Impacts of 1.5 versus 2.0°C on cereal yields in the West African Sudan Savanna

SI Materials

Table S1. Annual absolute change (average absolute change ± standard deviation) of daily maximum and minimum temperature (°C) and annual precipitation sum (mm) for two warming scenarios (1.5°C, 2°C) and three general circulation models (GCM) relative to the baseline (2006-2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

Variable	Scenario	GCM		
		ECHAM6	MIROC5	NorESM1
T_{max}	1.5°C	1.0 ± 0.3	1.0 ± 0.1	0.8 ± 0.2
	2.0°C	1.4 ± 0.2	1.4 ± 0.1	1.3 ±0.2
T_{min}	1.5°C	1.1 ± 0.1	0.9 ± 0.1	0.8 ± 0.1
	2.0°C	1.7 ± 0.1	1.2 ± 0.1	1.4 ± 0.1
Precipitation	1.5°C	-79 ± 65	-5 ± 30	-11 ± 53
	2.0°C	-90 ± 55	-2 ± 42	6 ± 48

Table S2: Absolute change (average absolute change ± standard deviation) of daily maximum and minimum temperature (°C) and precipitation sum (mm) during the growing season for West Africa (assumed here as June to end of September) for two warming scenarios (1.5°C, 2°C) and three general circulation models relative to the baseline (2006-2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

Variable	Scenario	GCM		
		ECHAM6	MIROC5	NorESM1
T_{max}	1.5°C	0.9 ± 0.2	1.2 ± 0.1	0.8 ± 0.2
	2.0°C	1.5 ± 0.2	1.5 ± 0.1	1.3 ±0.2
T_{min}	1.5°C	0.9 ± 0.1	0.9 ± 0.1	0.7 ± 0.0
	2.0°C	1.5 ± 0.1	1.2 ± 0.1	1.2 ± 0.1
Precipitation	1.5°C	-35 ± 32	8 ± 24	4 ± 41
	2.0°C	-28 ± 32	12 ± 31	21 ± 44

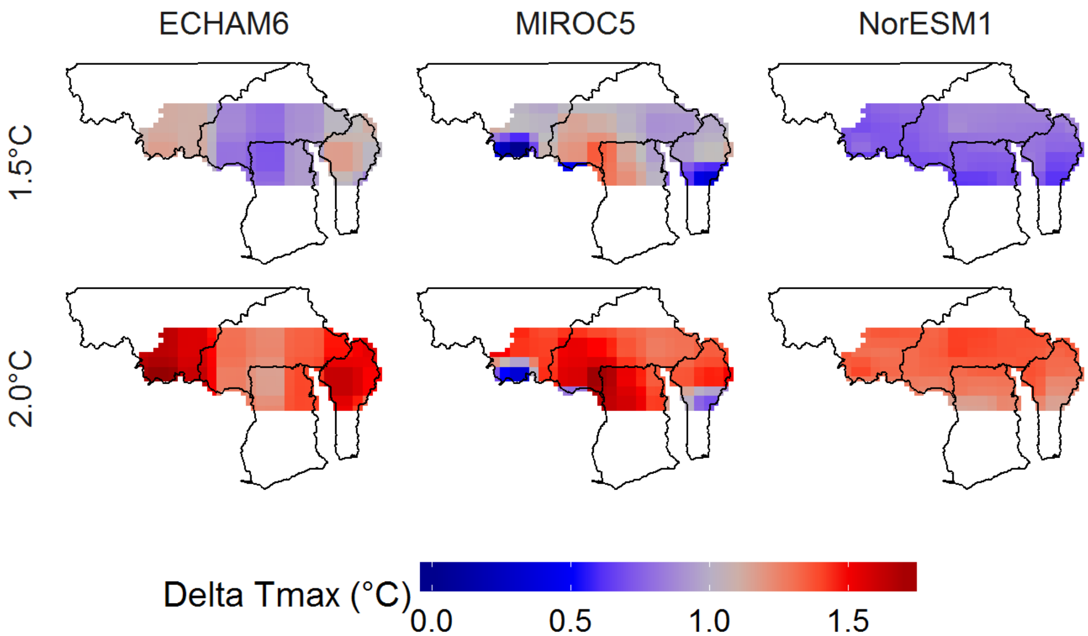


Figure S1. Average absolute changes (Delta Tmax) in average daily maximum temperature (T_{max}, °C) for two warming scenarios (1.5°C, 2°C) and three general circulation models (GCM) relative to baseline climate (2006 to 2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

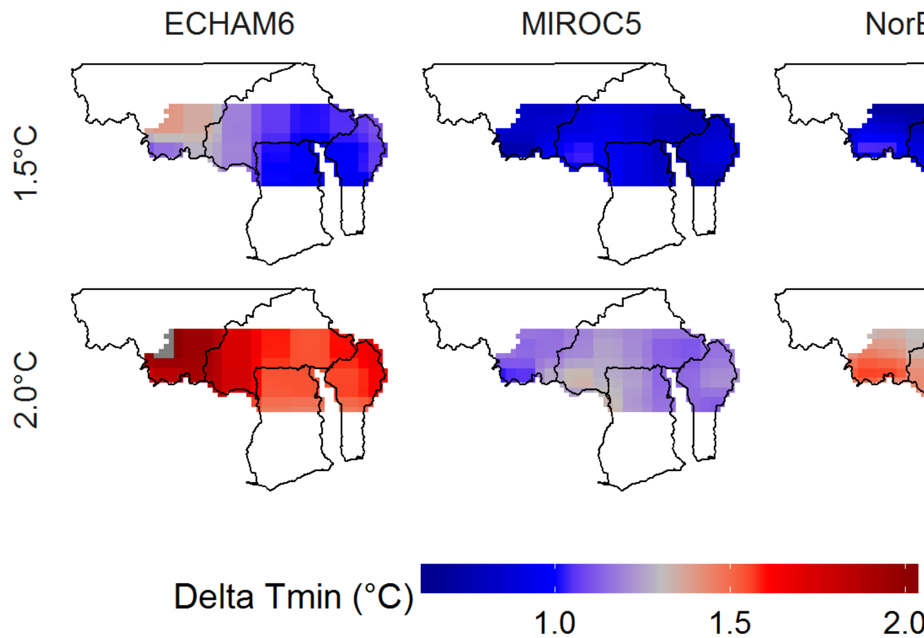


Figure S2. Average absolute changes (Delta Tmin) in average daily minimum temperature (T_{min}, °C) for two warming scenarios (1.5°C, 2°C) and three general circulation models (GCM) relative to baseline conditions (2006 to 2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

