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Adapting the CROPGRO model to simulate growth, development, and yield of Bambara groundnut (*Vigna subterranea* L. Verdc), an underutilized crop

A.S. Karunaratne [a,*], G. Hoogenboom [b], K.J. Boote [b]

[a] *Karunaratne A.S., Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya 70140, Sri Lanka*
[b] *Global Food Systems Institute & Department of Agricultural & Biological Engineering, University of Florida, PO Box 110570, Gainesville, FL 32611-0570, USA*

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ABSTRACT

Technology development has progressed in recent decades in terms of breeding and agronomy of major crops such as wheat, rice, and maize. Nevertheless, production of these major crops is under pressure from climate change and threats of marginal soil nutrients in degraded agricultural lands. Underutilized crops are identified as resilient to local environments that can cope with climatic variations. Bambara groundnut, an African legume that is grown in low input subsistence farming systems in sub–Saharan Africa and Asia has been identified as a potential future crop under climate change. Improving its productivity and suitability under future climates and future locations, requires comprehensive analysis of growth and development of Bambara groundnut under different growing conditions. Process-based crop simulation models facilitate the evaluation of management options for variable growing environments and soil conditions. Therefore, the current study was aimed to evaluate growth and development of Bambara groundnut and to adapt the generic legume model CROPGRO for explaining crop response to management and environment. The parameters used for modelling growth and development of peanut (*Arachis hypogea*) served as the initial reference values for adapting CROPGRO model. Crop information from the published sources were applied to the functions and parameters of the model. Crop phenology, canopy development, growth and yield were calibrated for two contrasting Bambara groundnut landraces using experimental data from controlled-environment experiments conducted in 2003 and 2006 at Tropical Crops Research Unit (TCRU), Sutton Bonington Campus, University of Nottingham, UK. Overall, the model calibration results of Leaf Area Index (LAI), total biomass and yield were well predicted with d-statistics greater than 0.89. The cardinal base temperatures for leaf photosynthesis of Bambara groundnut had to be set higher than those for peanut, in order to simulate the reduced growth observed during relatively low temperatures. The value for the specific leaf weight (SLWREF) at which light-saturated leaf photosynthesis is defined, was increased from 0.0043 to 0.0063 g cm^{-2} to reduce the productivity of Bambara groundnut compared to peanut. The new model will be incorporated in the DSSAT version 4.8 software and will provide capability for assessing management practices in matching environments and suggesting potential regions for future expansion of Bambara groundnut cultivation into resilient cropping systems.

1. Introduction

Present agriculture is dominated by few 'major' crop species accompanied by a global system that underpins their current productivity, supply chains and future improvements. Underutilized crops are primarily grown by native communities with less demands and popularity since the main food systems have mainstreamed with limited number of crops (Mabhaudhi et al., 2019; Jahanshiri et al., 2020). Although the advocates of major crop species have access to a wide range of quantitative and qualitative data, the underutilized crops are limited in terms of such research and are underfunded considering comparatively less importance than 'major' crops in the global food market (Nhamo et al., 2022). Although underutilized crops have limited research information and less attention in global food basket, many hundreds of these neglected crops can meet the global challenges by playing a key role for diversifications of production systems, and especially being resilience to adverse climate conditions (Akinola et al., 2020). These crops are well adapted to native environments, and fulfill farmers' needs in marginal agricultural systems due to their low demands for input, thus providing them an economic advantage over

* Corresponding author.
E-mail address: ashas@agri.sab.ac.lk (A.S. Karunaratne).

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commercial crops like wheat, rice, maize and soybean (Chibarabada et al., 2017). There is a renewed interest in underutilized crop as shown by a new study initiated by the U.S. State Department in collaboration with the African Union (AU) and the United Nations Food and Agricultural Organization (FAO) entitled "Vision for Adapted Crops and Soils (VACS)" (Fredenberg et al., 2014).

Bambara groundnut (*Vigna subterranea* (L.) Verdc) is a relatively under-researched legume, an exemplar crop for climate resilience that is cultivated in subsistence farming systems in sub-Saharan Africa and the third most important food legume after cowpea (*Vigna unguiculata* L. Walp) and groundnut (*Arachis hypogaea* L.) (Mkandawire, 2007) in Africa. Bambara groundnut has potential to combat future challenges of climate change (Mabhaudhi et al., 2019; Khan et al., 2020). Similar studies have revealed that in South Africa, the yield and water productivity are projected to increase by ~ 37.5 % and 33 % respectively under climate change (DALRRD, 2011; Mabhaudhi et al., 2018). The breeding potentials of Bambara groundnut for food and nutritional security in the face of climate change has been studied recently (Olanrewaju et al., 2022). Currently, Bambara groundnut cultivation is limited to Asia, especially in India, Indonesia, and Malaysia on a small scale, and its cultivation is rare outside the African continent. The center of origin of wild Bambara groundnut extends from the Jos Plateau and Yola in Nigeria to Garoua in Cameroon (Goli, 1997). Most of world's Bambara groundnut is grown in West Africa where it is most prominent in the tradition of rural and indigenous communities. Bambara groundnut is important for smallholder farmers and their households because the beans are an important source of food security because they are very nutritious compared to other legumes. They play a vital role in supplying protein in resource poor households (Linnemann and Azam-Ali, 1993). The seed of Bambara groundnut contains approximately 24 % protein, 64 % carbohydrates (53 % starch, 10 % dietary fiber), and 6 % total fat, providing nutrition and a balanced diet for humans (Okpuzor et al., 2010; Halimi et al., 2019). As a common feature in legumes, Bambara is deficient in sulphur-containing amino acids; however, some genotypes are rich in methionine and lysine (Azam-Ali et al., 2001). Since Bambara groundnut is cultivated using local landraces (farmer-selected) in the absence of true varieties of the species, the phenotypic diversity in growth habit, morphology, and crop growth patterns among landraces are common (Linnemann and Azam-Ali, 1993). The growth cycle, which is landrace dependent, ranges from 90 to 150 days, with 30–40 days for pod filling after flower fertilization. Some genotypes are photoperiod sensitive, and maturity is faster when the photoperiod is less than 12 h (Massawe et al., 2003; Basu et al., 2007). In most of the landraces flowering starts from 30 to 45 days after planting and may continue until the end-of-life cycle. The phenological stages vary with landraces and depend on the environment (Berchie et al., 2010). The atmospheric nitrogen fixation by the root nodules is an important trait for soil fertility enhancement and is useful in crop rotation and intercropping (Victoria et al., 2015).

