Field Crops Research 219 (2018) 148–159

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Potential impact of climate change on peanut yield in Senegal, West Africa

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ARTICLE INFO

Keywords:
Climate change
Peanut
Canopy temperature
Air temperature
[CO_2]
Senegal

ABSTRACT

Crop models are useful tools to investigate climate change impacts and suitable adaptations strategies on crops. In order to evaluate the impact of climate change on peanut yield in Senegal, a solution of the SIMPLACE crop modelling framework using the Lintul5 crop model together with a T_c model and FAO-56 based approach to simulate evapotranspiration was used with consideration of T_c versus T_a in driving heat stress with output from four regional climate models (RCMs) and two climate change scenarios (RCP4.5 and RCP8.5). Results from six field experiments at two sites (Bambey and Nioro) in Senegal in the dry seasons of 2014 and 2015 and the rainy season of 2014, were used for calibration and evaluation for two peanut varieties. Our calibration and evaluation exercise revealed that simulation skill was markedly improved when T_c was considered under irrigated, dry season conditions during which time the plants were subject to periodic heat stress. Under future climatic conditions, positive changes of up to 2.4% for RCP4.5 and 8.3% for RCP8.5 for seed yield were found when increasing [CO_2] is taken into account for the period 2016–2045 in dry season. While, in rainy season seed yield increased by 11.0% for RCP4.5 and 19.0% for RCP8.5. The effect of climate change on seed yield was negative in the dry season where maximum T_a is often higher than 38 °C compared to the rainy season in particular when T_a is used for simulating heat stress effects. It is concluded that climate change could have limited negative impacts on peanut yield in Senegal due to the effect of elevated [CO_2]. However, simulated T_c should be used instead of T_a to accurately account for heat stress impact on peanut especially during the dry season.

1. Introduction

Peanut (*Arachis hypogaea* L.) is an important oil seed and food crop, grown across West Africa, a region characterized by high temperature and low or erratic rainfall (Hamidou et al., 2013). Peanut is cultivated mainly by small-holder and resource-poor farmers (Tarawali and Quee, 2014), providing the main source of income in rural areas. Together with Nigeria, Senegal is one of the largest producers in the West African region, with peanut production occurring in all districts of the country. However, peanut productivity has decreased in Senegal since 1990 due to soil degradation, seed quality, delay of distribution of inputs (Montfort, 2005; Noba et al., 2014). As high temperature and drought stress are the main yield limiting climatic factors for peanut (Prasad et al., 2010; Hamidou et al., 2013), downward pressure on productivity can be expected to be further exacerbated by climate change.

Climate change is expected to lead to increased temperatures and a decline in average rainfall, including repeated droughts in West Africa (IPCC, 2014). The impact of climate change on crop yields in West Africa without adaptation of crop management is expected to be negative across the main crops (Roudier et al., 2011). While the exact impacts remain highly uncertain when elevated temperatures, higher atmospheric [CO_2] and changed rainfall occur simultaneously (Roudier et al., 2011), temperature is expected to be the largest driver of negative impacts (Schlenker and Lobell, 2010; Roudier et al., 2011). However, differences in study methodologies, data, models and assumptions (Webber et al., 2014), as well as scientific uncertainty in process interactions at the canopy scale (Tubiello et al., 2007) and likely adaptations make climate change impact projections highly uncertain.

To support the improvement of peanut yield and provide policy makers and planners with information to formulate strategies to adapt to climate change, a clear picture of what is likely to happen in the future is necessary. In this regard, crop models are commonly used for scenario analysis. Recent improvements for their application in West Africa with peanut include responsiveness to abiotic stresses, such as

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https://doi.org/10.1016/j.fcr.2018.01.034
Received 16 July 2017; Received in revised form 29 January 2018; Accepted 30 January 2018

Table 1
Summary of the treatments in the six field experiments.

Sites	Seasons	Irrigation Levels	Fertilizer Levels	Variety Levels	Repetition	Experi-mental Design	Planting Month
Bambey	Rainy season (RS) 2014	No irrigation	Six (T0, T1, T2, T3, T4, T5)	Fleur11, 73-33	Four	RCBD	August
Nioro							July
Bambey	Dry Season (OS) 2014	Three (E,S1,S2)	Two (T0, T3)	Fleur11, 73-33	Four	Split split plot	March
Nioro		One (E)	Four ((T0, T1, T2, T3)	Fleur11, 73-33	Four	RCBD	March
Bambey	Dry Season (OS) 2015	Three (E,S1,S2)	Two (T0, T3)	Fleur11, 73–33	Four	Split split plot	February
Nioro							February

T0 without fertilizer, T1 = 50 kg $ha^{-1}$of 6-20-10 (33% of recommended dose), T2 = 100 kg $ha^{-1}$of 6-20-10 (66% of recommended dose) and T3 = 150 kg $ha^{-1}$of 6-20-10 (recommended dose), T4 = 150 kg $ha^{-1}$of 6-0-10 and T5 150 kg $ha^{-1}$of 6-10-10. RCBD = Randomized Complete Block Design.

soil phosphorus, disease and nutrient deficiencies (Prasad et al., 2010; Naab et al., 2015). 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 with aflatoxin in Mali (Boken et al., 2008) and low phosphorus soils in Ghana (Naab et al., 2015). CROPGRO-peanut is the most widely used crop model in West Africa in published studies, and though it considers the impacts of heat stress on seed yield it does not yet integrate the effect of canopy temperature (T_c). While large scale observational evidence suggests that high temperature, not rainfall, will drive losses in crop yield in much of Sub Saharan Africa (Schlenker and Lobell, 2010), we expect heat and drought stress to interact and reinforce one another. In fact, some observational evidence suggests that the interaction of heat and drought stress is already evident in panel datasets for SSA in which yield losses above 30 °C are greater under water stressed conditions than well-watered ones (Lobell et al., 2011). To capture these interactions, T_c is here suggested as a more appropriate indicator to estimate the effect of heat stress than air temperature (T_a) (Siebert et al., 2014). Use of T_a alone neglects the interaction between crop soil water status and temperature, which can cause an error in temperature by up to six or more degrees in hot dry environments resulting in large under or over predictions of crop heat stress (Siebert et al., 2014; Webber et al., 2016).

The current study quantifies the effects of climate change and elevated [CO_2] on crop growth under well-watered and typical rainfed conditions, capturing the interaction of high temperature, crop water status and [CO_2] through consideration of crop T_c (De Boeck et al., 2016). The model structure was developed with the SIMPLACE modelling framework (www.simplace.net), which offers the flexible combination of re-usable model sub-routines into so called model solutions. From this model basis, the first objective of this study was to evaluate the performance of the model solution SIMPLACE < Lintul5,Slimwater,CanopyT,HeatStressHourly > to simulate peanut growth and yield under varying conditions of heat and water stress in Senegal. The evaluation was conducted using both T_a and simulated T_c to drive the heat stress response. The second and main objective was to assess the impacts of climate change on peanut yield in Senegal based on the calibrated and validated model solution.

2. Materials and methods

2.1. Field experiments for model calibration and evaluation

Field experiments were conducted in Bambey located at 14°42′ N and 16°29′ W and in Nioro located at 13°45′ N and 15°46′ N in Senegal during the dry and rainy seasons of 2014 and dry season of 2015 (Faye et al., 2016). A total of six field experiments were carried out; two dry season and one rainy season field experiment at each site (Table 1). The peanut cultivars selected were Fleur11 and 73-33 which are known to be early (90 days) and medium (110 days) maturity cultivars, respectively. Compound fertilizer NPK 6-20-10 was applied one day after sowing as recommended by the National Agricultural Research Institute of Senegal (ISRA) and incorporated at a depth of 5 cm with a hoe. However, during the rainy season single doses of Urea (N 46%), DSP (24% P2O5) and KCl (60% K_2O) were applied in treatment T4 and T5 (Table 1). The three irrigation levels were: E (field capacity), S1 (water stress during flowering) and S2 (water stress during seed filling). Experimental units measured 16 m^2 (4 m by 4 m); rows were spaced at 50 cm, with 15 cm within rows plant spacing. Before sowing each year, the field was disc-plowed to a depth of 12 cm, harrowed and leveled. The seeding was done by hand at a depth of about 4 cm with two seeds per seed hole. Thinning to one plant per seed hole was done after emergence at 11 days after sowing (DAS). Weed control was conducted by hand. Insecticide and fungicide were applied to avoid insects' attacks and diseases.

Phenology observations were taken approximately every seven 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; Meier, 2001). Total dry matter was determined in leaves, stems and pods at weekly basis. Time series of leaf area index (LAI) were measured before each biomass sampling at both sites with a Plant Canopy Analyzer (LAI 2000). At final harvest biomass and seed yield was determined in each plot in an area of 3.9 m^2 (1.95 m × 2 m). Ten composite soil samples were collected in 10 cm intervals from 0 to 100 cm depth using an auger two weeks before sowing. Chemical and physical analyses of the soil were done at the Water-Soil-Plant laboratory of (ISRA). Weather stations were located at less than 1 km from the field experiments and rainfall, maximum and minimum T_a, sunshine hours, maximum and minimum relative humidity and wind speed were measured daily.

2.2. Soil properties

The model solution requires initial values for the total mineral soil N, P and K available at the start of the growth period ($g\,m^{-2}$). Laboratory analyses for chemical soil properties were used to estimate these values at 100 cm depth (Table 2) in all soil layers in which effective peanut root can access (Faye et al., 2016). The value of 0.025

Table 2
Soil properties at the start of the growth seasons 2014 and 2015 used in the model.

	2014		2015	
	Bambey	Nioro	Bambey	Nioro
Depth (cm)	100	100	100	100
N ($g\,m^{-2}$)	8.2	8.7	9.1	10.1
P ($g\,m^{-2}$)	42.0	17.8	3.8	6.9
K ($g\,m^{-2}$)	67.4	68.9	9.8	9.3
LL ($cm\,cm^{-1}$)	0.08	0.1	0.08	0.1
DUL ($cm\,cm^{-1}$)	0.19	0.2	0.19	0.2
SAT ($cm\,cm^{-1}$)	0.29	0.38	0.29	0.38
OC (%)	0.13	0.30	0.24	0.29
BD ($g\,cm^{-3}$)	1.43	1.32	1.43	1.32
pH	5.8	5.7	6.8	5.3
Sand (%)	92.0	82.0	68	65
Silt (%)	2.4	8.2	23	24
Clay (%)	5.6	10.1	9	11

LL: permanent wilting point, DUL: Field capacity, SAT: volumetric water content at saturation, OC: organic carbon, BD: bulk density.