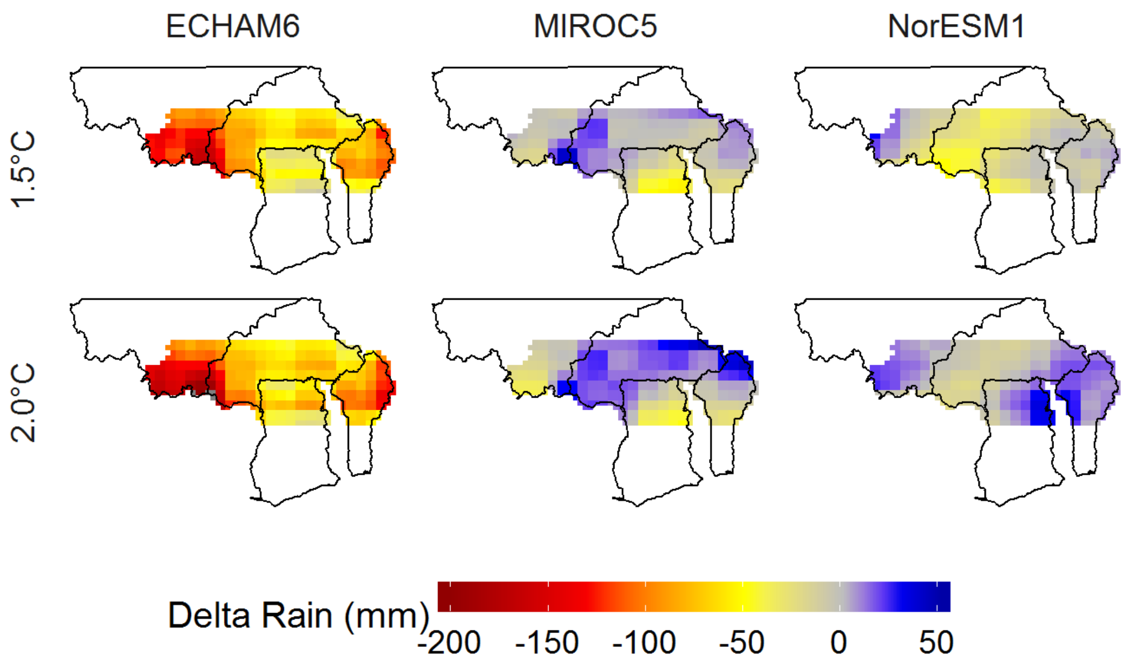


Figure S3. Average absolute changes (Delta Rain) in annual precipitation sum (P, mm) for two warming scenarios (1.5°C, 2°C) and three general circulation models (GCM) relative to baseline climate (2006 to 2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

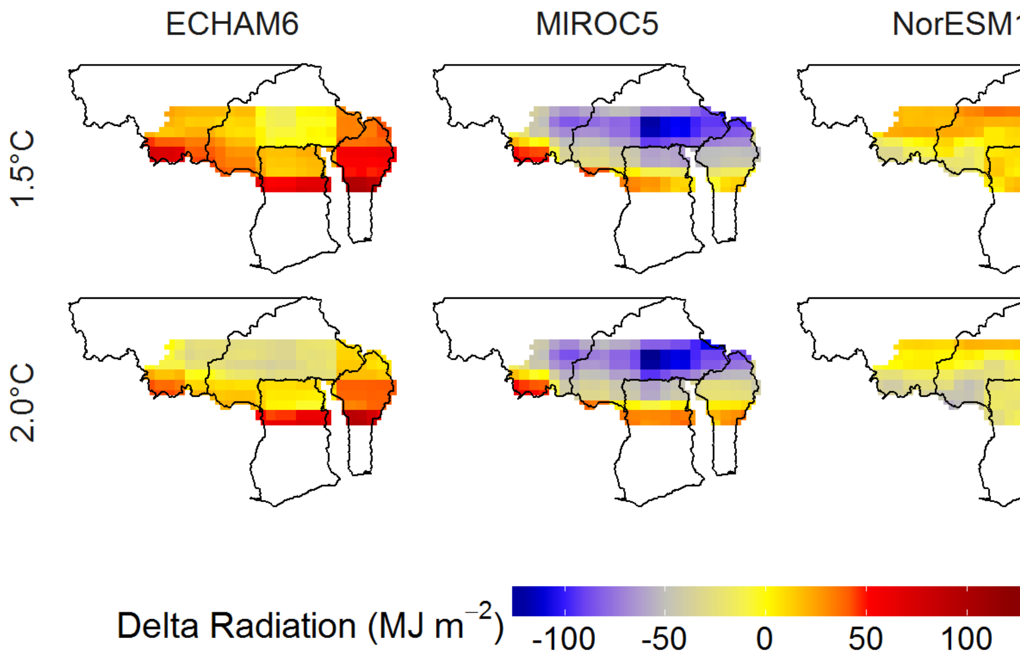


Figure S4. Average absolute changes (Delta Radiation) in annual solar radiation sum (R, MJ m^2) for two warming scenarios (1.5°C, 2°C) and three general circulation models (GCM) relative to baseline climate (2006 to 2015). Summary statistics were calculated over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

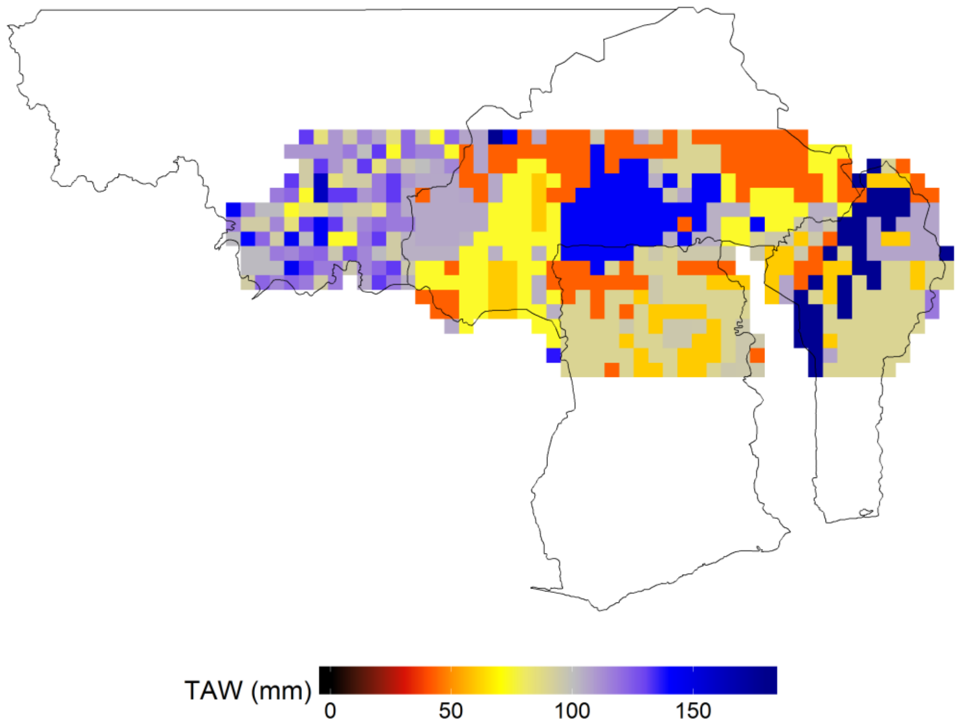


Figure S5. Variation of soil total available water (TAW, mm) for each simulation unit.