The mechanistic crop models represent the major processes of crop response to weather, soils, crop management practices, and genetic characteristics and play a key role in estimating crop yield and assessments of climate impact (Hoogenboom, 2000; 2017). The PARCH (Predicting Arable Resource Capture in Hostile Environment) model (Bradley and Crout, 1993) that was developed at University of Nottingham, UK began the concepts of modelling Bambara groundnut and followed by BAMnut (Bannayan, 2001) and BAMFOOD models (Cornelissen, 2005) that focused only on water-limited situations with limited experimental data sets. Subsequently, adapting some features of the CROPGRO model, BAMGRO (Karunaratne et al., 2011) was developed to capture the genotypic differences of two contrasting landraces, and soil moisture and temperature as major abiotic stress factors using a simplified approach. In BAMGRO model, the water and temperature stress factors were considered for different growth and developmental processes depending on the timing, severity, duration and genotype with three stress effects due to independent and cumulative effects of drought and temperature stress on leaf production, leaf senescence and dry matter partitioning. However, the specific photosynthesis processes, sink source relationships, growth functions at different growth stages, plant compositions of protein, lipid and minerals as well as cultivar-specific phenology and growth traits are not considered in BAMGRO. The model, therefore, has insufficient details for adapting the model for other landraces.

Mechanistic crop simulation models incorporate quantitative information of crop physiology, genotypic parameters and growing conditions (climate and soil) (Boote et al., 1998). The CROPGRO model is embedded within the Decision Support System for Agrotechnology Transfer (DSSAT) software system (Hoogenboom et al., 2019), which provides a convenient system for the input of weather, soils, management, and crop genetic information, as well as handling model output for graphical, statistical, and application purposes. This has potential value for Bambara groundnut research and decision makers in Africa and Asia. The CROPGRO model has been adapted for more than 20 species so far, including canola (Brassica napus) which is a winter or spring-grown food-quality oilseed (Deligios et al., 2013) (Jing et al., 2016), *carinata* as a bioenergy crop (Boote et al., 2020), and guar (Boote et al., 2023).

Therefore, the current study is aimed to adapt the CROPGRO module of the Cropping System Model (Jones et al., 2003; Hoogenboom et al., 2019) of DSSAT for selected Bambara groundnut landraces to predict the growth and yield response under differing temperature regimes.

2. Materials and methods

2.1. Controlled environment experiments for model development

The growth and development analysis data from growth room and controlled experiments of Tropical Crops Research Unit (TCRU), the School of Biosciences, Sutton Bonington Campus, University of Nottingham, UK from 2003 and 2006 were used for the adaptation of CROPGRO model for Bambara groundnut grown under different moisture levels and temperatures (Table 1).

The growth and developmental measurements from the glasshouse experiments in Nottingham, UK were used for model development as explained in Table 1. The details of experimental design, plant sampling procedures, irrigation treatments and standard measurements have been previously described by (Mwale et al., 2007), (Karunaratne, 2009) and (Karunaratne, et al., 2010).

As explained in Karunaratne et al., (2010) two main experiments were conducted at the five glasshouses of the Tropical Crops Research Unit (TCRU) at the University of Nottingham, School of Biosciences, Sutton Bonington Campus, United Kingdom (52° 50' north, 1° 15' west; 45 m altitude). The five glasshouses are constructed 15 m apart between each glasshouse, aligned to North-South direction avoid mutual shading. The TCRU glasshouses are made of glass and conventional aluminum for long term research on tropical crops at the University of Nottingham (Cambridge Glasshouse Company, UK). The glasshouse is 10.1 m long, 4.7 m wide, 2.3 m high at the eave and 3.5 m to the central ridge with 32 m^2 for crops and a 0.2 m pathway around the perimeter (Monteith, 1986). A layer of sandy loam soil (0.3 m) was overlaid to replace gravelly / stony sand subsoil of the cropping area. The soil pH was measured and maintained at a mean of 6.7 ± 0.2. at the beginning of each cropping cycle during the summer months of UK.

For the purpose of preventing horizontal and vertical movement of water from and to the external environment especially to separate plots within the house for managing water levels within each plot, butyl sheeting was laid by removal of the soil to a depth of 1.25 m. In order to maintain the bulk density of the soil approximately around 1.41 g cm^{-3}, the excavated soil was replaced to restore the soil profile with 0.3 m loamy "plough soil" overlying a gravel loam subsoil. Excess water from the glasshouses were pumped out using four "dip wells" (two in each plot) of one-meter depth. The soil water content was measured using

Table 1
Experimental details of model data sets used for adaptation of CROPGRO to Bambara groundnut.

