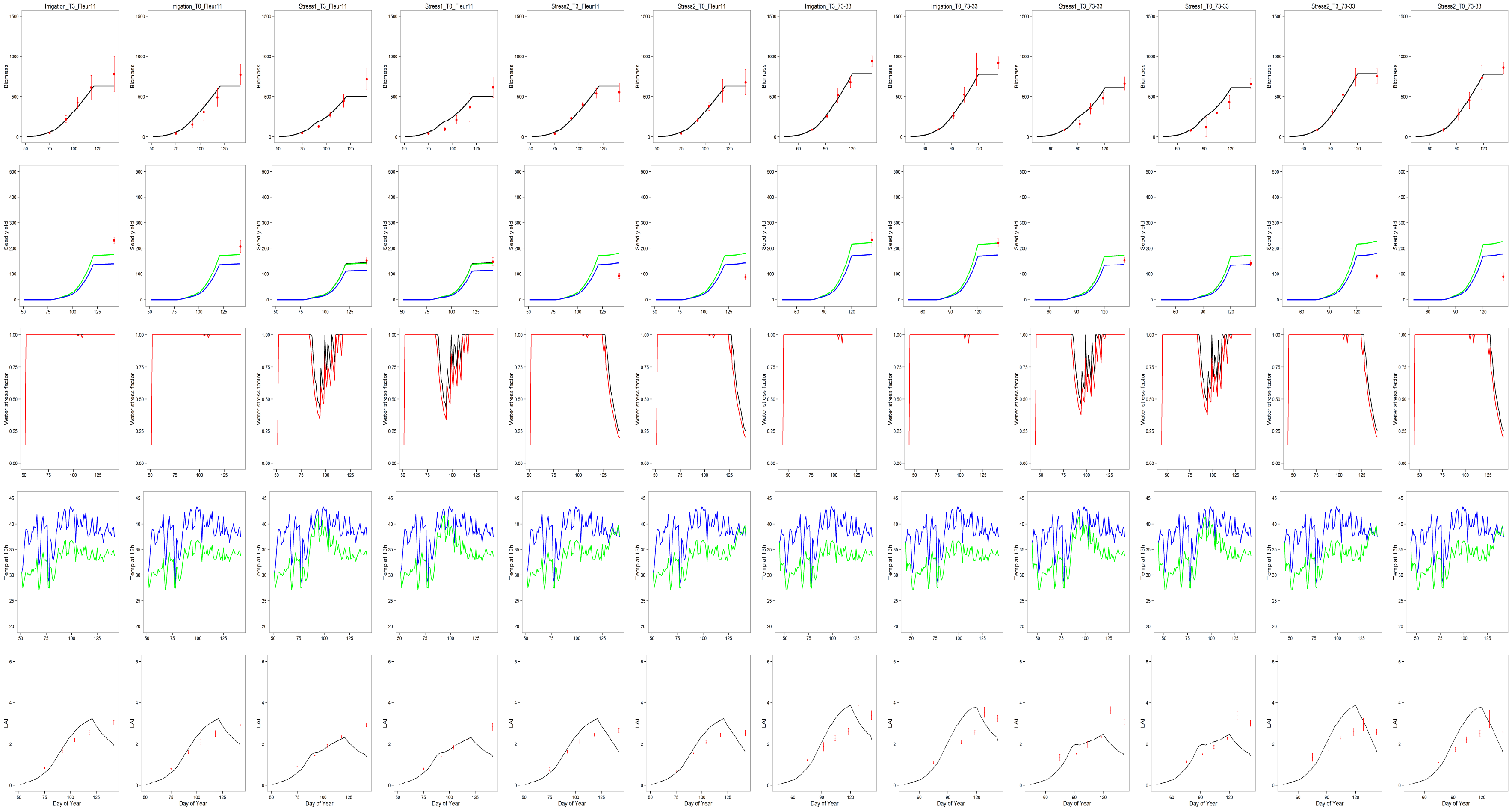
Appendix 4: *Anova for seed yield interaction in three different sites in rainy season 2014*

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Variety	1	39419	39419	0.404	0.527
Fertilizer	5	216479	43296	0.443	0.817
Site	2	27107482	13553741	138.823	< 2e-16 ***
Variety: Fertilizer	5	526490	105298	1.079	0.376
Variety: Site	2	2686364	1343182	13.757	4.76e-06 ***
Fertilizer: Site	10	1431817	143182	1.467	0.162
Var: Ferti: Site	10	999769	99977	1.024	0.428
Residuals	108	10544388	97633		

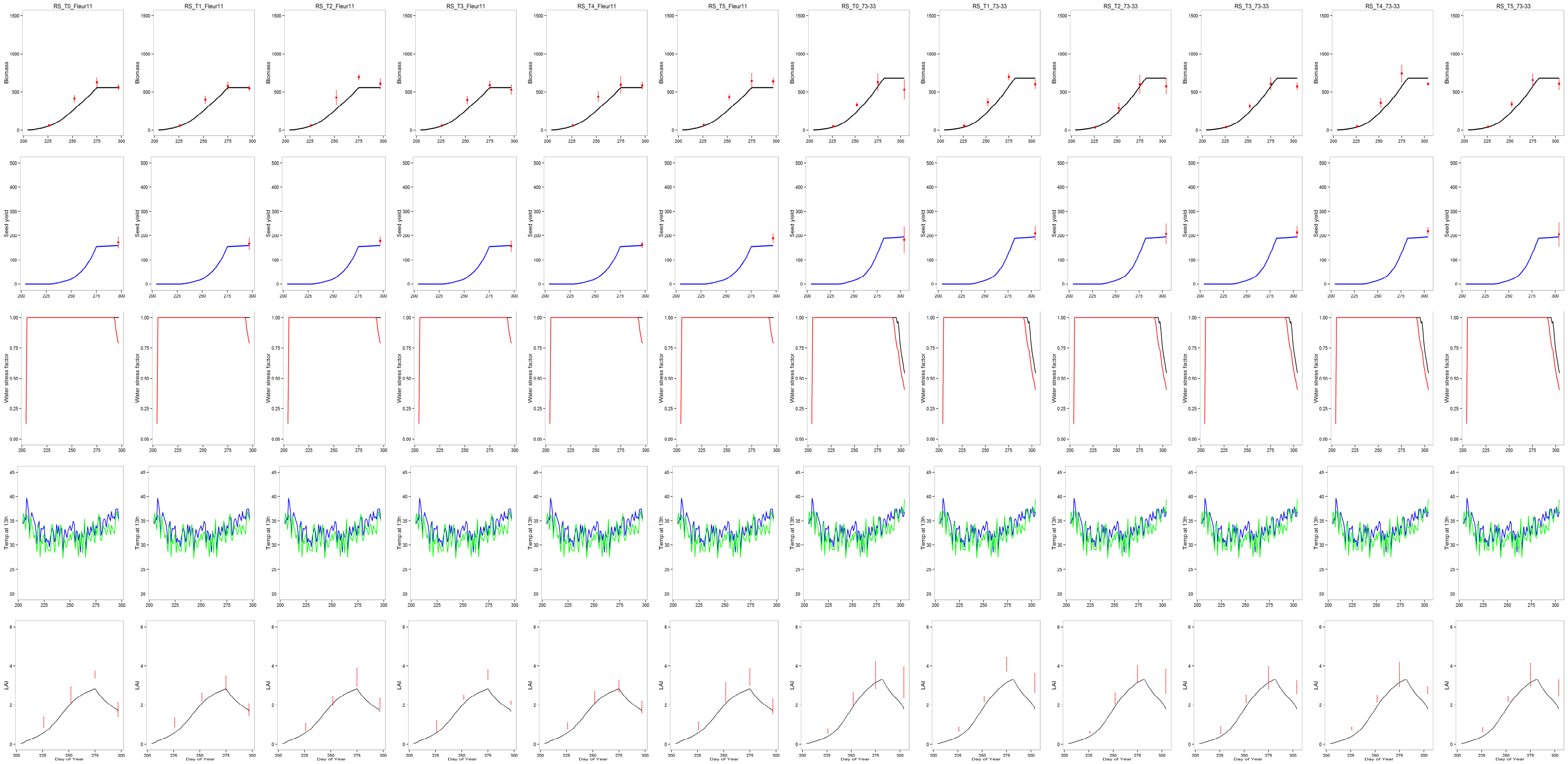
Appendix 5: *Model calibration in heat stress and in drought conditions for all treatments Nioro dry 2014*



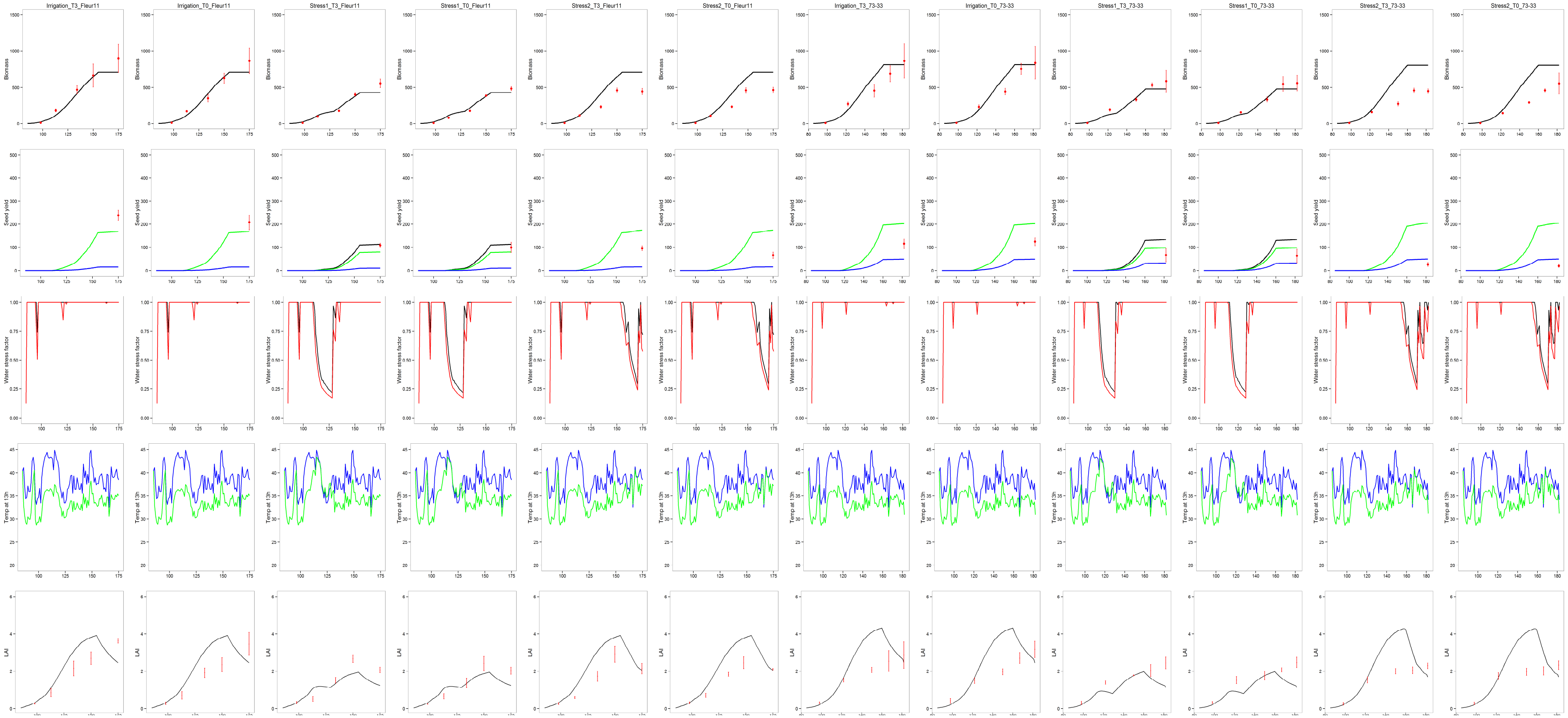
Appendix 6: *Model calibration in heat stress and in drought conditions for all treatments Nioro dry 2015*



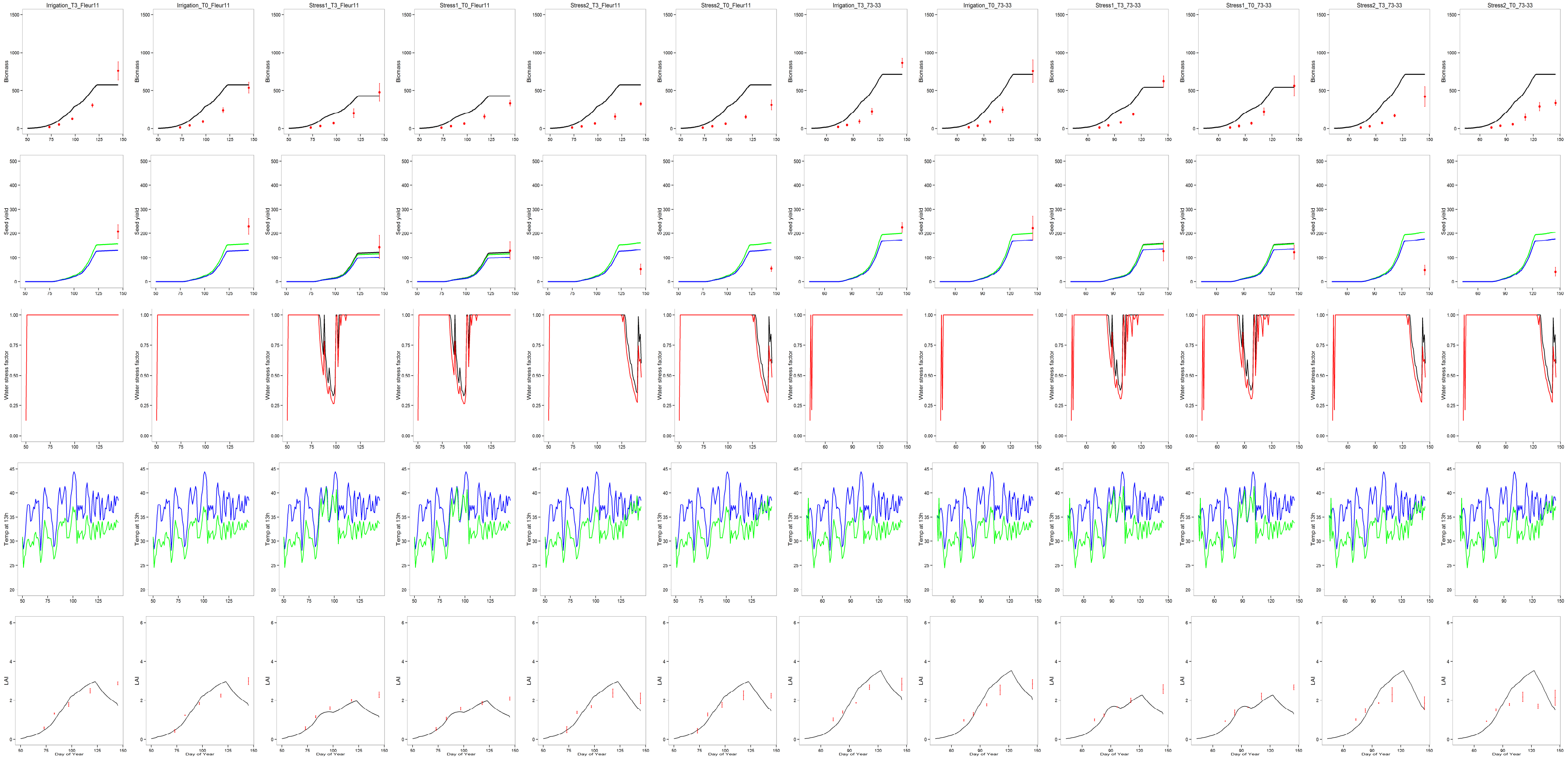
Appendix 7: *Model calibration in no heat stress and in no drought conditions for all treatments Nioro rain 2014*