Table 3
Weather conditions observed during the growing seasons in 2014 and 2015 of rainfall sum (mm), total irrigation (mm) in dry season, average daily maximum, mean and minimum T_a (°C) and Average Solar radiation (MJ m^{-2} d^{-1}) in two sites in Senegal.

Season	Sites	Rainfall (mm)	Average Solar RD (MJ m^{-2} d^{-1})	Average MinT (°C)	Average MeanT (°C)	Average MaxT (°C)	Irrigation (mm)
Dry season 2014	Bambey	0	22.3	21.3	30	38.7	588
	Nioro	13.8	24.2	21.4	30.5	39.6	609.8
Rainy season 2014	Bambey	407	19.5	24.3	29.7	35.2	28.8
	Nioro	513	19.2	23.6	28.5	33.5	26.2
Dry season 2015	Bambey	0	20.5	20.1	28.5	36.9	602.4
	Nioro	0	21.7	20.1	29.3	38.5	615.5

was used as fraction of soil mineral N, P and K becoming available per day for the plant as parameterized by Lintul5 model.

2.3. Site climatic description

At both sites, mean solar radiation was greater during the growth cycle in the dry season than during the rainy season. The maximum mean value of 24.6 MJ m^{-2} d^{-1} was recorded in Nioro during the dry season 2014. The average maximum T_a of 39.6 °C in the dry season of 2014 was recorded at Nioro. The annual rainfall in 2014 was higher in Nioro (513 mm) than in Bambey (407 mm) which confirm the rainfall gradient of the country between the southern to the northern part (Table 3).

Average long-term seasonal rainfall in Bambey is 500 mm and 700 mm in Nioro and the rainy season lasts from June to October (JJASO); representing more than 95% of the annual rainfall (Fig. 1a) with a uni-modal distribution. The average monthly minimum and maximum T_a are 24 °C–35 °C, respectively during the rainy season and 20 °C–40 °C, respectively during the dry season (Fig. 1c, d). The mean solar radiation is 19.5 MJ m^{-2} d^{-1} during the rainy season and 24 MJ m^{-2} d^{-1} (Fig. 1b) during the dry season.

2.4. Model description

The model implemented in SIMPLACE (Scientific Impact assessment and Modelling PLatform for Advanced Crop and Ecosystem management) modelling framework (Gaiser et al., 2013) was linked with the above ground growth modules of the Lintul5 crop growth model (Wolf, 2012), the soil water balance Slimwater (Addiscott et al., 1986; Addiscott and Whitmore, 1991) model, the FAO-56 procedures for calculating crop evapotranspiration (Allen et al., 1998), the hourly T_c model CanopyT (Webber et al., 2016), and the heat stress impact model HeatStressHourly (Gabaldón-Leal et al., 2016). The combined model solution was SIMPLACE < Lintul5, Slimwater, CanopyT, HeatStressHourly > though further referred to as SIMPLACE. Lintul5 calculates 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 (RUE), which is a function of daily mean T_a, water or nutrient limitation and atmospheric [CO_2]. Crop development is a function of daily accumulated thermal time above a base temperature and crop specific thermal time requirements from emergence to anthesis (TSUM1) and

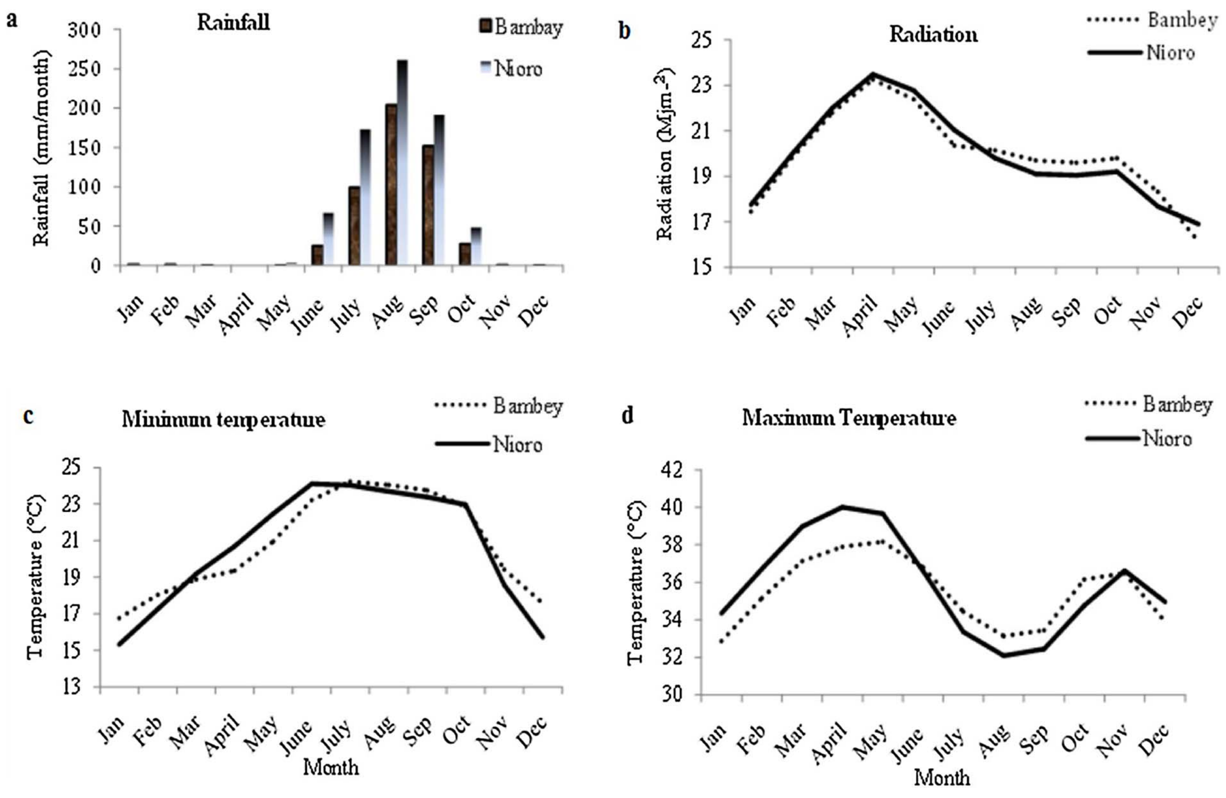

Fig. 1. Seasonal cycle of rainfall, radiation, minimum and maximum T_a at Bambey and Nioro (1981–2014).
Source: CNRA (Centre National de Recherche Agronomique de Bambey) Bambey and ANACIM (Agence Nationale de l'Aviation Civile et de la Météorologie).

from anthesis to maturity (TSUM2). Slimwater is used to simulate crop water uptake. Crop water demand was calculated using the FAO Penman-Monteith method (Allen et al., 1998) with a reference crop and the dual crop coefficient method.

T_c is calculated 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; Webber et al., 2016). It accounts for feedback between crop water status and crop temperature. To avoid explicit calculation of stomatal resistance for the canopy (r_c), simplifying assumptions about the variation of T_c with water stress are made in which T_c estimated by interpolating between a high (full water stress), with r_c equal to a very high value and low (no water stress) estimate of T_c estimated with r_c equal to a constant daily value determined in the literature for no stress conditions. Under conditions of elevated [CO_2], r_c is increased slightly as reported in (Leakey et al., 2009; Vaidya et al., 2014). Actual T_c is calculated by interpolating between these two values as a function of the crop water stress factor (Webber et al., 2016). The hourly crop water stress factor is calculated as the ratio of actual hourly to potential hourly transpiration.

The hourly heat stress model (Gabaldón-Leal et al., 2016) reduces seed yield when the hourly temperature is above a critical threshold temperature at which reduction in final yield due to kernel abortion occurs. It is based on an approach implemented in the APSIM crop model Lobell et al. (2015), modified for hourly time steps with the possibility to use either T_c or T_a as input. Yield reduction is a function of total hourly stress thermal time (TTh) calculated in the sensitive period, around flowering (6 days before anthesis to 15 days after anthesis), given by:

$$TTh = \sum (T - T_{critical}) \tag{1}$$

where T can be either hourly T_a or hourly simulated T_c and $T_{critical}$ is the critical temperature above which reduction in final yield occurs (38 °C) (Prasad et al., 1999).

The yield reduction was determined as:

$$AdjYield = RedHS * Yield \tag{2}$$

where AdjYield is the seed yield adjusted for high temperatures near flowering, Yield is the grain mass, RedHS is the yield reduction factor due to cumulative high temperatures above $T_{Critical}$ (38 °C). RedHS is calculated based on the TT_h accumulated during the critical period as reduction in seed yield (Gabaldón-Leal et al., 2016).

$$RedHS = 1 - ReductionPerDHAboveTempCritical * TTh \tag{3}$$

Where ReductionPerDHAboveTempCritical is reduction in kernel yield per degree-hour above a threshold temperature set at 0.0025 in this present study.

2.5. Model parameterizations

Most of the parameters used in the Lintul5 model are default values reported in Wolf (2012). However, as no published studies exist with Lintul5 for peanut or other legumes, some parameters values were adjusted based on literature and from field measurements. Some parameter values 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.

2.6. Model calibration and evaluation

The Nioro experimental dataset was used for model calibration and the data set from Bambey for model evaluation. Model calibration and evaluation was carried out in three steps:

1: Calibration and evaluation of treatments with no heat (rainy season experiments); 2: Calibration and evaluation of treatments under heat stress but no drought stress conditions (dry season experiments with full irrigation E); 3: Calibration and evaluation of treatments under heat and drought stress conditions (dry season under water stress).

In step 1, first phenology was calibrated by adjusting two parameters, TSUM1 and TSUM2, to correctly simulate the occurrence of anthesis and the maturity dates. Next, LAI and biomass were calibrated simultaneously by adjusting RGRLAI (maximum relative increase rate in LAI), SLATB (specific leaf area) and RUETB (radiation use efficiency for biomass production) parameters. Finally, to calibrate seed yield, two parameters were considered: (1) FRTDM (fraction of above ground biomass that is available for translocation) was adjusted, as it is considered here to affect yield independent of heat and drought stress. In step 2, RedHS was calibrated for the experiments with heat stress, but no or minimal drought. Finally, in step 3 canopy resistance (r_c) was calibrated by accounting the interaction between heat and drought.