Year	Location	Landraces	Treatments		Reference
			Water regime	Temperature	
2003	Tropical Crops Research Unit, Sutton Bonington Campus, UK	S19–3 UniswaRed	Irrigated	28° C ± 5° C	(Mwale et al., 2007)
2006	Tropical Crops Research Unit, Sutton Bonington Campus, UK	S19–3 UniswaRed	Irrigated	23° C ± 5° C 33° C ± 5° C	(Karunaratne, 2009; Karunaratne et al., 2010)

capacitance probes (PR2; Delta-T Device) to a depth of 100 cm using four aluminum access tubes that were installed in each plot.

As details are explained in Karunaratne et al., (2010), a portable building was maintained on the site with a central control computer system that is regulated through the ventilation, air temperature, relative humidity, and the CO_2 concentration in each house separately (Monteith, 1986). Accordingly, ventilation and heating of the house was achieved through spinning disc humidifiers (Mellor-Bromley, UK) that were erected close to the heaters and 2.4 m above the ground level. Tube solarimeters were installed both below and above the canopy to measure incident, reflected and transmitted solar radiation when crops are growing in the glasshouses. Campbell Scientific CR 10 data loggers were used to record the solar radiation measurements at every 30 seconds. In addition, a trickle irrigation system with plastic pipes (seep hose) was directed to each crop row.

Two Bambara groundnut landraces that were originated from contrasting climates in Africa (UniswaRed, from Swaziland, and S19–3, from Namibia) were grown in five glasshouses (TCRU) during the summer period of 2003 and 2006 (April to September) representing plots of UniswaRed and S19–3 in each glasshouse. In 2003, the treatments consisted of irrigated and drought (irrigation was terminated beginning 33 days after sowing) at the temperature of 28 ± 5°C. In 2006 experiment, two temperatures, 23 ± 5 °C (LT) and 33 ± 5 °C (HT), with fully irrigated condition was maintained across the five glasshouses (total irrigation 381 mm for LT and 437 mm for HT).

The treatment allocation and experimental design are previously explained in Karunaratne et al., (2010), for the 2006 experiment (split-plot design; two landraces and two temperatures). The day length was controlled to 12 h per day, from 21 DAS between 2000 and 0800 h to provide short-day condition to the crop stand.

Approximately 300 kg ha^{-1} of Potassium at 57 days before sowing (DBS) and 100 kg ha^{-1} of Nitrogen at 34 days after sowing (DAS), were applied through hand-cultivation and rake-harrowing. The seeds from previous years' TCRU experiments (432 seeds per plot), were sown on 28 April in 2003 and May 11 in 2006. Following the experimental protocol of TCRU experiments, three seeds per hole were sown maintaining the spacing level of 10 cm within rows and 35 cm between rows. The thinning of additional plants at 19 and 22 DAS, in the glasshouses at high and low temperature, respectively, were performed to maintain the spacing of 35 cm by 20 cm having plant density of 15 plants per m^2 until harvest. The trickle irrigation system was operated once per week from 0 to 97 DAS with the estimate of water to be applied to each plot based on potential evaporation calculations for the temperature treatments.

2.2. Measurements

2.2.1. Crop development measurements

Emerged seedlings were counted every morning between 5 and 16 DAS in selected five rows in the center of each plot. Each seedling that emerged each day was tagged with a white peg on which the date of emergence was recorded. In this study, a seedling was considered to have emerged when its first pair of leaves had broken from the soil. The recorded values were converted to percentage, based on the number of seeds sown in the central five rows. After 16 DAS, 10 plants were randomly tagged in each plot and used for counting leaves, flowers and pods twice per week, starting at 35 DAS until 127 DAS.

2.2.2. Growth measurements

A random sample of 10 plants from each plot was selected every 2 weeks for eight sequential growth measurements from 33 DAS to 131 DAS. The number of leaves, number of pods were recorded for each harvested plant after separation of leaves, stems and pods. Leaf Area index (LAI) was calculated at sequential growth analysis using the green leaf area of each plant measured using a leaf area meter-model LI-3100 (LI-COR, Inc. Lincoln, Nebraska, USA). The oven dry weight (48 h at 80 °C) of each component leaves, stems and pods were recorded. The mean of 10 plants for each growth variable was considered for a particular replicate.

2.2.3. End of season yield measurement

The pod yield for the treatment was calculated using the pod weight from the central harvesting area (3.6 m^2 of each plot, 40 plants) and was considered as the final harvest.

2.2.4. Solar radiation and temperature measurements

The incoming (S_i) and transmitted solar radiation (S_t) through the crop canopy was measured from 20 DAS onwards using the tube solarimeters that had been installed in glasshouse. Accordingly solar radiation data were accessed from the Campbell Scientific CR10 data loggers (Campbell Scientific Ltd., using UK) during the crop growing period on daily basis between 0800 h and 2000 h at 10-minute intervals. The hourly and daily totals of solar radiation values were integrated to calculate the radiation use efficiency (ε_s) for each landrace. Aligning with radiation measurements, minimum and maximum temperatures, saturation deficit and irrigation amounts were recorded for each glasshouse throughout the crop cycle.