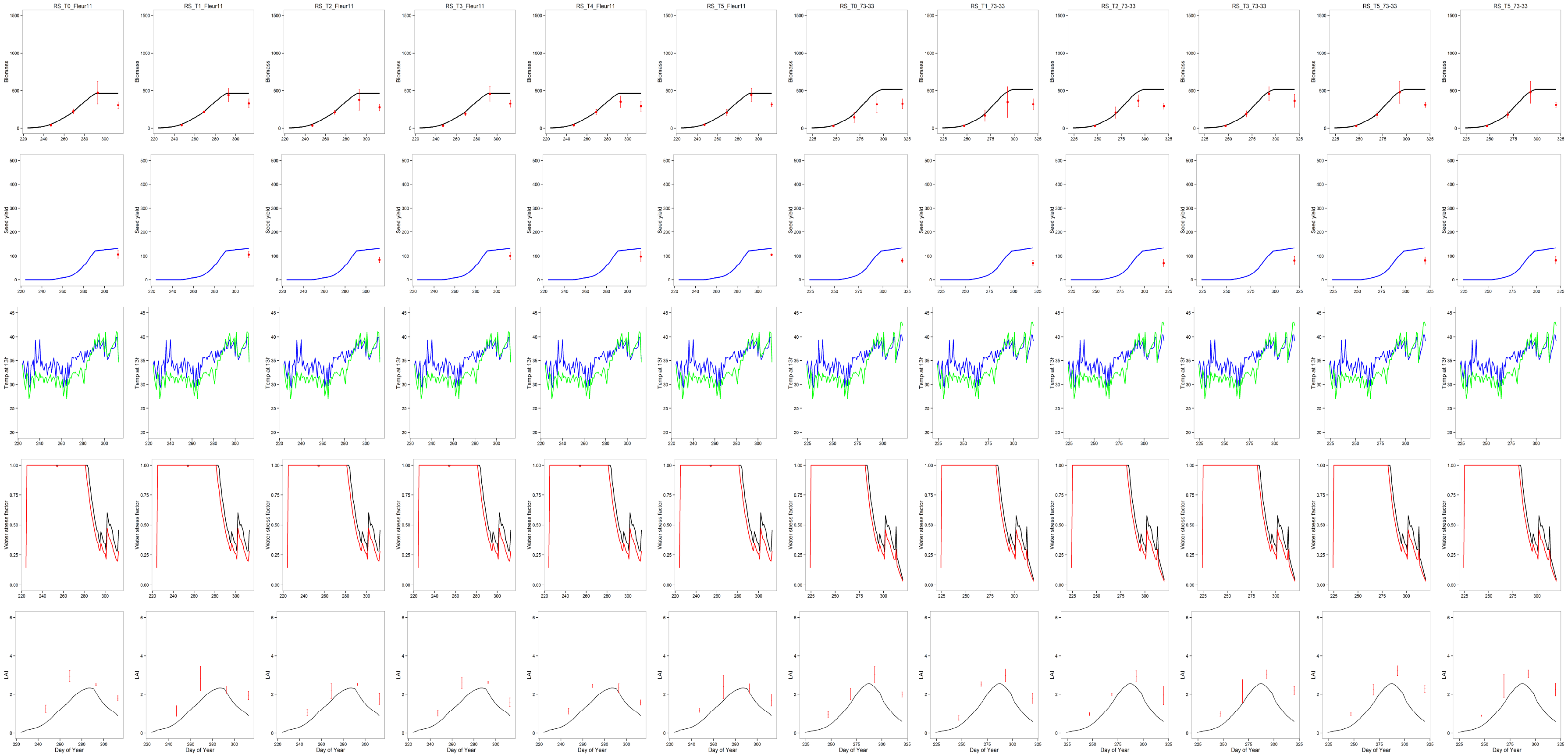
Appendix 8: *Model validation in heat stress and in drought conditions for all treatment, Bambey dry 2014*



Appendix 9: *Model validation in heat stress and in drought conditions for all treatments, Bambey dry 2015*



Appendix 10: *Model validation in no heat stress and in no drought stress condition for all treatments Bambey rain 2014*



Appendix 11: Relative yield change for Bambey

							Relative yield change RCP4.5			Relative yield change RCP 8.5		
Site	Season	Fertilizer	Variety	irrigation	CO_2	Model	Biomass _no_HS	Yield_HS _H_TCan	Yield_HS _H_Tair	Biomass _no_HS	Yield_HS _H_TCan	Yield_HS _H_Tair
Bambey	dryseason	T0	Fleur 11	1	369	DMI-HIRHAM5	-2.263	0.947	-1.612	-8.512	-5.559	-21.243
Bambey	dryseason	T0	Fleur 11	1	369	KNMI-RACMO22T	-8.187	-7.001	-18.247	-14.118	-11.982	-26.504
Bambey	dryseason	T0	Fleur 11	1	369	MPI-CLM	-9.226	-6.827	-19.324	-9.521	-8.270	-24.121