The evaluation of the performance of the model to simulate peanut yield was based on a comparison of observed data and simulated data using the following three statistical indicators.

(i) The 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.
(ii) Root Mean Square Error (RMSE) used to measure the deviation between the observed and simulated values (Cao et al., 2002).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (X_o^i - X_s^i)^2} \tag{4}$$

X_o^i, X_s^i are the observed and simulated values respectively, and N is the sample size.

- Index of agreement (d) Willmott (2012) as a standardized measure of the degree of model prediction error and varies between 0 and 1.

$$d = 1 - \frac{\sum_{i=1}^{n} (X_o^i - X_s^i)^2}{\sum_{i=1}^{n} (|X_s^i - \overline{X_o}| + |X_o^i - \overline{X_o}|)^2} \tag{5}$$

X_o^i, X_s^i are the observed and simulated values respectively, and $\overline{X_o}$ is mean observed.

2.7. Simulation setup for the climate change impact analysis

For assessing the impact of climate change on peanut seed yield, the output of four regional climate models (RCMs) from the COordinated Regional climate Downscaling Experiment (CORDEX) was used. SIMPLACE was run for the historical period 1981–2010 (baseline) and, in the future period 2016–2045 for the scenarios RCP4.5 and RCP8.5. Two atmospheric [CO_2] scenarios were considered: in the first [CO_2] was kept constant at 369 ppm in both the historical and climate scenario periods. In the second, [CO_2] was set at 439 ppm for RCP4.5 and at 469 ppm for RCP8.5 (Meinshausen et al., 2011). The transpiration was reduced by 12% when [CO_2] increased from 375 to 550 ppm, as it has been reported for soybean under free air CO_2 enrichment (FACE) experiment (Bernacchi et al., 2007; Leakey et al., 2009; Kimball, 2016) and peanut in chamber studies (Vaidya et al., 2014). The radiation use efficiency will increase by 8% when [CO_2] increase from 369 to 439 ppm and by 11% when [CO_2] increase from 369 to 469 ppm based on the Lintul5 (Wolf, 2012) parameterization. A correction factor was used on the canopy resistance term to account for the effect of heat under CO_2 fertilization.

Due to the biases of RCM outputs (Hay et al., 2000; van Roosmalen et al., 2011; Gbobaniyi et al., 2014; Mbaye et al., 2016), the delta change method was used to project changes from the RCMs into the scenario periods by absolute (temperature) or relative (precipitation) change factors derived between RCM data for the present day climate

Table 4
Parameters of the model and values used for the two peanut varieties.

Parameters	Values used in the model		Value range in literature	Units	References or comments
	Fleur 11	73–33			
Temperature sum from emergence to anthesis (TSUM1)	422	510	NA – variety dependent	°C day	Calibrated with observed emergence and anthesis date
Temperature sum from anthesis to maturity (TSUM2)	1285	1330	NA – variety dependent	°C day	Calibrated with observed anthesis and maturity date
Radiation use efficiency* ([1]RUE)	3.2–1.8	3.2–1.8	1.45–2.66	$g\,MJ^{-1}$	Kiniry et al. (2005), Haro et al. (2007)
Specific leaf area ([2]SLATB)	0.016–0.014	0.016–0.014	0.015–0.027	$m^2\,g^{-1}$	Songsri et al. (2009)
			0.015–0.017	$m^2\,g^{-1}$	Kalariya et al. (2015)
			0.001–0.002	$ha\,kg^{-1}$	Belko (2006)
Maximum Relative increase in LAI (RGRLAI)	0.03	0.03	0.05	$haha^{-1}\,d^{-1}$	
Partitioning of above ground biomass to grains: fraction (FOTB)*	0 (emergence to anthesis) 0.1 (after anthesis) 0.73 (maturity)				Wolf (2012)
maximum amount of reserves to be remobilized with no stress (FRTDM)	0.05	0.05	0.05		Wolf (2012)
Reduction in yield per degree hour above a threshold temperature	0.0025	0.0025	0.0025		Wolf (2012)
maximum N concentration in leaves as function of development stage ([3]NMXLV)	0.06–0.03	0.06–0.03	0.03–0.062	$g\,g^{-1}$	Sinclair et al. (1993), Benton et al. (1991)
maximum P concentration in leaves as function of development stage ([4]PMXLV)	0.006–0.00253	0.006–0.00253	0.0025–0.006	$g\,g^{-1}$	Benton et al. (1991), Reuter (1997)
maximum K concentration in leaves as function of development stage ([5]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 et al. (2004)
			0.025–0.047	$g\,g^{-1}$	Hafner et al. (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 et al. (2013)
maximum K concentration in storage organs	0.0091	0.00914	0.0087–0.00914	g g-1	Wu et al. (1997)
fraction of crop N uptake by biological fixation (NFIXF)	0.8	0.8	0.53–0.97		Sinclair et al. (1995)
			0.8		Wolf (2012)
Threshold maximum temperature near flowering at which reduction in final yield occurs due to kernel abortion (Tcritical)	38	38	38	°C	Prasad et al. (1999)
Critical N concentration as fraction of maximum N concentration (FRNX)	0.7	0.7	0.5–1	$g\,g^{-1}$	Shibu et al. (2010)
Critical P concentration as fraction of maximum P concentration (FRPX)	0.7	0.7	0.5–1	$g\,g^{-1}$	Shibu et al. (2010)
Critical K concentration as fraction of maximum K concentration (FRKX)	0.5	0.5	0.5–1	$g\,g^{-1}$	Shibu et al. (2010)

[1] 3.2 from emergence to anthesis, decreasing linearly to 1.8 from anthesis to maturity for both varieties.

[2] 0.016 from emergence to anthesis, decreasing linearly to 0.014 from anthesis to maturity for both varieties.

[3] 0.06 from emergence to anthesis, decreasing linearly to 0.03 from anthesis to maturity for both varieties.

[4] 0.006 from emergence to anthesis, decreasing linearly to 0.002 from anthesis to maturity for both varieties.

[5] 0.104 from emergence to anthesis, decreasing linearly to 0.044 from anthesis to maturity for both varieties.

and a projected climate scenario (Hay et al., 2000). The delta change method is widely used in many climate change impact studies for developing local climate change projections (Wilby et al., 2004; Gago Da Silva et al., 2012; Teutschbein and Seibert, 2012; Watanabe et al., 2012). The baseline data was determined by combination model results of the historical simulations (1981–2005) with the first five years of the projection run (2006–2010) under RCP4.5 (Dosio and Panitz, 2015). A multiplicative correction was used for rainfall, whereas an additive correction was used to adjust temperature (Teutschbein and Seibert, 2012).

Crop growth and development and yield were simulated at both sites Bambey and Nioro for 30 years data. The simulations were conducted under fully irrigated condition in the dry season and rainfed conditions in the main growing season. To quantify climate change impact, relative yield changes (Zhao et al., 2015) were calculated as:

$$\Delta Yield = \frac{Yield_{scen} - Yield_{baseline}}{Yield_{baseline}} * 100[\%] \tag{6}$$

Where

$\Delta Yield$ is the relative yield change, $Yield_{scen}$ is the simulated yield for the climate scenarios and $Yield_{baseline}$ is the simulated yield for the baseline scenarios.

3. Results

3.1. Model calibration and evaluation

After calibration, the model accurately reproduced the seed yield for the no heat and drought stress conditions, as in the evaluation process the model had good agreement with the observed seed yield for both varieties. As expected, under no heat or drought stress, the seed yield simulated with T_a was the same as the seed yield simulated with T_c because the average maximum T_a was less than 38 °C and little drought stress occurred which meant that T_c rarely differed from T_a.

Good agreement was obtained between observed and simulated data for above ground biomass (AGB) but less for LAI for both varieties in calibration (Fig. 2a, b, i, j) and in evaluation (Fig. 2k, l, s, t) with heat stress but without drought stress. Likewise, simulated seed yield exhibited good agreement with observed data for calibration of both Fleur 11 and 73-33 (Fig. 2c, d). The same result is noted for Fleur11 during model evaluation, while the model over estimated seed yield for 73-33 (Fig. 2m, n). Seed yield simulated with T_c agreed well with observed data. However, seed yield simulated with T_a were underestimated in both model calibration and evaluation. The underestimation was higher during the model evaluation (Bambey) than the model calibration (Nioro) due the higher T_a observed in Bambey (44 °C) around flowering period from 100 to 125 days of year contrary to Nioro (39 °C), which provide more yield reduction (Fig. 2g, h, q, r).

It was found that the maximum mean T_a was around 40 °C for both sites whereas maximum mean T_c was less than 35 °C.

Under combined heat stress and drought stress, the simulated AGB and LAI values were in good agreement with observations after calibration and evaluation. The model accurately simulated the seed yield when water stress occurred during the flowering (Fig. 3c, m) period. However, it overestimated seed yield when water stress occurred during seed filling in model evaluation (Fig. 3n). Simulated T_c was higher than T_a in period with drought stress as expected.

Yields simulated with no heat stress (No_HS), heat stress with simulated T_c (HS_Tc), and heat stress determined with measured T_a (HS_Tair) are shown in Fig. 4. Model agreement with observations indicated a higher correlation between observed and simulated values for simulations with no heat stress and when T_c was used for both varieties (Fig. 4a, b, d, e), as compared to the use of T_a to simulate yield under heat stress (Fig. 4c, f). Heat stress was overestimated in conditions with T_a as driver for heat stress response in both calibration and evaluation and for both varieties (Table 5) with higher RMSE of 51 and 82 g m^{-2} for Fleur11 and 41 and 92 g m^{-2} for 73–33 respectively. Lower values were observed for R^2, 0.1 for Fleur 11 for both calibration and evaluation and 0.3 for 73–33 for calibration and 0.1 for evaluation. The index of agreement had lower values of 0.3 and 0.5 for Fleur 11 and 0.6 for 73–33 for calibration and evaluation respectively. In contrast, when T_c is used as driver for heat stress response the statistical indicators indicate lower values of RMSE of 44 and 32 g m^{-2} for Fleur11 and 38 and 70 g m^{-2} for 73-33, and higher value for R^2, 0.3 and 0.9 for Fleur 11 and 0.6 and 0.4 for 73-33 and higher d values of 0.7 and 0.9 for Fleur 11 and 0.7 for 73-33 respectively for calibration and evaluation.