2.2.5. Soil moisture measurements

During the TCRU experiments, soil moisture content at 10, 20, 30, 40, 60 and 100 cm in the soil profile was monitored in all plots using a PR2 probe (Delta-T Devices, UK). The mean amount of water in the soil profile in each plot was calculated as the average soil moisture contents from the four access tubes that have installed in each plot. According to Mwale (2005), the soil physical characteristics (soil depth, soil texture, bulk density, soil water capacity at saturation, field capacity, permanent wilting point) for the TCRU glasshouses were considered for the 2006 experiment.

2.3. Model evaluation

Model performance during and after calibration was evaluated based on visual graphical presentation of time-series simulations against observations, and three statistical measures; (1) Mean, (2) Root Mean Square Error (RMSE; Eq. (1)) and (3) Willmott agreement index (*d*-statistic; Eq. (2); Willmott et al., 1985).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2} \quad (1)$$

where n is the total number of data points for comparison, Yi are the observed values, and $\hat{Y}_i$ are the simulated values. A smaller RMSE represents a better model prediction.

The Willmott agreement index is given by:

$$d = 1\lfloor \frac{\sum_i^n (Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^n \left(|\widehat{Y}_i - Y| + |Y_i - Y|^2 \right)} \rfloor, 0 \le d \le 1 \quad (2)$$

where N is the total number of data points for comparison, Y_i are the observed values, $\widehat{Y}_i$ are the simulated values, and Y is the mean of the observed data. For good model prediction, the d index should be near 0.90, that is, close to 1.

2.4. Adapting the CROPGRO model: methods and statistics

A new crop was added in the DSSAT version 4.8 (Hoogenboom et al., 2021) shell as Bambara groundnut with the crop code BG. Accordingly, the species, ecotype and cultivar files were created with the crop code BG for adapting the crop growth parameters for Bambara groundnut. The required files for each experiment were generated to execute the DSSAT software (Hoogenboom et al., 2021). The crop management information (sowing date, row spacing, plant population, fertilization, irrigation, soil type and landrace specific genetic coefficients) were entered into the crop management file. The measured growth and development data and soil profile moisture data were entered into end-of-season and time-series data files. The soil profile data (drained upper limit: DUL, lower limit of plant extractable soil moisture: LL, saturated water content: SAT and bulk density) of each layer for a 100 cm depth were used to create the soil profile information. Weather data for the growing period were obtained from the meteorological station data of the experimental site and glass house climate control data logger to create weather files for each experiment with controlled temperatures as explained in Table 1.

The model adaptation procedure was considered from similar work conducted by Boote et al., (2002) for adaptation of CROPGRO for faba bean (*Vicia faba*) and by Boote et al., (2020) for *Brassica carinata*, a bio-fuel crop. Since Bambara groundnut is similar to peanut in terms of phenology and growth habit, the existing template of the CSM-CROPGRO-Peanut module was used to adapt species, ecotype and cultivar files. The experiments in 2003 and 2006 were simulated with soil water and nitrogen balance and nitrogen fixation (symbiosis) turned on. There was minor optimization of the water-holding characteristics of the soil horizons and the depth-shape of the root profile (soil root growth factor) based on observed soil water data. The 2003 experiment was considered to be under relatively optimum temperature (28° C ± 5), while the 2006 experiment allowed for further calibration of model performance under cold (23°C ± 5) or hot (33°C ± 5) temperature conditions.

Model adaptation followed a logical sequence series of steps in deriving species and cultivar coefficients; (1) the relationships and relevant data from the literature were used where available, (2) life cycle phenology was set, (3) observed time-series data of Bambara groundnut experiments were compared with model simulated values and (4) optimization of model parameters through sensitivity analysis to improve the statistical comparison of observed time-series variables. The adaptation of species coefficients initially involved setting cardinal temperatures obtained from the literature and setting plant tissue compositions obtained from the literature. Then model simulations were run to set photothermal phase durations (getting the life cycle right). Subsequently, model simulations were compared to observed time-series observations to calibrate functions including rate of leaf appearance, rate of change to particular phenological events, photosynthesis, pod growth, and seed growth rate, along with further modifications of temperature response functions of temperature-dependent processes, based on the response to growth dynamics apparent in the cold versus hot treatments. Cultivar parameters that were adjusted included photothermal phase durations, duration to end of leaf area expansion, duration of pod addition, leaf photosynthesis, leaf size, specific leaf area, seed protein, seed lipid, and single seed-filling duration.

After each set of model simulations, the graphical interface (GBuild) of DSSAT was used to compute model evaluation statistics with observed and simulated means, root mean square error (RMSE), and d-statistic of model fit. These statistical measures and visual evaluation were used to calibrate the species and cultivar coefficients, basically with the goal to arrive at simulated mean compared to observed value, lowest RMSE, and highest d-statistic for the different time-series variables such as LAI, leaf, stem, total crop mass, pod mass, pod number, and pod harvest index. Based on prior sensitivity analysis experience, different species and cultivar parameters were known to affect given different time-series variables. This process using GBuild was mostly manually iterative because DSSAT lacks an optimizer for time-series observation. Note that the existing GLUE optimizer uses only end-of-season variables and is not useful for initial adaptation of the CSM-CROPGRO module for a new crop.

The model adaptation consisted of multiple iterations of (1) simulating phenology timing (cultivar parameters and temperature response curve of species parameters) (2) simulating LAI, specific leaf area (SLA) and biomass accumulation (based on species and cultivar parameters); (3) simulating biomass partitioning among different organs; leaf, stem, and root tissue (these are species parameters). As mentioned previously, the soil moisture and rooting shape parameters were calibrated to match with observed soil moisture measurements of the 2003 experiment, both irrigated and droughted. Minor additional adjustments that improved simulations of the 2003 drought treatment included increasing the root length per unit root mass and increasing dry matter partitioning to roots to minimize early season water deficit which resulted in less acceleration of maturity under drought stress.