Bambey	dryseason	T0	Fleur 11	1	369	SMHI-RCA4	-11.827	-12.115	-28.340	-13.895	-14.985	-36.029
							-7.876	-6.249	-16.881	-11.512	-10.199	-26.974
Bambey	dryseason	T0	Fleur 11	1	469	DMI-HIRHAM5	10.004	12.069	9.492	8.349	9.373	-8.177
Bambey	dryseason	T0	Fleur 11	1	469	KNMI-RACMO22T	5.854	6.433	-6.401	5.347	7.039	-10.717
Bambey	dryseason	T0	Fleur 11	1	469	MPI-CLM	3.116	4.602	-9.232	8.045	7.498	-10.631
Bambey	dryseason	T0	Fleur 11	1	469	SMHI-RCA4	-0.645	-2.485	-20.097	2.087	-1.513	-25.227
							4.582	5.155	-6.560	5.957	5.599	-13.688
Bambey	rainyseason	T0	Fleur 11	1	369	DMI-HIRHAM5	-11.741	-11.621	-11.679	-10.840	-11.104	-11.223
Bambey	rainyseason	T0	Fleur 11	1	369	KNMI-RACMO22T	-17.290	-17.238	-17.298	-17.167	-16.592	-16.658
Bambey	rainyseason	T0	Fleur 11	1	369	MPI-CLM	-4.915	-5.301	-5.348	-9.631	-9.864	-9.992
Bambey	rainyseason	T0	Fleur 11	1	369	SMHI-RCA4	-13.622	-13.687	-13.741	-14.249	-12.821	-12.882
							-11.892	-11.962	-12.016	-12.972	-12.595	-12.689