3.2. Climate change impact analysis

Average rainfall at both sites decreased for both scenarios (RCP 4.5 and RCP 8.5) for the climate model outputs from DMI-HIRHAM5 and MPI-CLM RCMs in the period 2016–2045 compared to the baseline (1981–2010). In contrast, for the climate model SMHI-RCA, rainfall increased at both sites, whereas in the case of KNMI-RACMO22T rainfall increased in Nioro for both RCPs and in Bambey, rainfall increased only for RCP 8.5 but decreased for RCP 4.5. All models projected higher rainfall in Nioro than in Bambey. Mean temperature increased by approximately 1 °C for RCP4.5 whereas for RCP8.5 temperatures increased by 1.2 °C between baseline (1981–2010) and scenario conditions (2016–2045) at both sites. Over the course of a year, temperature varied between a daily minimum average of 20 °C to a maximum average of 40 °C.

3.2.1. Relative yield changes under irrigated conditions in the dry season with projected climate change

Under dry season conditions and full irrigation, the effects of climate change under ambient [CO$_2$] on simulated peanut yields at both sites was negative irrespective of whether T_c or T_a was used to determine heat stress (Fig. 5). However, the negative effects were larger when T_a was used instead of T_c at both sites. Yield losses were greater in Nioro site and ranged from 8.7% for RCP4.5 to 11.4% for RCP8.5 across all RCMs for T_c and from 42.4% for RCP4.5 to 55.5% for RCP8.5 for T_a (Fig. 5c). In Bambey however, losses ranged from 8.8% for RCP4.5 to 11.5% for RCP8.5 across all RCMs for T_c and from 19.1% for RCP4.5 to 27.5% for RCP8.5 for T_a (Fig. 5a). RCP4.5 showed smaller yield losses compared to RCP8.5.

With elevated [CO$_2$], all RCMs projected a negative effect on yield for T_a at both sites, at 16.1% for RCP4.5 and 11.3% for RCP8.5 in Bambey and by 48.3% for RCP4.5 and 45.3% for RCP8.5 at Nioro (Fig. 5b.d). Relative yield changes were positive when T_c was used to simulate heat stress with 2.3% and 8.2% for RCP4.5 and RCP8.5 respectively in Bambey and by 2.6% for RCP4.5 and 8.6% for RCP8.5 in Nioro.

3.2.2. Relative yield changes in the rainy season with projected climate change

The relative changes in seed yield in the rainy season are shown in Fig. 6. Under ambient [CO$_2$], the effect of climate change on peanut seed yield in Bambey was negative when both T_c and T_a were used to determine the heat stress response regardless of the climate model under ambient [CO$_2$] by 6.7% for RCP4.5 and 11.6% for RCP8.5, respectively. On the other hand, a positive impact on seed yield was simulated under elevated [CO$_2$] by 7.9% for RCP4.5 and 16.3% for RCP8.5 for both T_c and T_a (Fig. 6a. b). In Nioro, a negative impact of climate change on seed yield was simulated for the ambient [CO$_2$] for all the models by 2.3% for RCP4.5 and 6% for RCP8.5 when using both T_c and T_a (Fig. 6c). In contrast, for future elevated [CO$_2$], positive yield changes were simulated across all RCMs by 14.0% for RCP4.5 and 21.5% for RCP8.5 irrespective of whether T_c or T_a was used to calculate heat stress on seed yield (Fig. 6d).

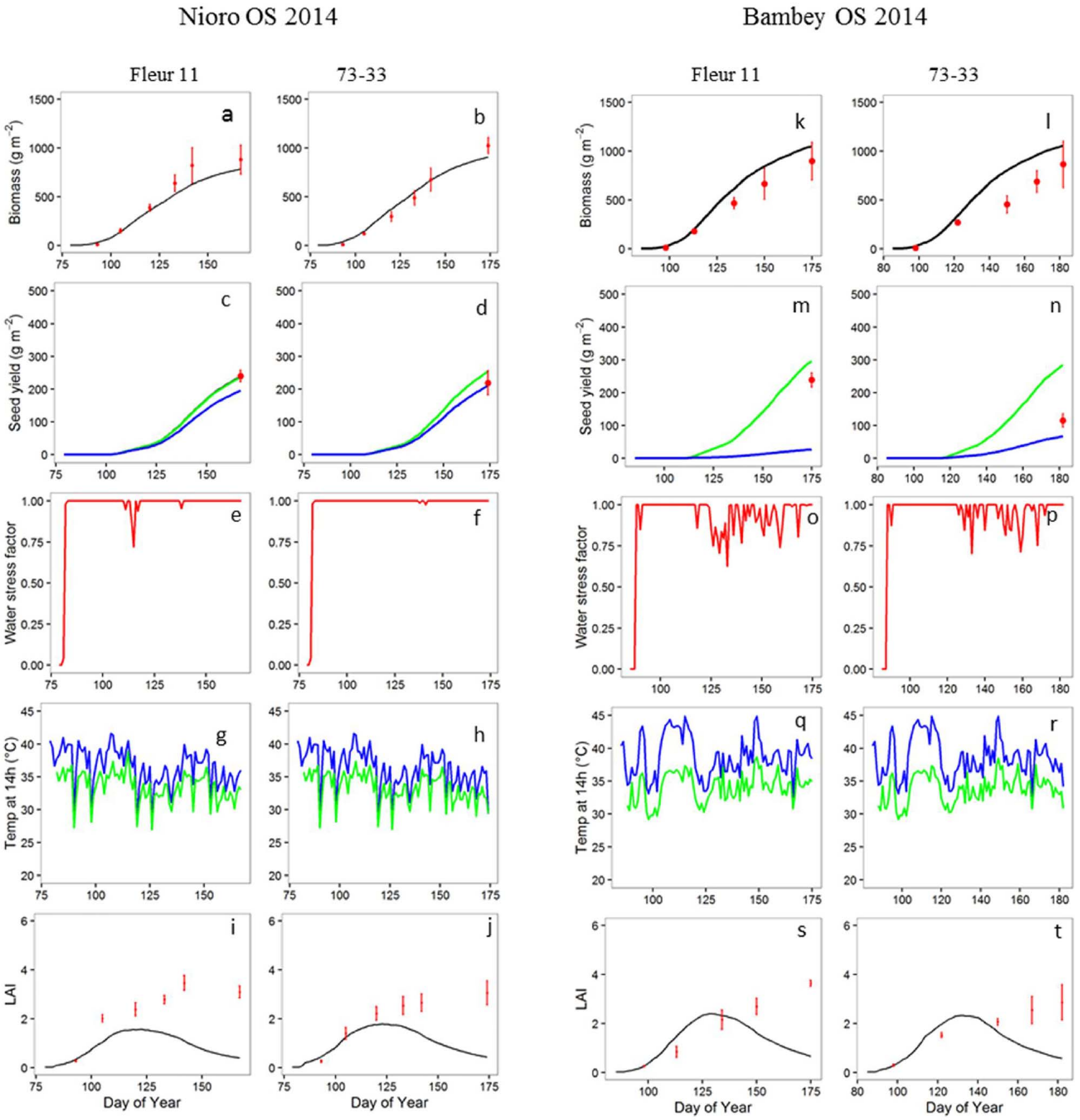

Fig. 2. Model calibration (Nioro) and evaluation (Bambey) with heat stress and without drought stress. Simulated ([1]black line) versus observed (red points) values for AGB (a, b,k,l) and for LAI (i, j, s,t). Simulated seed yield (black line = yield no heat stress, green line = yield with heat stress using T_c, blue line = yield with heat stress using T_a) versus observed (red points) values (c, d, m, n). Blue line = simulated T_a and green line simulated T_c (g, h, q, r). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Model performance

The model solution SIMPLACE < Lintul5,Slimwater,CanopyT, HeatStressHourly > was able to simulate seed yield accurately for two peanut varieties and at sites representative of the main peanut production areas across seasons and production conditions in Senegal.

Yield simulated with T_c had lower values of RMSE between 38–70 g m^{-2} and higher value of R^2 between 0.3–0.9 and d values between 0.6–0.9 for both varieties and sites. This range of values of RMSE and d values showed that the model could be used in the region to simulate accurately peanut growth and yield. However, yield simulated with T_a without recalibrated sensitivity tend to perform less accurately with higher RMSE and lower R^2 and d values. These results corroborate the findings of Siebert et al. (2014) that suggest to consider T_c instead of T_a in simulating heat stress. However, the model performance was less satisfactory for LAI under combined heat and drought stress (Fig. 3) perhaps explained by the difficulty for calibrating and validating LAI for peanut as both varieties were of indeterminate growth types. We should caution, that while consideration of T_c is expected to lead to more accurate simulation of heat stress effects on

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[1] The seed yield with no heat stress (black line) did not appear in Fig. 2 because it was masked by the seed yield with heat stress using T_c (green line) as they had similar yield.