The 2006 experiment with low temperatures (23°C ± 5) and high temperatures (33°C ± 5) without water stress was used for adapting the temperature response for phenology, biomass, LAI, leaf weight, stem weight, pod weight, pod harvest index, and end of season pod yield. Finally, the model iterations were performed among the listed parameters that are associated with modification of the cardinal temperatures for photosynthesis, partitioning intensity, pod addition, and seed growth to enhance the simulated growth and yield for both the low and high temperature conditions while maintaining good performance for the 2003 optimum temperature regime.

3. Results

3.1. Model adaptation to relationships with cardinal temperatures

The adaptation of the CSM model for temperature responses was initiated with the CROPGRO-Peanut template, but changes were made in the temperature functions that affect the physiological processes of Bambara groundnut. The temperature thresholds for the individual processes are described in Table 2 with references to published information.

According to (Massawe et al., 2003), there is a significant ($p < 0.001$) linear relationship between rate of leaf appearance (RLA) and temperature for all 10 landraces originating from different locations in sub-Saharan Africa that they tested. The RLA increased with an increase in mean temperature from 20 to 30°C, held constant at 32.5°C but decreased at 35°C. Based on the linear regression of RLA versus mean temperature (Fig. 1 in Massawe et al., 2003), the T_b solved to be 10°C. Based on these results, the temperature parameters for RLA were set at T_b, T_{opt1}, T_{opt2}, and T_{ceil} of 10, 30, 32, and 55°C. The T_b values for flowering and podding have been reported as low as 3°C in Bambara groundnut (Linnemann and Craufurd, 1994). However, the temperature function for RLA is for vegetative growth and development and has less impact on reproductive growth and development.

Since there are no experimental data on T_b, T_{opt1}, and T_{opt2} for reproductive progression, these temperature values and the shape of the curve (SIN) were initially taken from peanut but were modified to improve the closeness of model simulations to observed values. Thus, the T_b, T_{opt1}, and T_{opt2} of 11, 28 and 28 °C of peanut were modified to

Table 2
Cardinal temperatures (°C): base (T_b), first optimum (T_{opt1}), second optimum (T_{opt2}), and ceiling (T_{ceil}) used for development, photosynthesis, pod addition, and seed growth rate of CROPGRO-Bambara groundnut. The development functions use hourly temperature with linear lookup for interpolation, while pod addition and seed growth rate use a quadratic function with an hourly temperature.

Growth and development processes	T_b	T_{opt1}	T_{opt2}	T_{ceil}	Reference
Vegetative development	10	30	32	55	(Massawe et al. 2003)
Reproductive development	11	18	30	55	Based on experimental data
Light saturated leaf photosynthesis	11	41	45*	55	Based on experimental data
Tmin effect on leaf photosynthesis	8**	24**	50	60	Based on experimental data
Leaf area expansion	12	27	27	42$	Based on experimental data
Height/ width increase	11	27	27	50$	Based on experimental data
Pod and seed addition	15	24.5	28.0	40	From CROPGRO-Peanut
Seed growth rate	6.0	21.0	23.5	41	From CROPGRO-Peanut

* 45°C is temperature at which the relative photosynthesis rate is 0.8; ** describes an asymptotic function with T_b at 8°C and an asymptote at 24°C; 42°C is temperature at which relative expansion is 0.7; 50°C is temperature at which relative height is 0.95.

values of 11, 18, and 30 °C, respectively, for Bambara groundnut (Table 2).

For leaf photosynthesis, the T_b which is different when compared to peanut, had to be increased from 8 to 11°C and the asymptotic response to night temperature (T_{min}) for next day's rate was increased from 4 and 22°C to 8 and 24°C (Table 2). These two modifications were essential for simulating the reduced growth observed during the relatively low temperatures (23°C ± 5) and suggest that Bambara groundnut is more sensitive to cold temperature than peanut. An additional change in the species file was to increase the value for the specific leaf weight reference (SLWREF) from 0.0043 to 0.0063 g cm^{-2}, to reduce the productivity of Bambara groundnut compared to the long-season runner peanut calibration. The SLWREF defines the specific leaf weight at which single leaf photosynthesis is measured. The reciprocal (1/SLWREF) should be reasonably close to the specific leaf area.

Leaf area expansion (specific leaf area of new leaves) was made slightly more sensitive to cold temperature by increasing the cardinal base temperature for leaf expansion to an effective T_b of 12°C, keeping the T_{opt} at 27°C. To reduce SLA of the hot temperature treatment, leaf expansion (SLA) was allowed to be reduced as temperature increased above 27°C, reaching a relative (0.7) expansion at 42°C. Internode expansion and width increase were made more sensitive to cold temperature by increasing the cardinal base temperature by 3°C to 11°C also with optimum at 27°C. These changes to SLA and canopy height, and width in Table 2 were made to reduce early canopy expansion of the cold temperature treatment, thus resulting in more correctly reduced early season biomass.

The rate of pod and seed addition, T_{opt1} and T_{opt2} were adjusted to improve model performance under low and high temperatures. The T_{opt1} and T_{opt2} for pod addition were increased from 21 and 23.5°C to 24.5 and 28.0°C, while the T_b remained at 15°C (Table 2). The upward shift of T_{opt1} acts to reduce pod addition for the cold treatment, while the upward shift of T_{opt2} acts mostly on the optimum and hot temperature treatments. There was no change in the temperature function for single seed growth rate (away from peanut).