Bambey	rainyseason	T0	Fleur 11	1	469	DMI-HIRHAM5	2.636	2.339	2.271	9.830	8.662	8.515
Bambey	rainyseason	T0	Fleur 11	1	469	KNMI-RACMO22T	-2.463	-1.640	-1.718	4.552	6.356	6.270
Bambey	rainyseason	T0	Fleur 11	1	469	MPI-CLM	11.929	12.207	12.146	13.715	14.518	14.352
Bambey	rainyseason	T0	Fleur 11	1	469	SMHI-RCA4	1.448	1.545	1.481	7.545	9.608	9.530
							3.387	3.613	3.545	8.910	9.786	9.667
Bambey	rainyseason	T0	Fleur 11	0	369	DMI-HIRHAM5	-8.018	-5.641	-5.677	-12.992	-13.240	-13.328
Bambey	rainyseason	T0	Fleur 11	0	369	KNMI-RACMO22T	-14.050	-13.468	-13.510	-11.607	-10.663	-10.726
Bambey	rainyseason	T0	Fleur 11	0	369	MPI-CLM	-3.972	-4.866	-4.882	-5.463	-7.359	-7.523
Bambey	rainyseason	T0	Fleur 11	0	369	SMHI-RCA4	-3.926	-1.227	-1.518	-7.914	-4.801	-4.960
							-7.491	-6.301	-6.396	-9.494	-9.016	-9.134
Bambey	rainyseason	T0	Fleur 11	0	469	DMI-HIRHAM5	6.776	9.204	9.188	6.461	5.396	5.297
Bambey	rainyseason	T0	Fleur 11	0	469	KNMI-RACMO22T	1.400	2.954	2.893	11.704	14.156	14.072