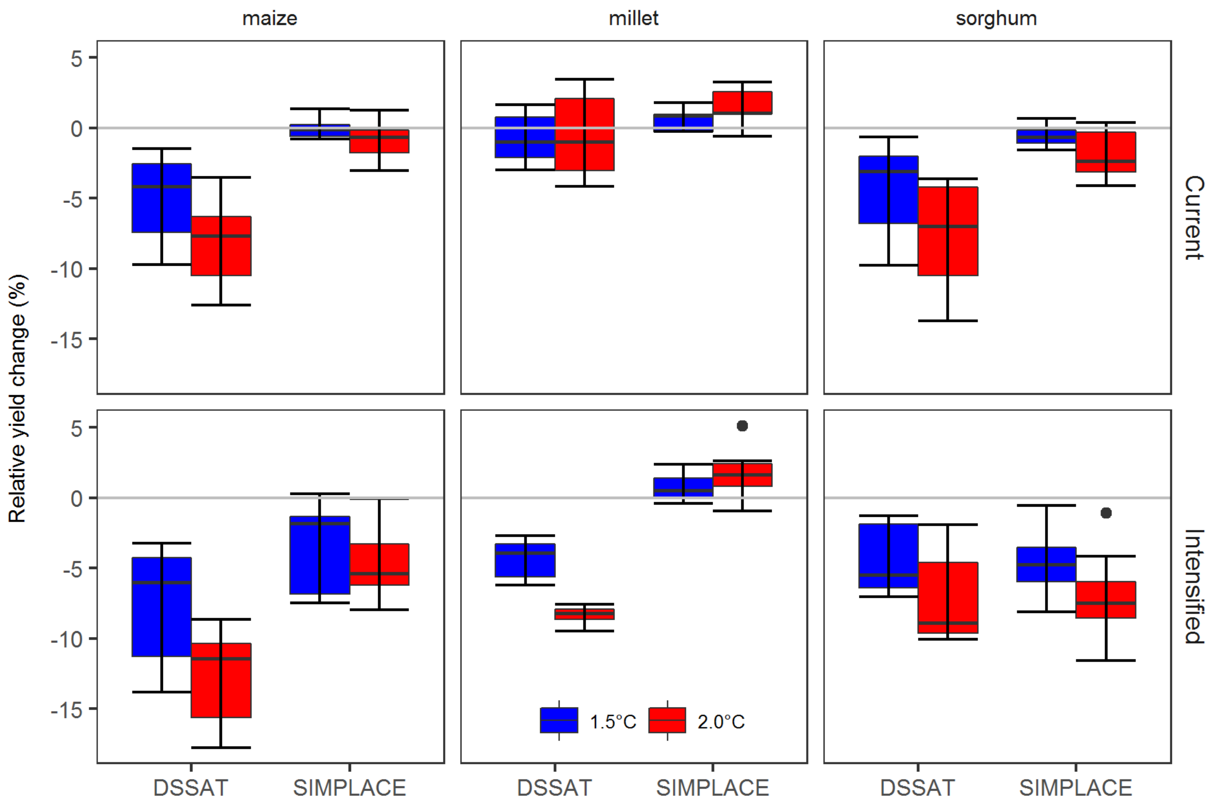


Figure S6. Difference between DSSAT and SIMPLACE simulated impact of 1.5°C (blue) and 2.0°C (red) of warming on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the current baseline period (2006 – 2015). Impacts are shown for current fertilizer levels (top row) and for fully fertilized case (Intensified, bottom row) systems. Uncertainty captured in the figure covers three GCMs and three sowing windows. All simulations shown include the effects of elevated atmospheric [CO_2].

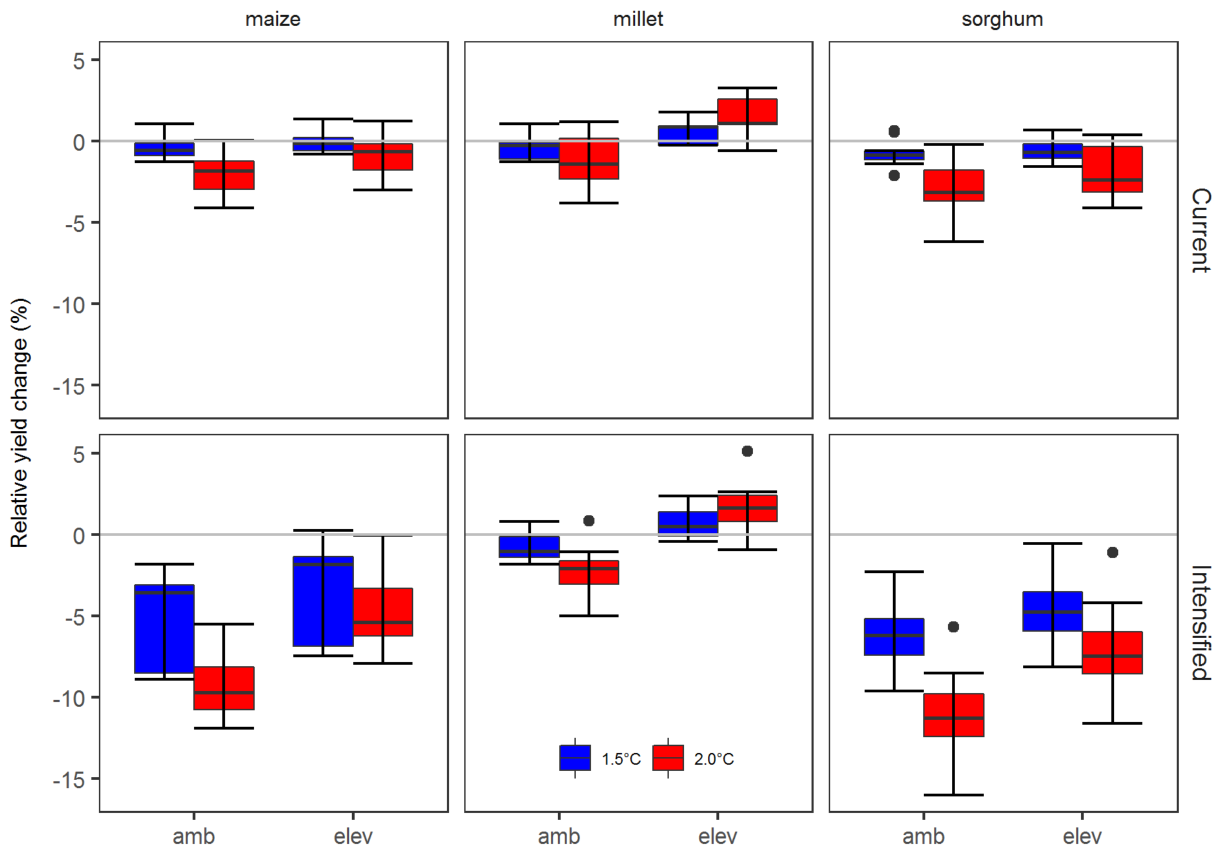


Figure S7. Simulated SIMPLACE-model impact of 1.5°C (blue) and 2.0°C (red) of warming on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the current baseline period (2006 – 2015). Impacts are shown for systems with current ambient (amb) and scenario projected atmospheric CO_2 concentrations (elev) for current fertilizer levels (top row) and for fully fertilized case (Intensified, bottom row). Uncertainty captured in the figure covers three GCMs and three sowing dates. Simulations were performed with the SIMPLACE model.

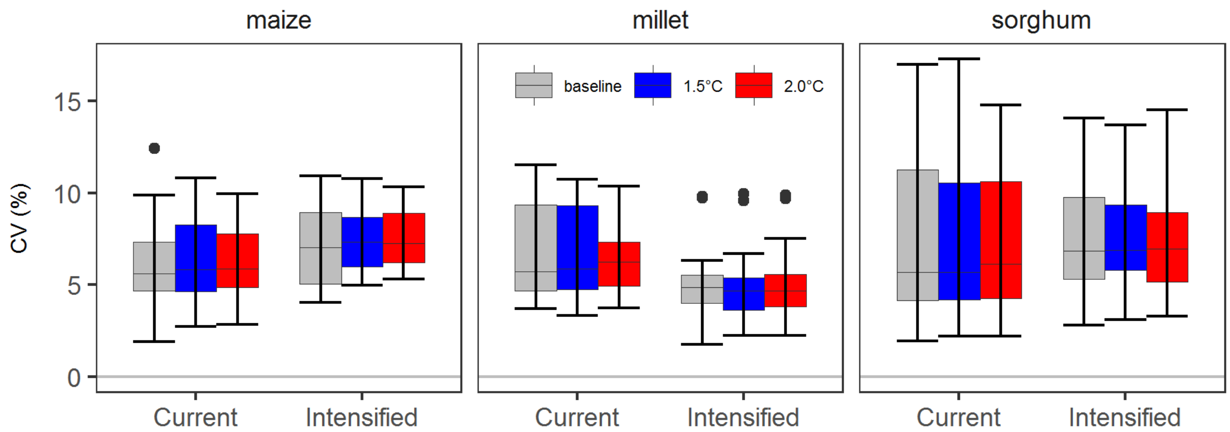


Figure S8. Effect of intensification on simulated coefficient of variation (CV) for baseline (grey, 2006 – 2015), 1.5°C (blue) and 2.0°C (red) of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region. Impacts are shown for both systems with current fertilizer levels and for fully fertilized case (Intensified), considering [CO_2] fertilization effects. Uncertainty captured in each boxplot is due to the three sowing windows, three GCMs and two crop models.