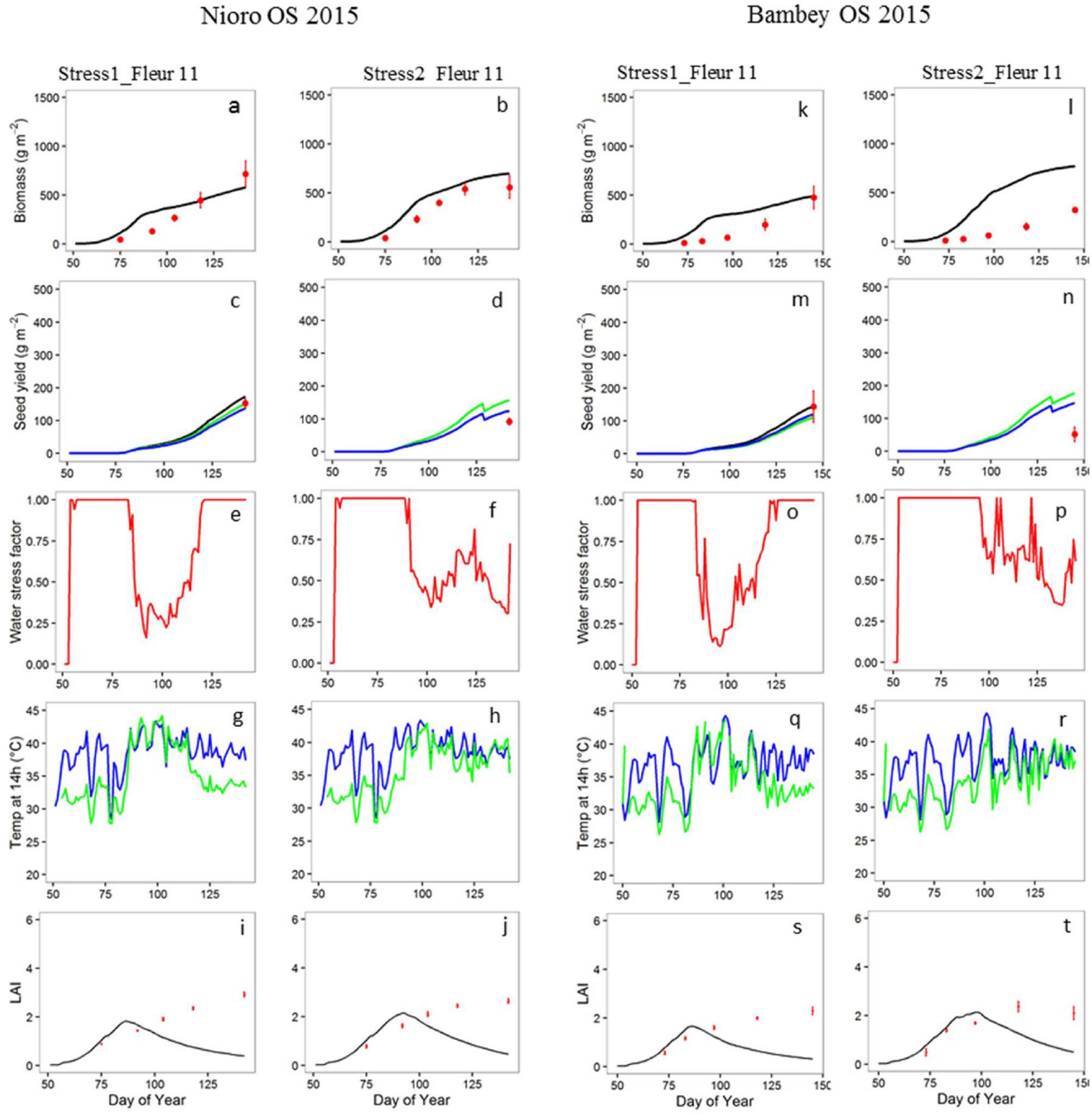

Fig. 3. Model calibration and evaluation with combined heat stress and drought stress.
Simulated (black line) versus observed (red points) values for AGB (a, b, k, l) and for LAI (i, j, s, t). Simulated seed yield (black line = yield no heat stress, green = yield with heat stress T_c, blue = yield with heat stress T_a) versus observed (red points) values (c, d, m, n). Simulated (red line) water stress factor (e, f, o, p) and simulated daily maximum temperature (g, h, q, r), air (blue line) and canopy (green line).

flowering, correct simulation of temperature effects on peanut should additionally consider soil temperature for stages after pegging and grain filling. Our study did not consider the later effect.

Under irrigated, dry season conditions, average maximum T_a were always greater than 38 °C which had negative effect on plant growth and yield. Crop T_a above 38 °C are known to significantly reduce dry matter production and the partitioning of dry matter to pods and seeds (Prasad et al., 1999), which explained the yield reduction simulated with T_a during the dry season in spite of full irrigation. Singh et al. (2014) demonstrated that high T_a affect growth and development of crops, thus influencing potential yields.

In contrast, during the rainy season, yield decline was mostly affected in the study area by drought stress due to the early cessation of rainfall. Our data show a low AGB ($< 500\,\mathrm{g/m^2}$) and seed yield ($< 100\,\mathrm{g/m^2}$) 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) are causing a decrease in peanut seed yields, regardless of the fertilizer rate and density of sowing. Despite the drought stress, T_a was low enough to prevent canopy heating above 38 °C, so there was minimal heat stress with either T_a or T_c.

Under heat stress, the impacts on AGB, LAI and seed yield were strongly related to combined heat and drought stress. Drought stress is known to substantially reduce AGB (Annerose, 1990), pod and kernel yield (Yao et al., 1982; Wright et al., 1991; Soler et al., 2013).

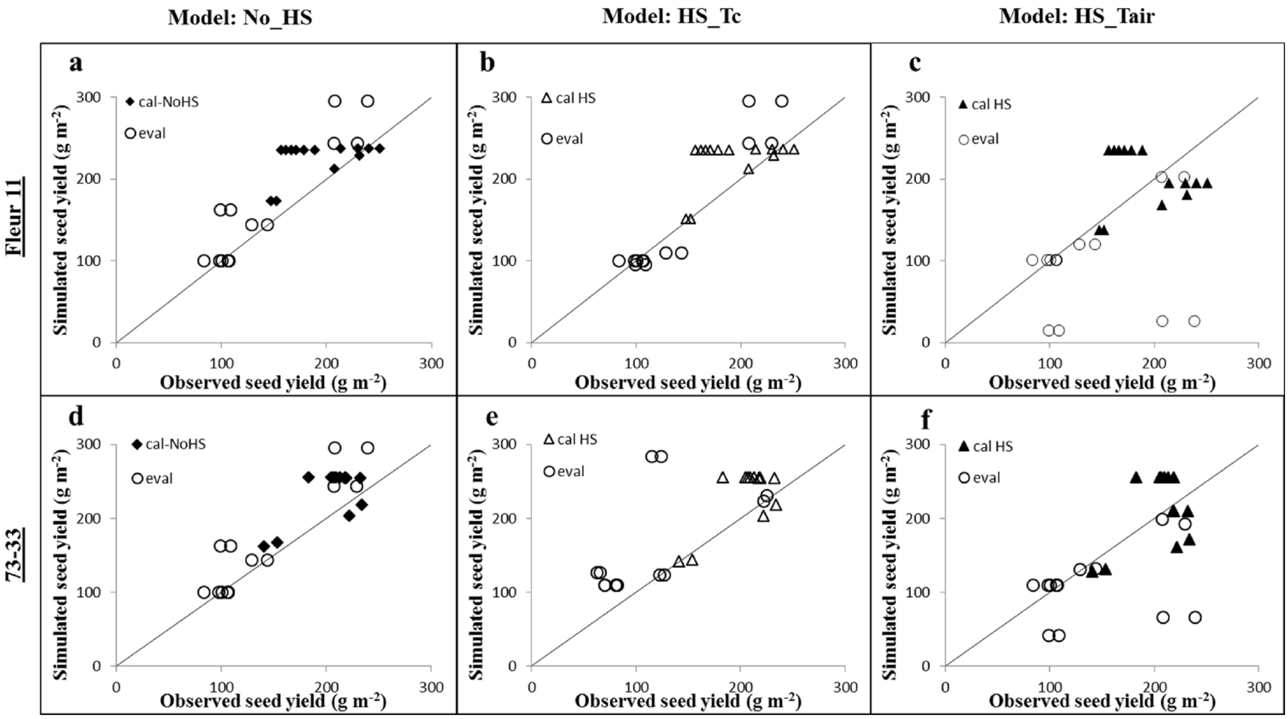

Fig. 4. Model performance for simulating seed yield. NoHS: calibration under no heat stress, diamond (a, d); HS_Tc: calibration under heat stress using T_c, hollow triangle (b, e); HS_Tair, calibration under heat stress using T_a, triangle (c, f) and for model evaluation, hollow circles, cal: calibration, eva: evaluation. The grey line is 1:1 line for visualization of goodness of fit.

Table 5
Statistics for evaluation of model performance of seed yield calibration under no heat stress (No_HS), under heat stress using T_c (HS_Tc) and under heat stress using T_a (HS_Tair), d (index of agreement).

Yield	FLEUR11			73–33		
	No_HS	HS_Tc	HS_Tair	No_HS	HS_Tc	HS_Tair
R^2_calibration	0.3	0.3	0.1	0.5	0.6	0.3
RMSE_calibration ($g\,m^{-2}$)	44	44	51	38	38	41
d_calibration	0.6	0.7	0.3	0.7	0.7	0.6
R^2_evaluation	0.8	0.9	0.1	0.8	0.4	0.1
RMSE_ evaluation ($g\,m^{-2}$)	38	32	82	80	70	92
d_ evaluation	0.9	0.9	0.5	0.6	0.7	0.6

Meanwhile, studies have shown the negative effect of higher temperature on reducing flower production and fruit-set in peanut (Prasad et al., 2001), and reduction of seed yield (Prasad et al., 2003). Previous studies have shown that there are strong interactions between heat and drought stress (Siebert et al., 2014) due to reduced cooling when transpiration is reduced under water stress. In fact, Pinto and Reynolds (2015) found that a common genetic basis for wheat genotypes that maintain higher seed yield under heat and drought stress, was associated with cooler T_c values than lower yielding varieties.

When seed yield simulated with T_c was compared to those simulated with T_a, they were always higher under heat stress condition with full irrigation. This result could be attributed to the fact that under irrigated conditions in hot and arid conditions, plants experience substantial cooling of up to 10 °C (Kimball et al., 2015; Webber et al., 2016). Therefore, if T_c is not considered, heat stress effects will be greatly overestimated, as the air will be hotter than the crop. These findings have been previously demonstrated in wheat (Webber et al., 2016) and maize (Gabaldón-Leal et al., 2016) where it was suggested to use T_c rather than T_a in simulating heat stress.

Although our simulations did consider nitrogen, phosphorus and potassium limitation, there was little evidence of nutrient limitation in our experimental dataset, as reported in Faye et al. (2016). Peanut is a nitrogen fixing crop, and the SIMPLACE simulations could account for this, with the result that no to minimal nitrogen stress was simulated. Further, the experiments were conducted at research stations which are regularly fertilized and therefore had high levels of residual phosphorus and potassium. Therefore, we cannot extend our results to nutrient limited conditions typical of large parts of the region and further studies should investigate the interactions of climate impacts and fertilization levels.