Bambey	rainyseason	T0	Fleur 11	0	469	MPI-CLM	11.404	10.645	10.620	16.999	14.946	14.737
Bambey	rainyseason	T0	Fleur 11	0	469	SMHI-RCA4	12.398	15.479	15.138	14.467	18.223	18.027
							7.995	9.570	9.459	12.408	13.180	13.033

Appendix 12: Relative yield change for Nioro

							Relative yield change RCP4.5			Relative yield change RCP 8.5		
Site	Season	Fertilizer	Variety	irrigation	CO_2	Model	Biomass _no_HS	Yield_HS _H_TCan	Yield_HS _H_Tair	Biomass _no_HS	Yield_HS _H_TCan	Yield_HS _H_Tair
Nioro	dryseason	T0	Fleur 11	1	369	DMI-HIRHAM5	-3.390	-2.209	-15.800	-6.845	-6.473	-41.441
Nioro	dryseason	T0	Fleur 11	1	369	KNMI-RACMO22T	-6.619	-5.181	-31.040	-12.795	-10.987	-42.550
Nioro	dryseason	T0	Fleur 11	1	369	MPI-CLM	-8.939	-7.582	-45.502	-7.602	-7.812	-53.425
Nioro	dryseason	T0	Fleur 11	1	369	SMHI-RCA4	-12.734	-13.963	-76.188	-12.901	-14.106	-85.728
							-7.920	-7.234	-42.132	-10.036	-9.845	-55.786
Nioro	dryseason	T0	Fleur 11	1	469	DMI-HIRHAM5	9.529	9.491	-5.473	11.389	9.691	-30.911