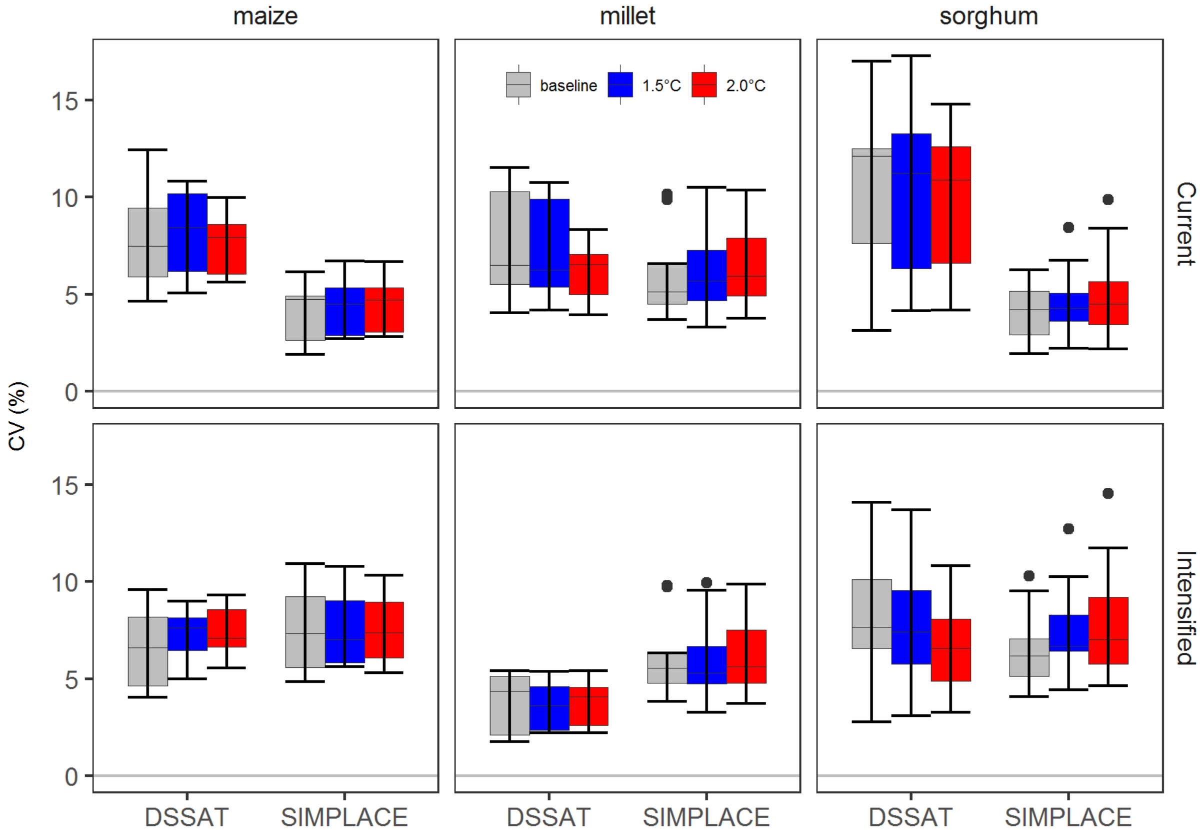


Figure S9. Effect of crop model on simulated coefficient of variation (CV) for baseline (grey, 2006 – 2015), 1.5°C (blue) and 2.0°C (red) of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region. Impacts are shown for DSSAT and SIMPLACE for both systems with current fertilizer levels (top row) and for fully fertilized case (Intensified, bottom row), considering [CO_2] fertilization effects. Uncertainty captured in each boxplot is due to the three sowing windows and three GCMs.

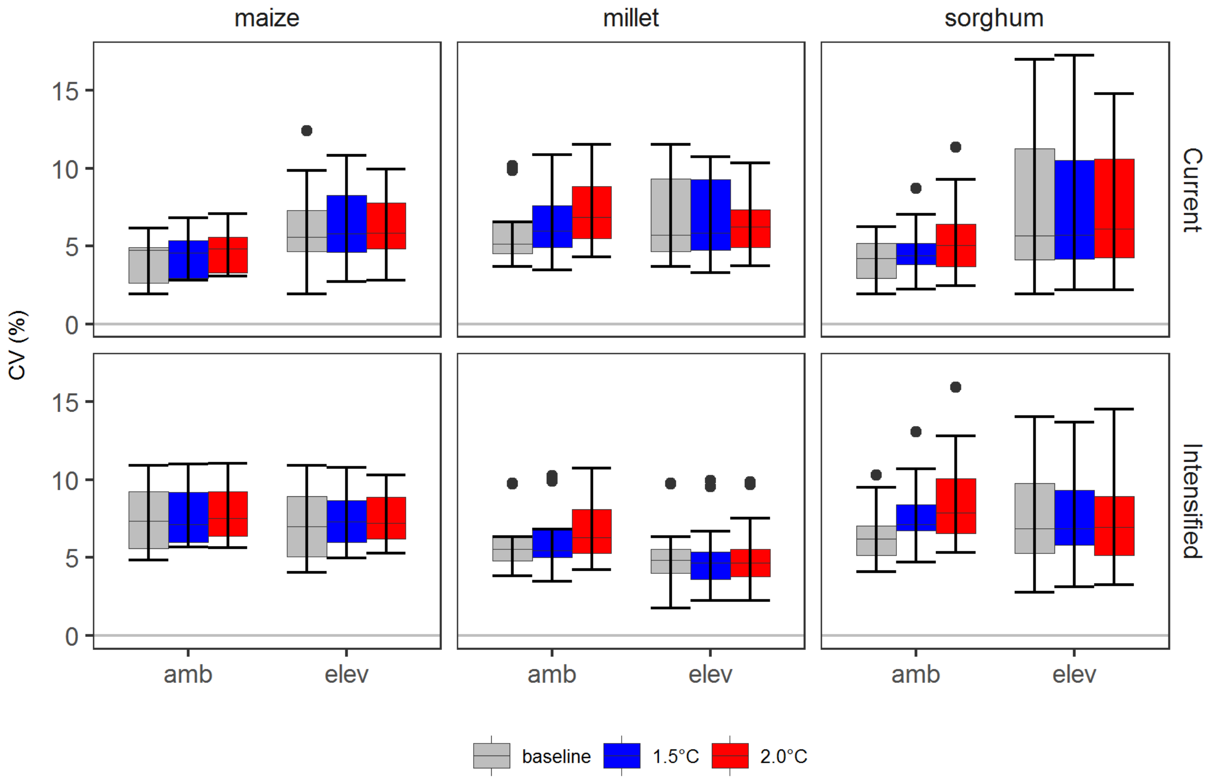


Figure S10. Effect of ambient versus elevated CO_2 (with SIMPLACE-model) on simulated coefficient of variation (CV) for baseline (grey, 2006 – 2015), 1.5°C (blue) and 2.0°C (red) of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region. Impacts are shown for current fertilizer use (top row) and intensified, non-limiting fertilizer use (bottom row) for both without [CO_2] fertilization effects (amb) and with consideration of [CO_2] fertilization effects (elev). Uncertainty captured in the figure covers 20 instances of each of three GCMs.