3.2. Model adaptation—tissue composition, protein, oil, and tissue N dynamics

In addition to N-fixation, CROPGRO also simulates N uptake from the soil similar to non-legumes, and the N balance in the model requires setting tissue compositions of the different organs for protein, cellulose, carbohydrate, lipid, lignin, organic acid, and ash, to simulate the growth respiration and synthesis conversion cost following the approach of (Penning de Vries et al., 1974). Plant composition values were set based in part on Table 3 of Olaleye et al., (2013). The seed crude protein was generally high which is typical for all legumes. However, the values obtained in this report, e.g., 15.2–22.2 g/100 g, were lower than the value, i.e., 29.0 g/100 g, reported for raw groundnut seeds (Adeyeye, 2011). The fractions of each component were calculated from published data as discussed above excluding the moisture content of the proximate analysis vales. Table 4 gives values used for CROPGRO-Bambara: seed protein set at 0.240, seed lipid at 0.06, seed ash (mineral) at 0.034 and lignin (fiber) at 0.073 based on means of Olaleye et al., (2013), and assuming a default organic acid fraction of 0.04. Since composition must

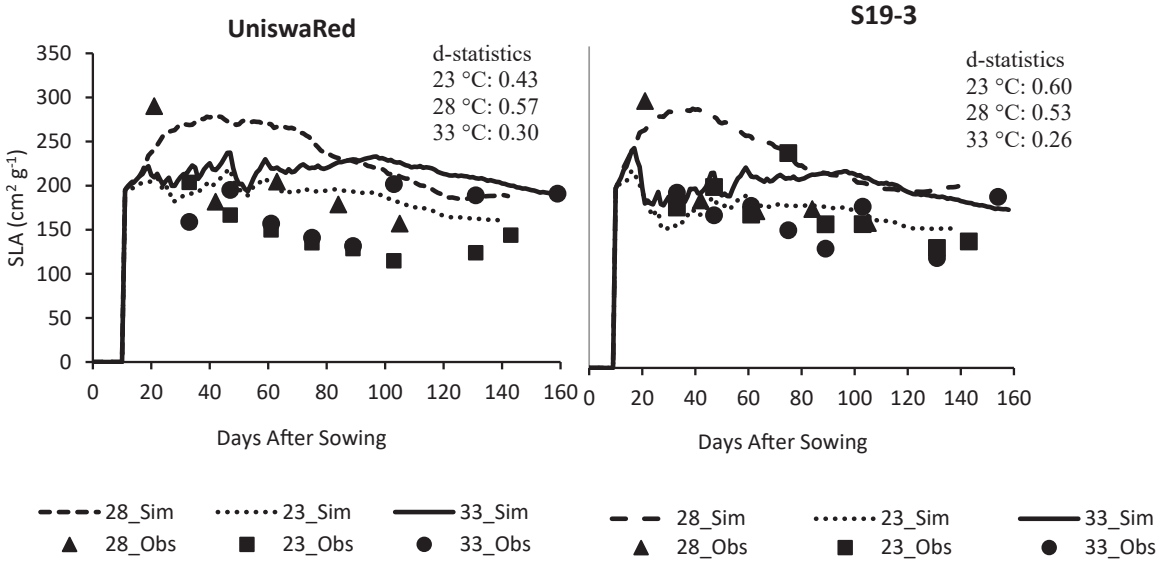

Fig. 1. Simulated (lines) and observed (points) specific leaf area (SLA) ($cm^2\ g^{-1}$) over time course for the landraces UniswaRed and S19–3 grown under optimum (28°C ±5) temperature in 2003, low (23°C ±5), and high (33°C ±5) temperatures in 2006 experiments.

Table 3
Estimated composition (g/100 g) of Bambara groundnut samples as reported by Olaleye et al., (2013).

Parameter	Samples			Mean	SD	CV%
	Testa	Dehulled	Whole seed			
Moisture (g/100 g)	5.36	5.23	9.23	6.61	2.27	34.3
Ash (g/100 g)	2.46	2.97	4.36	3.26	0.98	34.3
Lipid (g/100 g)	2.47	6.99	5.17	4.88	2.27	46.5
Protein (g/100 g)	15.2	22.2	18.4	18.6	3.50	18.8
Fibre (g/100 g)	22.9	1.03	2.05	8.66	12.30	142
Carbohydrate (g/100 g)	51.6	61.9	60.8	58.1	5.66	9.70
Energy (KJ/100 g)	91.4	259	191	180	84.3	46.8

Table 4
CROPGRO tissue compositions (mass per unit tissue dry mass), definitions, and values for leaf, stem, shell, and seed. For CROPGRO-Bambara model it was assumed that the tissue composition was the same as peanut for all tissues, except for seed which has a 0.240 fraction for protein and a 0.06 fraction for lipid.