4.2. Impact of climate change on peanut

Our study suggests that climate change could be expected to result in modest positive increase in peanut yields for Senegal. This is largely related to the fact that peanut is an indeterminate crop that is not as susceptible to earlier maturity with warmer temperatures as is the case with maize and sorghum. As peanut is currently the country's most important cash crop, as well as important food security crop, these results are encouraging and in broad agreement with a recent study by Hathie et al. (2017) and contrary to the expectation that climate change will inevitably lead to yield losses for West African agriculture mainly for cereals (Roudier et al., 2011; Sultan et al., 2013). As peanut is a legume that can fix atmospheric nitrogen, its wider inclusion in crop rotations and as an intercrop should be further explored as a climate smart option.

However, the positive results are fairly sensitive to the correct simulation of elevated [CO_2] fertilization effects. This research considered the effects of [CO_2] to assess the impact of climate change which will inevitably affect future crop growth productivity. The effect of elevated [CO_2] is known to reduce stomatal conductance and transpiration and improve water use efficiency and gives higher rates of photosynthesis for the plant. In soybean a decrease in evapotranspiration between 9% to 16% was noted when [CO_2] increased from 375 ppm to 550 ppm (Bernacchi et al., 2007). However, C3 plants such as peanut are more responsive to increased [CO_2] levels than C4 plants as shown by the study of Ainsworth and Long (2005). The effect of elevated [CO_2] is greater at high temperature than low temperature. This result corroborates the findings of Thinh et al. (2017) which showed positive growth responses of Chinese yam to elevated [CO_2] in summer.

While irrigated production is currently not prevalent in the region,

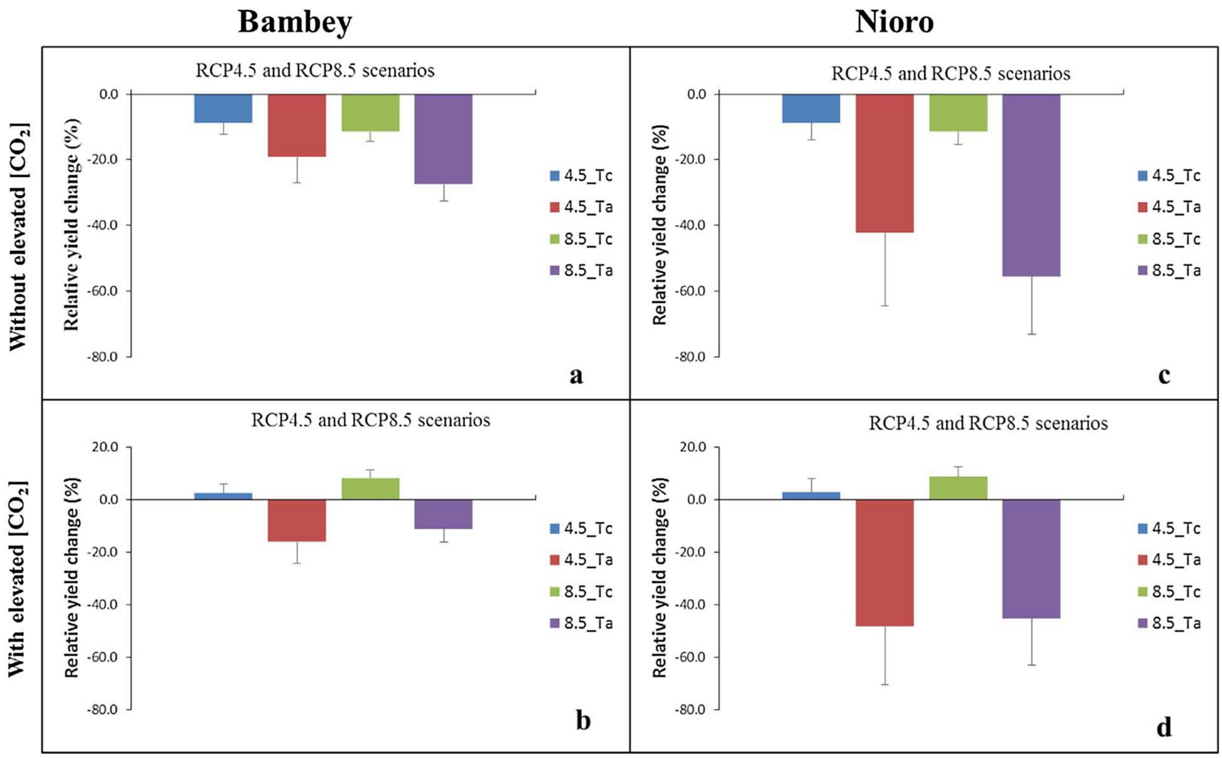

Fig. 5. Relative seed yield changes of peanut at Bambey and Nioro under dry season conditions with full irrigation, averaged across four RCMs with and without elevated [CO_2] for RCP4.5 and RCP8.5 using T_a and T_c to calculate heat stress response.

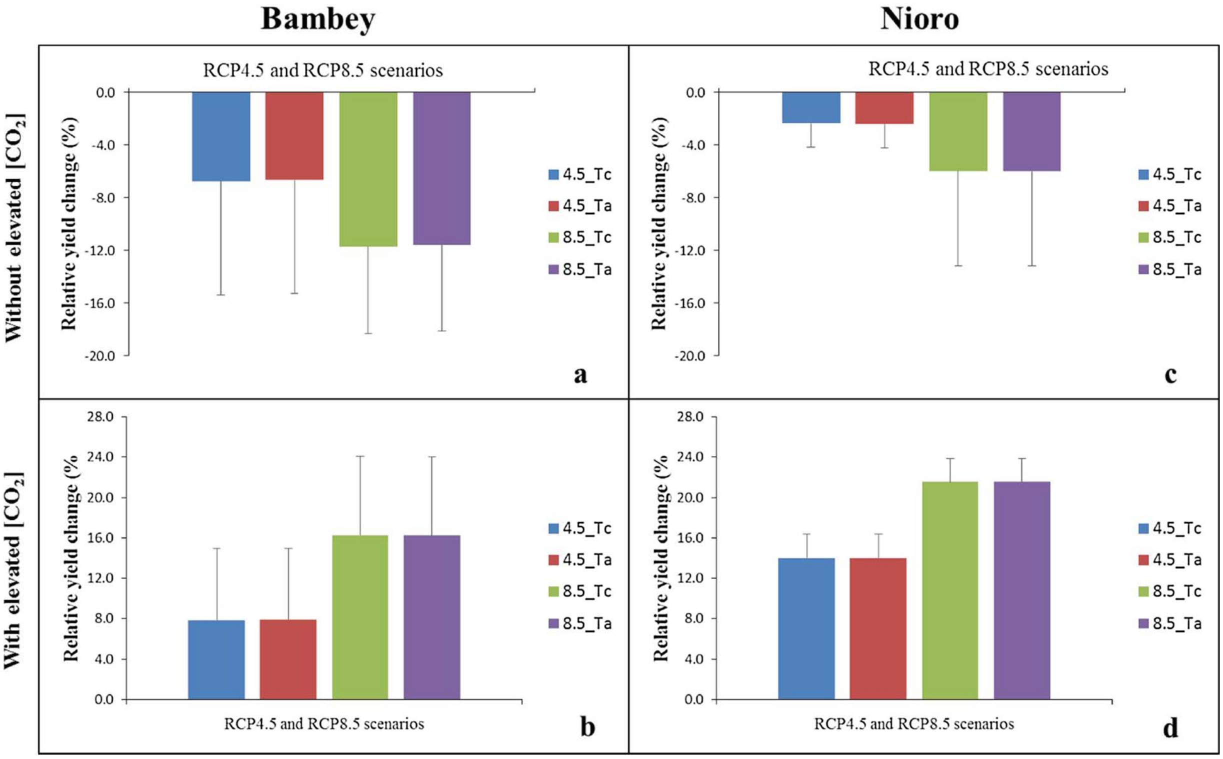

Fig. 6. Relative seed yield change at Bambey and Nioro under rainy season conditions, averaged across four RCMs with and without elevated [CO_2] for RCP4.5 and RCP8.5 using T_a and T_c to calculate heat stress response.

studying the growth and development of peanuts during the dry season allowed us to quantify the effects of high temperature likely to give more flowers but few are successfully fertilized and induce failure of seed abortion. During the dry season, mean daily maximum temperature is above 35 °C in most years. This increase in temperature without [CO_2] elevation, could shorten the length of the growing season and increases the vulnerability of peanut to heat and drought stress. Increased temperature had a negative effect on yield which was expressed by a reduction in yield (Ketring, 1984). However, the conditions are not analogous to those expected with climate change with lower radiation, higher humidity and intermittent soil water stress in the rainy season. In these cases, the rate of evaporative cooling will be considerably lower and heat stress greater. This phenomenon is accounted for in the T_c model for water stress conditions under both ambient and elevated [CO_2] in wheat (Webber et al., 2018).

Under current ambient [CO_2], climate change would have negative impact on seed yield, whereas, with elevated [CO_2], the impact would be positive for seed yield when considering T_c and negative with T_a. This was because under water-limited conditions, the plant might actually be hotter than the air. These results are supported by many simulation studies which suggest the use of T_c instead of T_a to account for the uncertainty in assessing the impacts of heat on crops (Siebert et al., 2014; Rezaei et al., 2015; Webber et al., 2017; Webber et al., 2018).

Under rainfed conditions a positive effect on seed yield was shown under elevated [CO_2] at both sites whether T_c or T_a is considered. These results emphasize the positive effect of [CO_2] when temperatures are beneath the high temperature thresholds (38 °C). Burkey et al. (2007) showed that, elevated [CO_2] had a positive effect on yield parameters in general. At both sites, the decrease in seed yield for the two RCPs could be attributed to decrease in rainfall associated with an increase in temperature under ambient current [CO_2]. High temperatures increased water losses through evaporation reducing soil moisture and leading to drought stress and reduced yield. Sultan et al. (2013) showed that high temperature cannot be counteracted by any rainfall change when warming exceeds +2 °C in Sahelian savannas of West Africa.