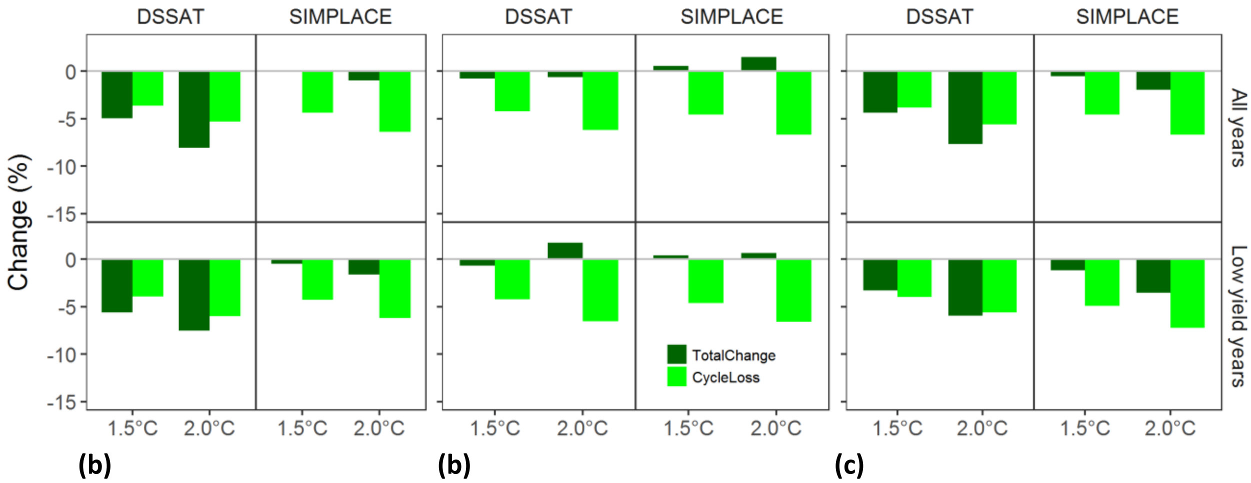
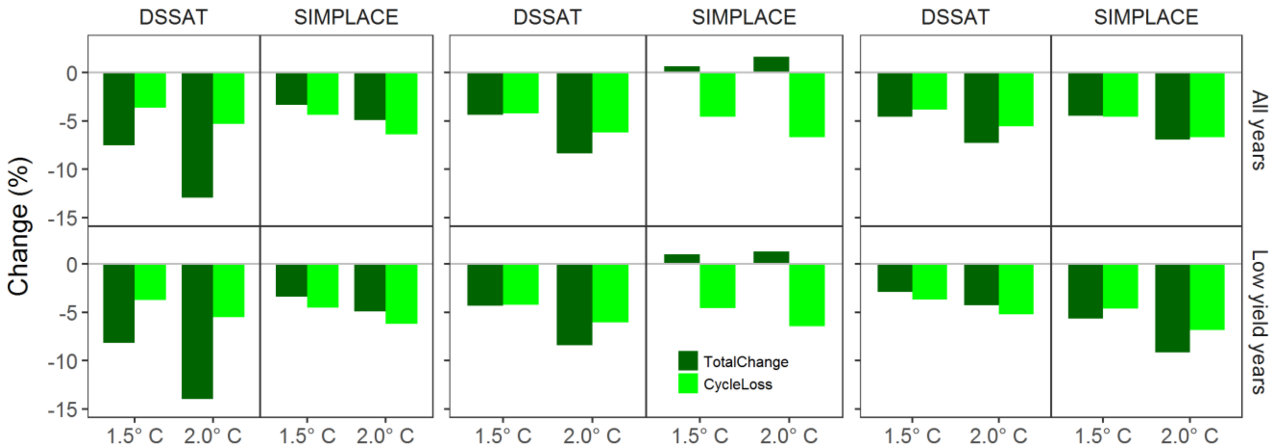


Figure S11. Comparing total yield changes (dark green) with the change in growing season duration (green) for 1.5°C and 2.0°C of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region across all years (top row) and in years with yields in the lowest decile (bottom row) relative to baseline climate (2006 to 2015) for current fertilizer case. Relative changes were determined over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario. Results are shown for both crop models in adjacent panels for (a) maize, (b) millet and (c) sorghum. All simulations considered elevated [CO_2] and are averaged across sowing dates and GCMs.



(a) **(b)** **(c)**

Figure S12. Comparing total yield changes (dark green) with the change in growing season duration (green) for 1.5°C and 2.0°C of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region across all years (top row) and in years with yields in the lowest decile (bottom row) relative to the baseline climate (2006 to 2006) for intensified, non-limiting fertilizer case. Relative changes were determined over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario. Results are shown for both crop models in adjacent panels for (a) maize, (b) millet and (c) sorghum. All simulations considered elevated [CO_2] and are averaged across sowing dates and GCMs.

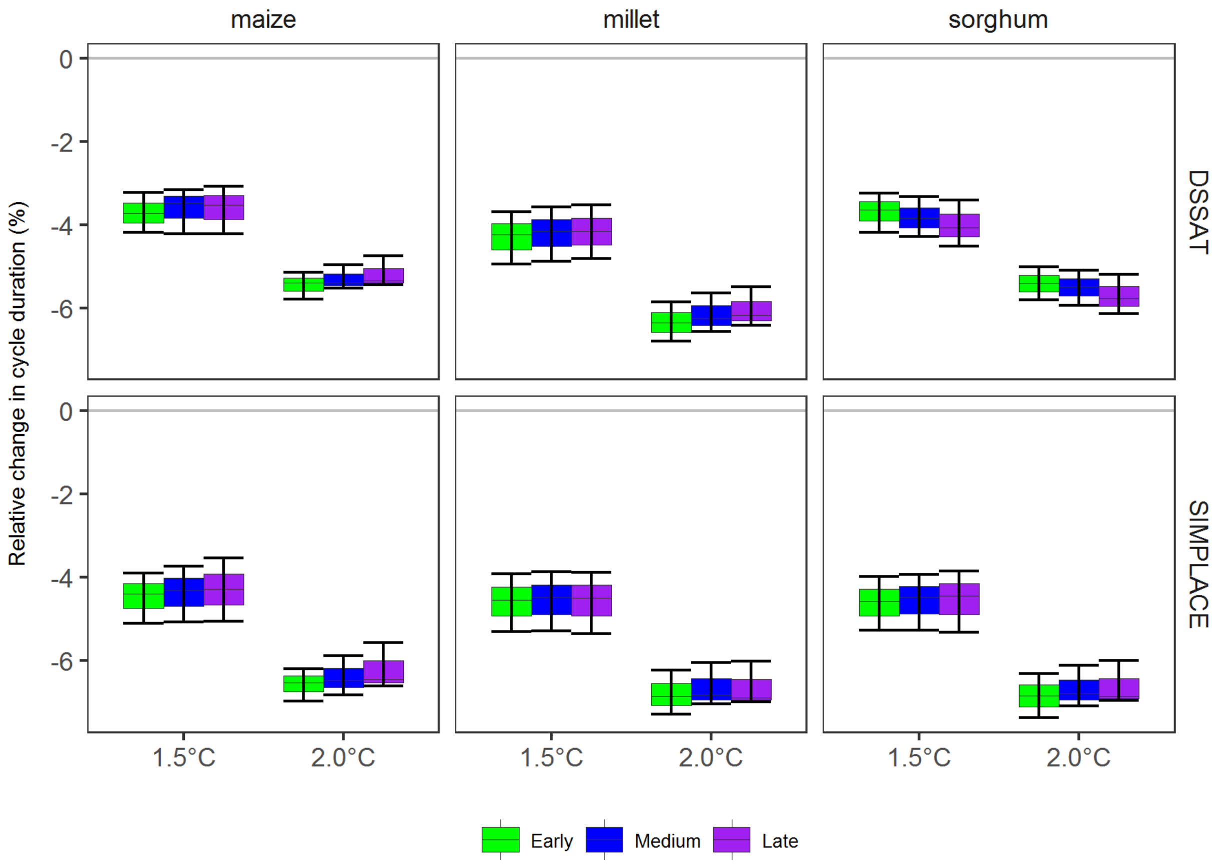


Figure S13. Simulated relative change in duration of the growing cycle for 1.5°C and 2.0°C of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region relative to the baseline climate (2006-2015). Change in cycle duration is shown early (green), medium (blue) and late (purple) sowing windows. The cycle is independent of nutrient or [CO_2] level. Uncertainty captured in the figure covers the three GCMs. Relative changes were determined over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