Nioro	dryseason	T0	Fleur 11	1	469	KNMI-RACMO22T	8.704	10.000	-19.944	8.049	9.865	-29.176
Nioro	dryseason	T0	Fleur 11	1	469	MPI-CLM	4.340	4.930	-38.014	11.708	9.543	-44.299
Nioro	dryseason	T0	Fleur 11	1	469	SMHI-RCA4	-0.803	-3.962	-73.172	4.117	-0.379	-83.280
							5.443	5.115	-34.151	8.816	7.180	-46.916
Nioro	rainyseason	T0	Fleur 11	1	369	DMI-HIRHAM5	-10.618	-10.522	-10.569	-7.377	-7.547	-7.604
Nioro	rainyseason	T0	Fleur 11	1	369	KNMI-RACMO22T	-11.792	-12.977	-13.026	-11.018	-12.462	-12.528
Nioro	rainyseason	T0	Fleur 11	1	369	MPI-CLM	-8.842	-10.043	-10.091	-10.058	-11.492	-11.517
Nioro	rainyseason	T0	Fleur 11	1	369	SMHI-RCA4	-10.494	-10.205	-10.166	-13.071	-12.774	-12.740
							-10.437	-10.937	-10.963	-10.381	-11.069	-11.097
Nioro	rainyseason	T0	Fleur 11	1	469	DMI-HIRHAM5	3.854	3.606	3.553	14.047	13.042	12.973
Nioro	rainyseason	T0	Fleur 11	1	469	KNMI-RACMO22T	3.790	3.259	3.201	11.832	11.220	11.137
Nioro	rainyseason	T0	Fleur 11	1	469	MPI-CLM	6.708	6.617	6.561	12.280	12.397	12.367