The results showed that an increase in [CO_2] results in an increase in peanut seed yield. This increase in seed yield could be explained by the increase of radiation use efficiency as a linear function of elevated atmospheric [CO_2] from 369 ppm to 469 ppm and a reduction of transpiration. These observations are supported by the findings of Kim et al. (2003); Heinemann et al. (2006); Bannayan et al. (2009) which found an increase in seed yield of crops under increased [CO_2]. However, in such conditions the crops became hotter which resulted from an increase of T_c. Kimball et al. (1999) demonstrated in wheat an increase in T_c with elevated [CO_2]. The effect of increase T_c was captured in the model used in this study. Durand et al. (2017) found that models with explicit stomatal control on transpiration perform better under elevated [CO_2] on maize yield.

5. Conclusion

The potential impact of climate change on peanut yield in Senegal was assessed using the process-based crop model, SIMPLACE < Lintul5,Slimwater,CanopyT,HeatStressHourly >. 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. It was validated successfully in the tropical zone in Senegal for irrigated and rainfed conditions at two sites and for two peanut cultivars. The adoption of the Monin-Obukhov Similarity Theory method for calculation of T_c used in the model was beneficial for the simulation of the seed yield when heat stress occurred. It was shown that the model performance improved when using T_c in place of T_a to simulate heat stress effects on seed yield under dry season conditions and full irrigation.

For both sites, climate change impacts may positively affect peanut yield due to elevated [CO_2] under irrigated and rainfed conditions. However, interactions between heat stress, drought and elevated [CO_2] are still highly uncertain and need consideration in modelling assessments. Further evaluation of the T_c simulations with observations is seen as critical.

Acknowledgments

This work was funded by the German Federal Ministry of Education and Research (BMBF) through the West Africa Science Service Center on Climate Change and Adapted Land Use (WASCAL). We thank ISRA for the field experiments setup, LPAOSF for providing RCMs data and INRES for support with the modelling software.

References

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

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

Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. New Phytol. 165, 351–372.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56 300. FAO, Rome, pp. D05109.

Annerose, J.M.D., 1990. Recherches sur les mécanismes physiologiques d'adaptation à la sécheresse. Application au cas de l'arachide (Arachis hypogea L.) cultivée au Sénégal. Paris VII University (p. 286).

Bannayan, M., Soler, C.T., Guerra, L., Hoogenboom, G., 2009. Interactive effects of elevated [CO2] and temperature on growth and development of a short-and long-season peanut cultivar. Clim. Change 93, 389–406.

Belko, N., 2006. Evaluation de la croissance et de la productivité de l'arachide (*Arachis hypogaea* L.): contribution au paramétrage d'un modèle de bilan carboné pour la prévision agricole au Sénégal. Faculté des Sciences et Techniques. Département de Biologie Végétale. UNIVERSITE CHEIKH ANTA DIOP DE DAKAR (p. 77).

Benton, J.J., Benjamin, J., Harry, A.M., 1991. Plant Analysis Handbook: A Pratical Sampling, Preparation, Analysis and Interpretation Guide. Publishing, Inc., Athens, GA, pp. 211.

Bernacchi, C.J., Kimball, B.A., Quarles, D.R., Long, S.P., Ort, D.R., 2007. Decreases in stomatal conductance of soybean under open-air elevation of [CO2] are closely coupled with decreases in ecosystem evapotranspiration. Plant Physiol. 143, 134–144.

Boken, V.K., Hoogenboom, G., Williams, J., Diarra, B., Dione, S., Easson, G.L., 2008. Monitoring peanut contamination in Mali (Africa) using AVHRR satellite data and a crop simulation model. Int. J. Remote Sens. 29, 117–129.

Boote, K.J., 1982. Growth stages of peanut (Arachis hypogaea L.). Peanut Sci. 35–49.

Burkey, K.O., Booker, F.L., Pursley, W.A., Heagle, A.S., 2007. Elevated carbon dioxide and ozone effects on peanut: II. Seed yield and quality. Crop Sci. 47, 1488–1497.

Cao, W., Liu, T., Luo, W., Wang, S., Pan, J., Guo, W., 2002. Simulating organ growth in wheat based on the organ–weight fraction concept. Plant Prod. Sci. 5, 248–256.

De Boeck, H.J., Van De Velde, H., De Groote, T., Nijs, I., 2016. Ideas and perspectives: heat stress: more than hot air. Biogeosciences 13, 5821.

Dey, R., Pal, K., Bhatt, D., Chauhan, S., 2004. Growth promotion and yield enhancement of peanut (Arachis hypogaea L.) by application of plant growth-promoting rhizobacteria. Microbiol. Res. 159, 371–394.

Dosio, A., Panitz, H.-J., 2015. Climate change projections for CORDEX-Africa with COSMO-CLM regional climate model and differences with the driving global climate models. Clim. Dyn. 1–27.

Durand, J.-L., Delusca, K., Boote, K., Lizaso, J., Manderscheid, R., Weigel, H.J., Ruane, A.C., Rosenzweig, C., Jones, J., Ahuja, L., Anapalli, S.S., Basso, B., Baron, C., Bertuzzi, P., Biernath, C., Deryng, D., Ewert, F., Gaiser, T., Gayler, S., Heinlein, F., Kersebaum, K.C., Kim, S., Muller, C., Nendel, C., Olioso, A., Priesack, E., Villegas, J.R., Ripoche, D., Rötter, R., Seidel, S.I., Srivastava, A., Tao, F., Timlin, D.J., Twine, T., Wang, E., Webber, H., Zhao, Z., 2017. How accurately do maize crop models simulate the interactions of atmospheric CO 2 concentration levels with limited water supply on water use and yield? Eur. J. Agron. http://dx.doi.org/10.1016/j.eja.2017.01.002. (In press) ISSN 116-0301.

Faye, B., Webber, H., Gaiser, T., Diop, M., Owusu-Sekyere, J.D., Naab, J.B., 2016. Effects of fertilization rate and water availability on peanut growth and yield in Senegal (West africa). J. Sustainable Dev. 9, 111.

Gabaldón-Leal, C., Webber, H., Otegui, M., Slafer, G., Ordóñez, R., Gaiser, T., Lorite, I., Ruiz-Ramos, M., Ewert, F., 2016. Modelling the impact of heat stress on maize yield formation. Field Crops Res. 198, 226–237.

Gago Da Silva, A., Gunderson, I., Goyette, S., Lehmann, A., 2012. Delta-Method Applied to the Temperature and Precipitation Time Series-An Example. http://dx.doi.org/10.13140/RG.2.1.3301.2882.

Gaiser, T., Perkons, U., Küpper, P.M., Kautz, T., Uteau-Puschmann, D., Ewert, F., Enders, A., Krauss, G., 2013. Modeling biopore effects on root growth and biomass production on soils with pronounced sub-soil clay accumulation. Ecol. Modell. 256, 6–15.

Gbobaniyi, E., Sarr, A., Sylla, M.B., Diallo, I., Lennard, C., Dosio, A., Dhiédiou, A., Kamga, A., Klutse, N.A.B., Hewitson, B., 2014. Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. Int. J. Climatol. 34, 2241–2257.

Hafner, H., Ndunguru, B., Bationo, A., Marschner, H., 1992. Effect of nitrogen, phosphorus and molybdenum application on growth and symbiotic N2-fixation of groundnut in an acid sandy soil in Niger. Fert. Res. 31, 69–77.

Hamidou, F., Halilou, O., Vadez, V., 2013. Assessment of groundnut under combined heat and drought stress. J. Agron. Crop Sci. 199, 1–11.

Haro, R.J., Otegui, M.E., Collino, D.J., Dardanelli, J.L., 2007. Environmental effects on seed yield determination of irrigated peanut crops: links with radiation use efficiency and crop growth rate. Field Crops Res. 103, 217–228.

Hathie, I., MacCarthy, D.S., Valdivia, R., Antle, J., Adam, M., 2017. Trade policy implications of climate change impacts on current and future agricultural systems in the semi-arid regions of West Africa. In: International Technical Conference on Climate

Change, Agricultural Trade and Food Security, 15–17 November 2017. FAO, Rome, ITALY. . http://www.agmip.org/wp-content/uploads/2017/11/Abstract_FAO-call_Hathie-et-al.pdf.

Hay, L.E., Wilby, R.L., Leavesley, G.H., 2000. A comparison of delta change and downscaled GCM scenarios for three mounfainous basins in the United States. JAWRA J. Am. Water Resour. Assoc. 36 (2), 387–397.

Heinemann, A.B., de HN Maia, A., Dourado-Neto, D., Ingram, K., Hoogenboom, G., 2006. Soybean (Glycine max (L.) Merr.) growth and development response to CO_2 enrichment under different temperature regimes. Eur. J. Agron. 24, 52–61.

IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. part B: regional aspects. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Contribution of Working Group II to The Fifth Assessment Report of The Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 688.

Kalariya, K., Singh, A., Chakraborty, K., Ajay, B., Zala, P., Patel, C., Nakar, R., Goswami, N., Mehta, D., 2015. SCMR: a more pertinent trait than SLA in peanut genotypes under transient water deficit stress during summer. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences 1–11.

Ketring, D., 1984. Temperature effects on vegetative and reproductive development of peanut. Crop Sci. 24, 877–882.

Kim, H.Y., Lieffering, M., Kobayashi, K., Okada, M., Miura, S., 2003. Seasonal changes in the effects of elevated CO_2 on rice at three levels of nitrogen supply: a free air CO_2 enrichment (FACE) experiment. Global Change Biol. 9, 826–837.

Kimball, B.A., 2016. Crop responses to elevated CO2 and interactions with H2O, N, and temperature. Curr. Opin. Plant Biol. 31, 36–43.

Kimball, B., LaMorte, R., Pinter, P., Wall, G., Hunsaker, D., Adamsen, F., Leavitt, S., Thompson, T., Matthias, A., Brooks, T., 1999. Free-air CO2 enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. Water Resour. Res. 35, 1179–1190.

Kimball, B., White, J., Ottman, M.J., Wall, G., Bernacchi, C., Morgan, J., Smith, D., 2015. Predicting canopy temperatures and infrared heater energy requirements for warming field plots. Agron. J. 107, 129–141.

Kiniry, J., Simpson, C., Schubert, A., Reed, J., 2005. Peanut leaf area index light interception, radiation use efficiency, and harvest index at three sites in Texas. Field Crops Res. 91, 297–306.