Compound		Leaf (LF) (g/g)	Stem (ST) (g/g)	Root (RT) (g/g)	Shell (SH) (g/g)	Seed (SD) (g/g)
PRO_I	Protein (luxury)	0.335	0.160	0.142	0.178	
PRO_G	Protein (growth)	0.270	0.110	0.102	0.168	
PRO_F	Protein (final)	0.178	0.071	0.056	0.069	
PCAR_	Carbohydrate-cellulose	0.426	0.654	0.661	0.446	0.553
PLIP	Lipid	0.025	0.020	0.020	0.026	0.050
PLIG	Lignin	0.070	0.070	0.070	0.280	0.073
POA	Organic acid	0.050	0.050	0.050	0.040	0.040
PMIN	Minerals	0.094	0.046	0.057	0.030	0.034

sum to 1.00, the remainder of the seed was set to 0.553 for carbohydrate-cellulose. The composition of the leaf, stem, root, and pod wall in Table 4 was assumed to be similar to peanut in the absence of any reported data in the literature.

3.3. Model adaptation—fractional partitioning to organs

Considering the experimental data from 2003 and 2006 experiments, the fraction of daily new growth partitioned to leaves (YLEAF) and stems (YSTEM) was calibrated to achieve correct simulations of leaf and stem biomass and subsequently LAI. Based on the literature, Bambara groundnut invests heavily in its root system compared to groundnut either with or without drought stress, which contributes to a better soil water availability for a relatively smaller canopy area. Partitioning to roots is high early and declines with vegetative progression to values during reproductive growth of 0.14–0.17 of daily assimilate allocated to roots. Partitioning to the stem is low early and increases over the life cycle. Accordingly, the fractional instantaneous daily assimilate partitioning to leaves, stems, and roots as a function of progressive V-stage was set in the CROPGRO-Bambara groundnut species file as listed in Table 5. ATOP was reduced from 0.8 to 0.7 to improve the performance of the model during early growth when drought stress occurred.

The nitrogen mobilization rate (NMOBMX, fraction of available protein pool per day) was increased from 0.098 to 0.125 to create a trend for late season plateau of biomass and pod yield to mimic reduction in photosynthesis as a result of N mobilization from vegetation to seed late during the growing season. Faster mobilization is also consistent with a shorter life cycle compared to the runner-type peanut for which the original CROPGRO-Peanut was developed and calibrated. The final leaf N concentration approached 2.6 %. Further, the senescence rate (SENRTE, g of leaf mass lost /g of protein mobilized) was increased from 0.55 to 0.57 to senesce more leaves and stems in order to create a greater tendency for a plateau for these two plant components. Carbohydrate mobilization rate was increased from 0.017 to 0.034 (fraction mobilized per day), because non-structural carbohydrate concentration needed to be reduced near the end of season for slight reduction (plateau) of stem, leaf, and top weight in late season.

3.4. Model adaptation—setting cultivar traits

Cultivar traits are defined in Table 6 for two contrasting Bambara groundnut landraces, i.e., UniswaRed originating from relatively cool and wet Swaziland and S19–3 originating from hot and dry Namibia. They were used for setting the cultivar traits in the CROPGRO-Bambara groundnut cultivar file. Bambara groundnut exhibits considerable variability within a genotype due to the array of diversity in a landrace compared to a cultivar. The details of the weather conditions of original locations in Namibia and Swaziland have previously been explained in Karunaratne (2009). The final values were based on the best fit statistics after the sensitivity analysis for a series of iterations for the key phenological stages, i.e., phenological days to anthesis and first pod set. Since photoperiod sensitivity of the landraces is not considered here (PPSEN=0.0, Table 6), the photothermal days are only a function of temperature sensitivity (Table 2), and, thus, flowering is not delayed by non-optimum photoperiod. There is an observed difference between two landraces for flowering time; UniswaRed is later than S19–3. The cultivar trait for photothermal days (ptd) from emergence to flowering (EM-FL) was set as 40.8 ptd for UniswRed and 35.0 ptd for S19–3 to predict the flowering time correctly for landraces. The ptd from first flower to first pod (FL-SH) was set at 12 and 11 for UniswaRed and S19–3, respectively. Since the information of first seed date was not recorded in any of the experiments, ptd from first flower to onset of seed (FL-SD) was set at 20.5 and 21.6 ptd for UniswaRed and S19–3, respectively. The exact time to maturity was weakly observed in the glasshouse experiments and was not recorded in any reasonable form because the majority of landraces are at least mostly indeterminate. Therefore, the cultivar trait SD-PM for the onset of seed growth until physiological maturity was set at 67.3 and 70.2 for UniswaRed and S19–3, respectively in order to achieve maximum final pod seed mass based on biweekly growth analysis and final harvest yield. The light-saturated leaf photosynthesis rate (LFMAX) was set somewhat lower than peanut, with values of 1.24 and 1.18 mg CO_2 m^{-2} s^{-1} for UniswaRed and S19–3, respectively (Table 6). The specific leaf area of a landrace under standard growth conditions (SLAVR) was calibrated from the simulated SLA values over time. The SIZELF (size of leaf) of each cultivar represents approximate leaf size of the fifth node leaf but

Table 5
CROPGRO vegetative partitioning parameters to leaves, stems, and roots as a function of V-stage progression as calibrated for Bambara groundnut.

Tissue (Fraction)		V STAGE								
		0	3.3	5.4	7.5	9.6	15	30	40	Final
YLEAF	Leaf	0.36	0.36	0.36	0.38	0.41	0.44	0.46	0.46	0.40
YSTEM	Stem	0.10	0.18	0.27	0.38	0.40	0.40	0.40	0.40	0.43
By difference	Root	0.54	0.46	0.37	0.24	0.19	0.16	0.14	0.14	0.17

Table 6
Calibrated cultivar traits for two Bambara groundnut landraces, i.e., UniswaRed and S19-3.