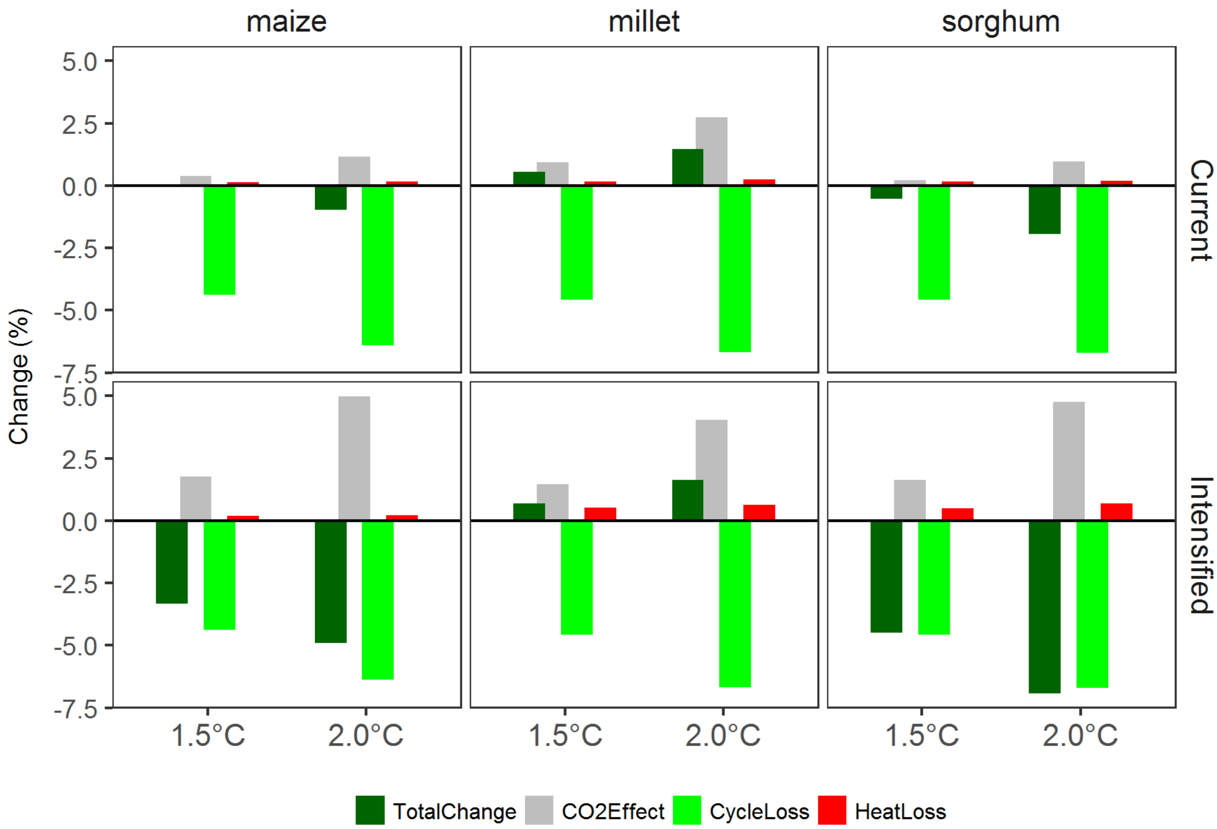


Figure S14. Drivers of yield change for 1.5°C and 2.0°C of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region with current fertilizer use (top row) and intensified, non-limiting fertilizer case (bottom row). The total yield change and change in cycle duration are relative to values in baseline climate (2006 to 2015). Change due to [CO_2] is in the climate of the scenario but relative to the case of no [CO_2] fertilization effects. The heat losses are determined as the difference between yield changes with heat-water-nutrient limitation and yield changes with water-nutrient limitation in a given warming scenario. Simulations are for the SIMPLACE model and considered elevated [CO_2], except to determine the CO_2 effects which considered simulations both with and without [CO_2] fertilization. Relative changes were determined over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario.

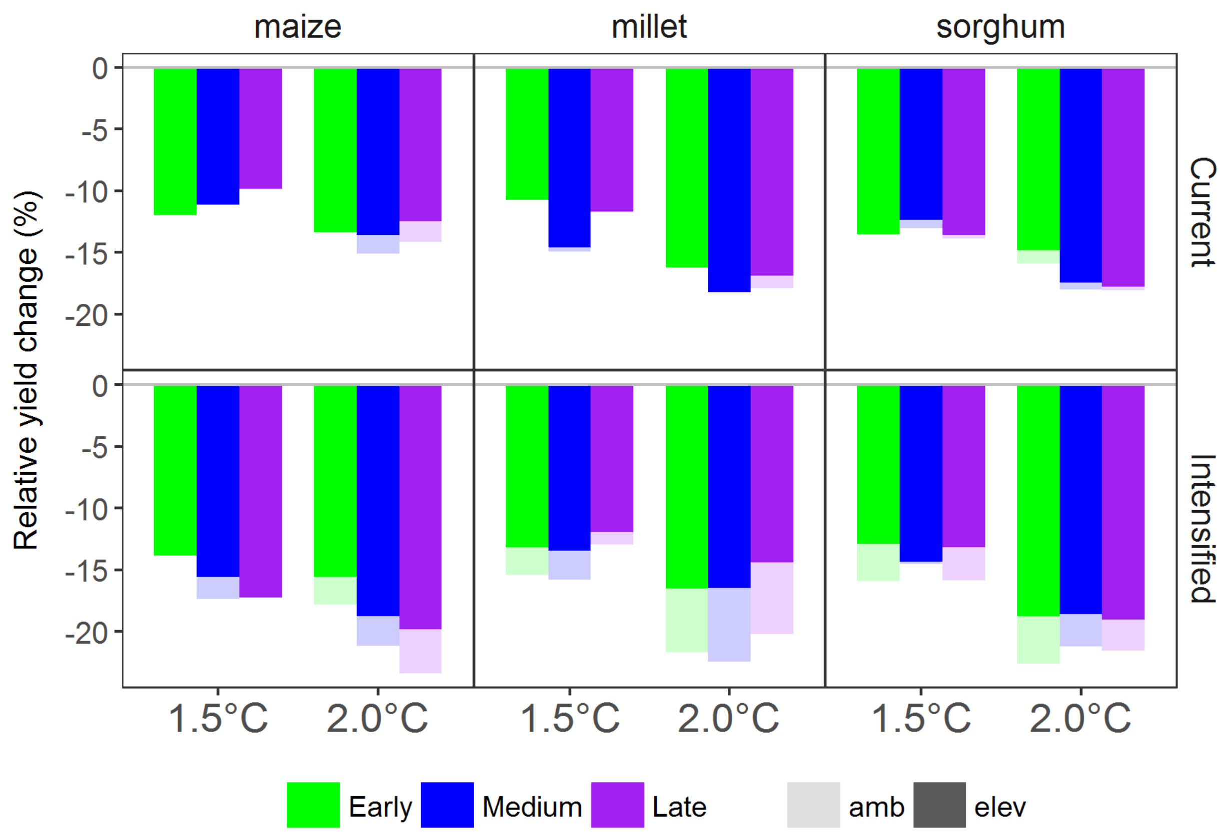


Figure S15 Simulated relative change in yield losses from heat stress for 1.5°C and 2.0°C of warming scenarios on maize, millet and sorghum yields for the West African Sudan Savanna region. Impacts are shown for early (green), medium (blue) and late (purple) sowing windows with current fertilizer use (top row) and intensified, non-limiting fertilizer use (bottom row) both with and without [CO_2] fertilization effects as indicated by the shading. Uncertainty captured in the figure the three GCMs. Relative changes were determined over 200 years (e.g. pooling the 20 sets of 10-year climate series) for each GCM and scenario with simulations from SIMPLACE.

Crop model description

SIMPLACE is a framework that enables linking crop models that represent different aspects and processes in agricultural systems for a variety of scientific purposes (Gaiser *et al.*, 2013). A combined model solution was SIMPLACE <Lintul5, SLIMWater, FAO ET, CanopyT, Heat Stress>, referred to as SIMPLACE< LINTUL5+>. LINTUL5 is a generic model, which can be used for 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 in turn 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 time requirements from emergence to anthesis (TSUM1) and from anthesis to maturity (TSUM2). Slimwater is used to simulate crop water uptake. Crop water demand is calculated according the FAO Penman-Monteith method (Allen *et al.*, 1998) with a reference crop and considering the dual crop coefficient method. Canopy temperature is estimated 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) (Webber *et al.*, 2016). A heat stress module (Gabaldón-Leal *et al.*, 2016) reduces grain yield when the hourly temperature is above a critical threshold temperature around anthesis to simulate failure of flowering and grain abortion.