Konlan, S., Sarkodies-Addo, J., Asare, E., Kombiok, M.J., 2013. Groundnut (Arachis hypogaea) varietal response to spacing in the Guinea Savanna agro-ecological zone of Ghana: nodulation and nitrogen fixation. Agric. Biol. J. N. Am. 324–335.

Leakey, A.D., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R., 2009. Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. J. Exp. Bot. 60, 2859–2876.

Lobell, D.B., Bänziger, M., Magorokosho, C., Vivek, B., 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat. Clim. Change 1, 42–45.

Lobell, D.B., Hammer, G.L., Chenu, K., Zheng, B., McLean, G., Chapman, S.C., 2015. The shifting influence of drought and heat stress for crops in northeast Australia. Global Change Biol. 21, 4115–4127.

Mbaye, M.L., Haensler, A., Hagemann, S., Gaye, A.T., Moseley, C., Afouda, A., 2016. Impact of statistical bias correction on the projected climate change signals of the regional climate model REMO over the Senegal River Basin. Int. J. Climatol. 36 (4), 2035–2049.

Meier, U., 2001. Stades phénologiques des mono-et dicotylédones cultivées BBCH Monographie, 2e éd. Uwe Meier (réd.) Centre fédéral de recherches biologiques pour l'agriculture et les forêts.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M., Lamarque, J., Matsumoto, K., Montzka, S., Raper, S., Riahi, K., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109, 213–241.

Monin, A., Obukhov, A., 1954. Basic laws of turbulent mixing in the surface layer of the atmosphere. Contrib. Geophys. Inst. Acad. Sci. USSR 151, 163–187.

Montfort, M.-A., 2005. Notes et etudes économiques. Filières oléagineuses. pp. 55–85.

Naab, J., Singh, P., Boote, K., Jones, J., Marfo, K., 2004. Using the CROPGRO-peanut model to quantify yield gaps of peanut in the Guinean Savanna Zone of Ghana. Agron. J. 96, 1231–1242.

Naab, J., Boote, K., Jones, J., Porter, C.H., 2015. Adapting and evaluating the CROPGRO-peanut model for response to phosphorus on a sandy-loam soil under semi-arid tropical conditions. Field Crops Res. 176, 71–86.

Noba, K., Ngom, A., Guèye, M., Bassène, C., Kane, M., Diop, I., Ndoye, F., Mbaye, M.S., Kane, A., Ba, A.T., 2014. L'arachide au Sénégal: état des lieux contraintes et perspectives pour la relance de la filière. OCL 21, pp. D205.

Pinto, R.S., Reynolds, M.P., 2015. Common genetic basis for canopy temperature depression under heat and drought stress associated with optimized root distribution in bread wheat. Theor. Appl. Genet. 128, 575–585.

Prasad, P., Craufurd, P., Summerfield, R., 1999. Sensitivity of peanut to timing of heat stress during reproductive development. Crop Sci. 39, 1352–1357.

Prasad, P.V.V., Craufurd, P.Q., Kakani, V.G., Wheeler, T.R., Boote, K.J., 2001. Influence of high temperature during pre-and post-anthesis stages of floral development on fruit-set and pollen germination in peanut. Funct. Plant Biol. 28, 233–240.

Prasad, P., Boote, K.J., Hartwell Allen, L., Thomas, J.M., 2003. Super-optimal temperatures are detrimental to peanut (Arachis hypogaea L.) reproductive processes and yield at both ambient and elevated carbon dioxide. Global Change Biol. 9, 1775–1787.

Prasad, P.V., Kakani, V.G., Upadhyaya, H.D., 2010. Growth and Production of Groundnut. UNESCO Encyclopedia, pp. 1–26.

Reuter, D.J., 1997. Plant Analysis: an Interpretation Manual. CSIRO publishing.

Rezaei, E.E., Webber, H., Gaiser, T., Naab, J., Ewert, F., 2015. Heat stress in cereals: mechanisms and modelling. Eur. J. Agron. 64, 98–113.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: what does the recent literature say? Global Environ. Change 21, 1073–1083.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010.

Shibu, M., Leffelaar, P., Van Keulen, H., Aggarwal, P., 2010. LINTUL3, a simulation model for nitrogen-limited situations: application to rice. Eur. J. Agron. 32, 255–271.

Siebert, S., Ewert, F., Rezaei, E.E., Kage, H., Grass, R., 2014. Impact of heat stress on crop yield—on the importance of considering canopy temperature. Environ. Res. Lett. 9, 044012.

Sinclair, T., Bennett, J., Boote, K., 1993. Leaf nitrogen content, photosynthesis and radiation use efficiency in peanut 1. Peanut Sci. 20, 40–43.

Sinclair, T., Leilah, A., Schreffler, A., 1995. Peanut nitrogen fixation (C2H2 reduction) response to soil dehydration. Peanut Sci. 22, 162–166.

Singh, P., Nedumaran, S., Ntare, B., Boote, K., Singh, N., Srinivas, K., Bantilan, M., 2014. Potential benefits of drought and heat tolerance in groundnut for adaptation to climate change in India and West Africa. Mitig. Adapt. Strategies Global change 19, 509–529.

Soler, C.M.T., Suleiman, A., Anothai, J., Flitcroft, I., Hoogenboom, G., 2013. Scheduling irrigation with a dynamic crop growth model determining the relation between simulated drought stress and yield for peanut. Irrig. Sci. 889–901.

Songsri, P., Jogloy, S., Holbrook, C., Kesmala, T., Vorasoot, N., Akkasaeng, C., Patanothai, A., 2009. Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water. Agric. Water Manage. 96, 790–798.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., Baron, C., 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ. Res. Lett. 8, 014040.

Tarawali, A.-R., Quee, D.D., 2014. Performance of groundnut (Arachis hypogaea L.) varieties in two agro-ecologies in Sierra Leone. Afr. J. Agric. Res. 9, 1442–1448.

Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J. Hydrol. 456, 12–29.

Thinh, N.C., Shimono, H., Kumagai, E., Kawasaki, M., 2017. Effects of elevated CO2 concentration on growth and photosynthesis of Chinese yam under different temperature regimes. Plant Prod. Sci. 20, 227–236.

Tubiello, F.N., Soussana, J.-F., Howden, S.M., 2007. Crop and pasture response to climate change. Proc. Natl. Acad. Sci. 104, 19686–19690.

Vaidya, S., Vanaja, M., Sathish, P., Anitha, Y., Jyothi-Lakshmi, N., 2014. Impact of elevated CO2 on growth and physiological parameters of groundnut (Arachis hypogaea L.) genotypes. J. Plant Physiol. Pathol. 3.

Watanabe, S., Kanae, S., Seto, S., Yeh, P.J.F., Hirabayashi, Y., Oki, T., 2012. Intercomparison of bias-correction methods for monthly temperature and precipitation simulated by multiple climate models. J. Geophys. Res.: Atmos. 117.

Webber, H., Gaiser, T., Ewert, F., 2014. What role can crop models play in supporting climate change adaptation decisions to enhance food security in Sub-Saharan Africa? Agric. Syst. 127, 161–177.

Webber, H., Ewert, F., Kimball, B., Siebert, S., White, J., Wall, G., Ottman, M., Trawally, D., Gaiser, T., 2016. Simulating canopy temperature for modelling heat stress in cereals. Environ. Model. Softw. 77, 143–155.

Webber, H., Martre, P., Asseng, S., Kimball, B., White, J., Ottman, M., Wall, G.W., De Sanctis, G., Doltra, J., Grant, R., Kassie, B., Maiorano, A., Olesen, J.E., Ripoche, D., Rezaei, E.E., Semenov, M.A., Stratonovitch, P., Ewert, F., 2017. Canopy temperature for simulation of heat stress in irrigated wheat in a semi-arid environment: a multi-model comparison. Field Crops Res. 202, 21–35.

Webber, H., White, J.W., Kimball, B.A., Ewert, F., Asseng, S., Rezaei, E.E., Pinter, P.J., Hatfield, J.L., Reynolds, M.P., Ababaei, B., Bindi, M., Doltra, J., Ferrise, R., Kage, H., Kassie, B.T., Kersebaum, K.-C., Luig, A., Olesen, J.E., Semenov, M.A., Stratonovitch, P., Ratjen, A.M., LaMorte, R.L., Leavitt, S.W., Hunsaker, D.J., Wall, G.W., Martre, P., 2018. Physical robustness of canopy temperature models for crop heat stress simulation across environments and production conditions. Field Crops Res. 216, 75–88.

Wilby, R., Charles, S., Zorita, E., Timbal, B., Whetton, P., Mearns, L., 2004. Guidelines for use of climate scenarios developed from statistical downscaling methods. Supporting Material of the Intergovernmental Panel on Climate Change, Available from the DDC of IPCC TGCIA 27.

Wolf, J., 2012. User Guide for LINTUL5: Simple Generic Model for Simulation of Crop Growth Under Potential, Water Limited and Nitrogen, Phosphorus and Potassium Limited Conditions. Wageningen University (p. 63).

Wright, G.C., Hubick, K.T., Farquhar, G.D., 1991. Physiological analysis of peanut cultivar response to timing and duration of drought stress. Aust. J. Agric. Res 42, 453–470.

Wu, W.-H., Lu, J.Y., Jones, A.R., Mortley, D.G., Loretan, P.A., Bonsi, C.K., Hill, W.A., 1997. Proximate composition, amino acid profile, fatty acid composition, and mineral content of peanut seeds hydroponically grown at elevated CO2 levels. J. Agric. Food Chem. 45, 3863–3866.

Yao, J.P., Luo, Y.N., Yang, X.D., 1982. Preliminary report on the effect of drought and seed development and quality of early groundnut. Chin. Oil Scops 3, 50–52.

Zhao, G., Webber, H., Hoffmann, H., Wolf, J., Siebert, S., Ewert, F., 2015. The implication of irrigation in climate change impact assessment: a European-wide study. Global Change Biol. 21, 4031–4048.

van Roosmalen, L., Sonnenborg, T.O., Jensen, K.H., Christensen, J.H., 2011. Comparison of hydrological simulations of climate change using perturbation of observations and distribution-based scaling. Vadose Zone J. 10, 136–150.