Nioro	rainyseason	T0	Fleur 11	1	469	SMHI-RCA4	5.003	5.728	5.774	8.953	9.831	9.874
							4.839	4.802	4.772	11.778	11.622	11.588
Nioro	rainyseason	T0	Fleur 11	0	369	DMI-HIRHAM5	-13.774	-14.051	-13.986	-12.279	-12.816	-12.896
Nioro	rainyseason	T0	Fleur 11	0	369	KNMI-RACMO22T	-17.050	-18.421	-18.469	-14.727	-16.343	-16.454
Nioro	rainyseason	T0	Fleur 11	0	369	MPI-CLM	-14.527	-16.430	-16.506	-23.290	-24.556	-24.581
Nioro	rainyseason	T0	Fleur 11	0	369	SMHI-RCA4	-12.155	-11.999	-11.952	-17.846	-17.207	-17.167
							-14.376	-15.225	-15.228	-17.036	-17.730	-17.774
Nioro	rainyseason	T0	Fleur 11	0	469	DMI-HIRHAM5	0.980	0.740	0.804	9.124	8.436	8.345
Nioro	rainyseason	T0	Fleur 11	0	469	KNMI-RACMO22T	-2.040	-2.614	-2.671	7.824	7.288	7.149
Nioro	rainyseason	T0	Fleur 11	0	469	MPI-CLM	0.224	-0.567	-0.656	-4.128	-3.662	-3.694
Nioro	rainyseason	T0	Fleur 11	0	469	SMHI-RCA4	3.494	4.384	4.439	3.953	5.887	5.938
							0.664	0.486	0.479	4.193	4.487	4.435