DSSAT is a process based, mechanistic and crop management oriented model comprising a suite of modules (Jones *et al.*, 2003). It utilizes information from soil profile, crop management, crop genetic coefficients, daily weather (maximum and minimum temperature, rainfall and solar radiation) to simulate soil and crop processes, thus predicting crop yield and other plant specific outputs. Optimal plant growth is a function of photosynthetic capacity, radiation capture, thermal time and photoperiod sensitivity whereas actual growth and development are constrained by nutrient and water stress as well as sub-optimal temperatures(Soler *et al.*, 2007). Growth is constrained by nutrient and water sub-modules through stress factors. Plant nitrogen availability is guided via fertilizer input and mineralization of soil organic carbon. The Century model (Parton *et al.*, 1988) embedded in DSSAT (Porter *et al.*, 2010) was used in simulating soil organic matter mineralization. The Ritchie (1998) cascading water balance approach describes movement of water between soil layers. Daily water balance is a function of precipitation, irrigation, transpiration, evaporation, drainage and runoff. DSSAT has been applied in the West African Sudan Savanna in a number of studies (Naab *et al.*, 2015; Akinseye *et al.*, 2017; Parkes *et al.*, 2017; Amouzou *et al.*, 2018).

Fertilizer rates

No fertilizer was applied for millet and sorghum while fertilization for maize was based on aggregated NPK rates for each sub-region. With the assuming that a compound NPK 15-15-15 is typically used in all sub-regions, the amount of N application was derived. The total amount of N was applied at the beginning of the growing season equal to 12 kg N ha^{-1} in Ghana-North, 15 kg N ha^{-1} in Benin-North, Burkina-Northeast, and Burkina South and 14 kg N ha^{-1} in Mali-South. Other nutrients were assumed non-limiting. In the non-limiting fertilizer intensification case, the crop models were run without nutrient limitation.

Calibration procedure

All cultivars were already calibrated in DSSAT and published or under process for publication (Table S3). The same datasets were used for calibration in SIMPLACE as described in the following section. Tables S4-S6 give an overview of the experiments used for maize, millet and sorghum calibration, respectively.

Table S3. Calibrated cultivars in DSSAT by crop and by region and reference sources to the experiment description/model validation results.

	Benin-north	Burkina-south	Burkina-centre	Mali-south	Ghana-north
Sorghum	Kadaga (Naab 2016, unpublished data)	CSM335 (Clerget et al unpublished)	CSM63E (Clerget et al unpublished)	CSM335 (Clerget et al unpublished)	Kadaga (Naab 2016, unpublished data)
Maize	EVDT-97 STR (Naab 2016, unpublished data)	Obatanpa (Naab 2004)	Obatanpa (Naab 2004)	Obatanpa (Naab 2004)	Obatanpa (Naab 2004)
Millet	Bolga-local (Naab 2016, unpublished data)	CIVT (Akponikpè *et al.*, 2010)	CIVT (Akponikpè *et al.*, 2010)	CIVT (Akponikpè *et al.*, 2010)	Bolga-local (Naab 2016, unpublished data)

TableS4. Datasets used in SIMPLACE for maize calibration

Description	Cultivar	Site	Year	Fertilizer application: treatment (bold) and rate (not bold)	Planting day of year (DOY)	Crop cycle length in days
Data collected in North Ghana (Wa, UWR) with 9 treatments	Obatanpa	Wa/Ghana	2004	**1:** N0 P0 **2:** N0 P60 **3:** N0 P90 **4:** N60 P0 **5:** N60 P60 **6:** N60 P90 **7:** N120 P0 **8:** N120 P60 **9:** N120 P90	169	100-105
Data collected in Dassari (North Benin) with two different NPK fertilizer applications	EVDT97-SPR	Dassari /Benin	2015	**192**: 30N13P26K **227**: 30N	177	90-95

TableS5. Datasets used in SIMPLACE for millet calibration

Description	Cultivar	Site	Year	Fertilizer application DOY (bold) and rate (not bold)	Planting day of year (DOY)	Crop cycle length in days
Data collected in Sadoré (Niger) for four different sowing dates	CIVT	Sadoré	2005	Sowing 1: **109**: 10N 12P 9K **139**: 25N **160**: 25N Sowing 2: **138**: 10N 12P 9K **169**: 25N **189**: 25N Sowing 3: **170**: 10N12P9K **200**: 25N **221**: 25N Sowing 4: **200**: 10N12P9K **231**: 25N **252**: 25N	Sowing 1: 109 Sowing 2: 138 Sowing 3: 169 Sowing 4:200	90-95
Data collected in Vea (North Ghana) without fertilizer application	Bolga_local	Northern Ghana	2015	without fertilizer application	178	90
Data collected in Vea (North Ghana) with 20N fertilizer application	Bolga_local	Northern Ghana	2016	**188**: 20N	171	90

TableS6. Datasets used in SIMPLACE for sorghum calibration

Description	**Cultivar**	**Site**	**Year**	**Fertilizer application DOY (bold) and rate (not bold)**	**Planting day of year (DOY)**	**Crop cycle length in days**
Data collected in Vea (North Ghana) with fertilizer application (N) in two different dates	Kadaga	North Ghana	2015	**209**: 20N **223**: 20N	178	90
Data collected in Vea (North Ghana) with fertilizer application (N) in two different date	Kadaga	Nord Ghana	2016	**188**: 20N **202**: 20N	171	90
Data collected in Samanko (North Mali) with two NPK fertilizer application levels for each of the three different sowing dates	CSM335	Samako	2010	Sowing 1: **157**: 18N 20P **203**: 23N Sowing 2: **185**: 18N **233**: 23N Sowing 3: **211**: 18N **245**: 23N	Sowing1-165 Sowing2-190 Sowing3-217	125
Data collected in Samanko (North Mali) with two NPK fertilizer application levels for each of the three different sowing dates	CSM63E	Samako	2010	Sowing 1: **157**: 18N 20P **203**: 23N Sowing 2: **185**: 18N **233**: 23N Sowing 3: **211**: 18N **245**: 23N	Sowing1-165 Sowing2-190 Sowing3-217	100

SIMPLACE calibration results

The calibration aims to ensure that the model could reproduce the phenology observations and the yields. The phenology for all crops was accurately simulated on average (Table S7).

Table S7: Observed and simulated by SIMPLACE phenology data for three crops

	Anthesis		Maturity	
	Observed	Simulated	Observed	Simulated
Maize				
EVDT97	236	236	273	273
Obatanpa	224	224	269	270
Millet				
CIVT	222	220	250	249
Bolga-local	261	261	279	280
Sorghum				
Kadaga	247	247	266	266
CSM335	279	274	307	304
CSM63E	253	252	282	280

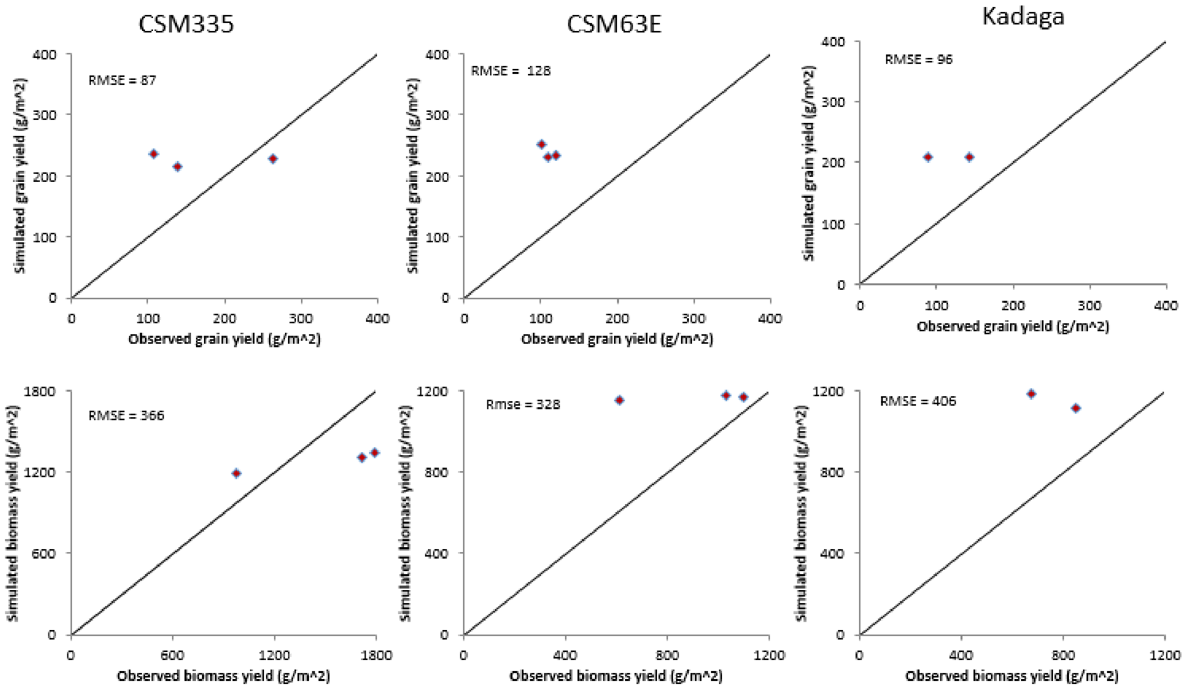


Figure S16. Simulated by SIMPALCE versus observed biomass (bottom row) and grain yield (top row) for three sorghum cultivars (CSM335, CSM63E and Kadaga). The black line is the 1:1 line added for improving visualization of the goodness of fit, RMSE – root mean square error. Note, 1 g m^{-2} is equivalent 10 kg ha^{-1}.

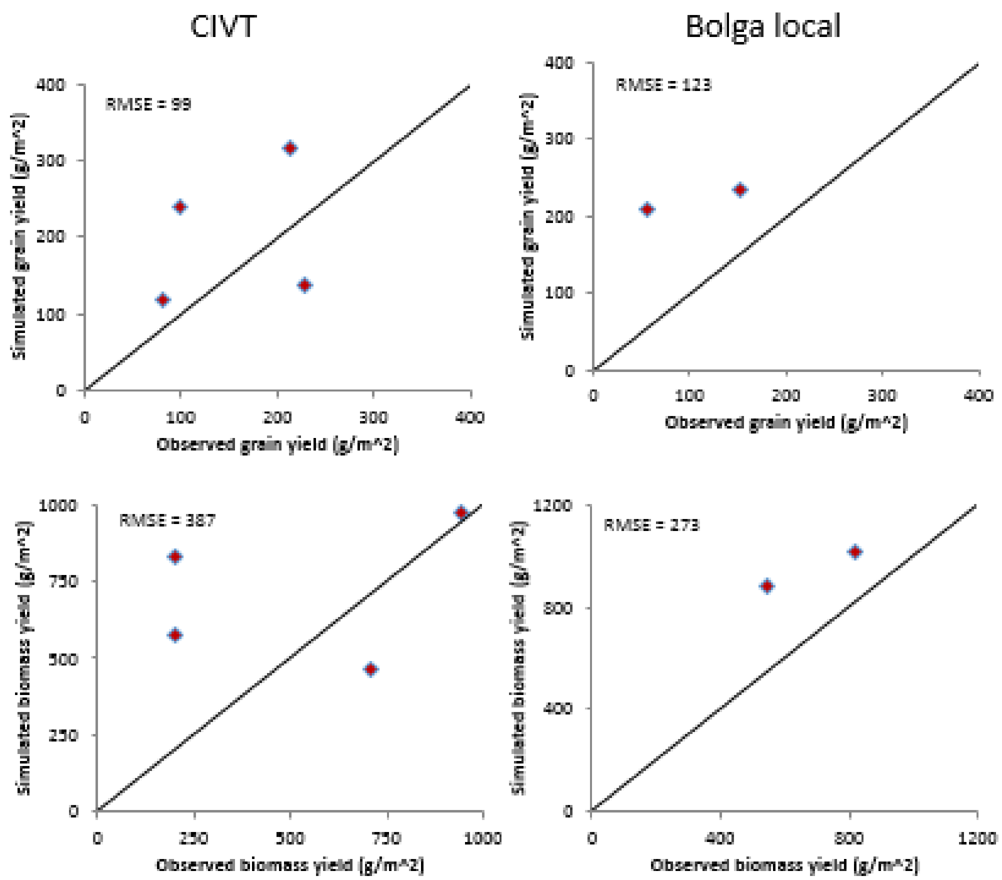


Figure S17. Simulated by SIMPLACE versus observed biomass (bottom row) and grain (top row) yield for two millet cultivars (CIVT and Bolga local). The black line is the 1:1 line added for improving for visualization of the goodness of fit, RMSE – root mean square error. Note, 1 g m^{-2} is equivalent 10 kg ha^{-1}.

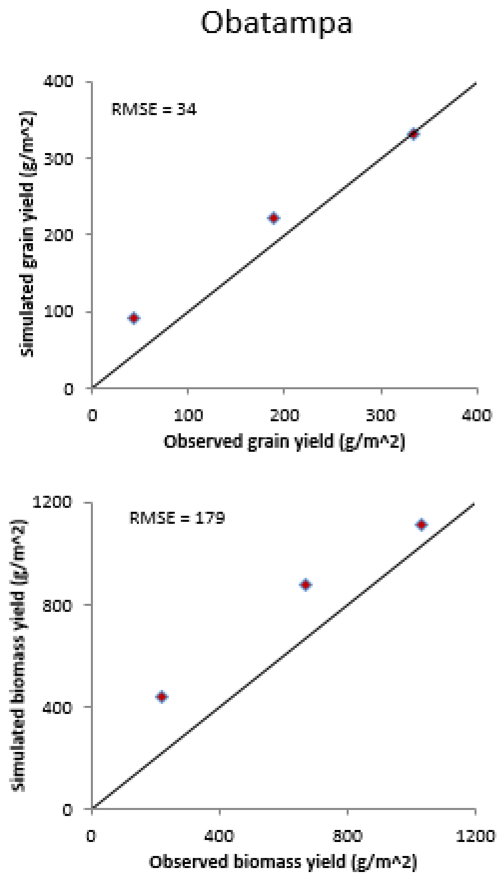


Figure S18. Simulated by SIMPLACE versus observed biomass (bottom) and grain (top) yield for maize cultivar (Obatanpa). The black line is the 1:1 line added for improving for visualization of the goodness of fit, RMSE – root mean square error. Note, 1 g m^{-2} is equivalent 10 kg ha^{-1}.

Table S8. Sowing windows by crop and by region

Crop	Region	Early sowing		Medium sowing		Late sowing	
		startdate	enddate	startdate	enddate	startdate	enddate
Sorghum	**Benin-north**	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	15.07____.
	Burkina-south	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	10.07____.
	Burkina-centre	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
	Ghana-north	10.06____.	20.06____.	21.06____.	05.07____.	06.07____.	15.07____.
	Mali-south	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
Maize	**Benin-north**	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	15.07____.
	Burkina-south	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
	Burkina-centre	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
	Ghana-north	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	01.07____.
	Mali-south	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
Millet	**Benin-north**	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	30.06____.
	Burkina-south	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
	Burkina-centre	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.
	Ghana-north	01.06____.	15.06____.	16.06____.	30.06____.	01.07____.	01.07____.
	Mali-south	10.06____.	20.06____.	21.06____.	30.06____.	01.07____.	10.07____.

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