Landrace coefficient	Description	Uniwa Red	S19-3	Reference
CSDL	Critical short daylength below which reproductive development progresses as rapidly as possible with no daylength effect (h)	11.84	11.84	
PP-SEN	Slope of the relative response of development versus photoperiod (h^{-1})	0.00	0.00	
EM-FL	Phenological time from emergence to flowering (ptd)	40.8	35.0	(Karunaratne, 2009) (Mwale, 2005)
FL-SH	Phenological time from first flower to first pod (ptd)	12.0	11.0	(Al-Shreef, 2011)
FL-SD	Time between first flower and first seed (ptd)	20.5	21.6	
SD-PM	Phenological time between beginning seed and physiological maturity (ptd)	67.3	70.2	
FL-LF	Phenological time from first flower to end of leaf expansion (ptd)	70	65	
LFMAX	Maximum leaf photosynthetic rate at 30 °C, 350 ppm CO_2 and high light (mg CO_2 m^2 s^{-1})	1.24	1.18	
SLAVR	Species leaf area of cultivar under standard growth (cm^2 g^{-1})	225	225	
SIZLF	Maximum size of full leaf (cm^2)	15	18	
XFRT	Maximum fraction of daily growth partitioned to shell+seed	0.87	0.91	
WTPSD	Maximum weight per seed (g)	0.540	0.460	
SFDUR	Seed filling duration for pod cohort (ptd)	48	48	
SDPDV	Average seeds per pod at standard conditions	1	1	
PODUR	Duration for pod addition under standard condition (ptd)	25	19	
SDPRO	Fraction of protein in seed (fraction)	0.240	0240	
SDLIP	Fraction of lipid in seed (fraction)	0.060	0.060	
THRESH	Weight percentage of seeds in pod (threshing percentage)	89.8	90.8	

was also calibrated to correctly simulate early LAI development (Table 6). The maximum fraction of daily growth partitioned to shell and seed combined (XFRT) was set as 0.87 for UniswaRed and 0.91 for S19–3, mainly based on the pod harvest index over time, but along with fitting the stem, pod, and seed mass accurately. The cultivar trait XFRT defines the maximum fraction allocation to pod and seed after a full fruit load is set. If XFRT is less than 1.00, the fraction (1-XFRT) allows assimilate to be reserved for vegetative biomass growth. XFRT and PODUR together determine how fast the "fruit load" is set. The ptd required to reach final pod load under optimal conditions (PODUR) was set at 25 and 19 for UniswaRed and S19–3, respectively, which influences the slope of pod number over time, as well as the initial increase in the pod harvest index over time. THRESH is the percent seed (of the pod plus seed) and was set based on the final harvest data of 2003 experiment for both landraces. This was set to 89.8 for UniswaRed and 90.9 for S19–3 to predict the yield correctly. The SFDUR parameter, which defines the duration of single seed growth but also influences the speed of increase in weight per seed and the shelling percentage over time, was set to 48 ptd.

4. Discussion

4.1. Model evaluation: phenology

The model simulated phenological stages were compared with observed data on days to emergence, anthesis, pod setting, seed setting and physiological maturity under optimum temperature and soil moisture regimes of the 2003 experiment for two contrasting landraces (Table 7). The phenological stages were correctly simulated indicating the model calibration for selected two landraces of Bambara groundnut was statistically acceptable.

When the crop was grown at 23 °C ± 5 °C, the emergence, flowering, and pod setting were not different from the optimum temperature (28 °C). However, the high temperature (33 °C ± 5) delayed the emergence (1–2 days), flowering (5–8 days) and pod setting (8–9 days). One of the reasons for setting relatively low Topt1 and Topt2 for reproductive development, was to achieve this delay at 33 °C.

4.2. Time series variations of crop growth: SLA, LAI, leaf weight, stem weight, pod weight and total biomass

4.2.1. Growth dynamics and statistics evaluated over all treatments

The simulated growth variables were statistically evaluated with the observed data from the three treatments (28 °C in 2003, 23 °C in 2006, 33 °C in 2006). The statistical analysis results of model evaluation over all treatments are provided in Table 8. The SLA for both landraces was in good agreement with declining trend during the course of the growing season (Fig. 1). The simulated leaf and stem mass were statistically in a good agreement with observed data for both landraces (Fig. 2). These results of correct simulation of leaf and stem biomass clearly indicate that the model is calibrated sufficiently to simulate the aboveground canopy correctly. Further, simulation of pod weight and yield was evaluated with the pod harvest index over the course of growing season from pod setting to harvest maturity. The comparison of simulated pod harvest index with observed values was statistically acceptable (Fig. 3). The model evaluation results of pod harvest index are a clear indication of accurate prediction of pod set and, thereby, the simulation of final yield.

4.2.2. Growth dynamics: temperature effects

The simulated growth dynamics were compared with observed LAI, pod weight and total biomass for the landraces UniswaRed and S19–3 for the 2003 experiment that was grown under optimum (28 °C ± 5), temperature and with full irrigation. Similarly, to evaluate the model performances for temperature response, the simulations were compared to observed data of LAI, pod mass and total biomass for the 2006 experiment that was grown under low (23 °C ±5) and high (33 °C ±5) temperature conditions and with full irrigation (Fig. 4, Fig. 5 and Fig. 6).

Table 7
Comparison of simulated phenological stages for the landraces UniswaRed and S19-3 with observed data of fully irrigated 2003 experiment grown at 28 °C.

Phenological stage	UniswaRed		S19-3	
	Simulated (days)	Observed (days)	Simulated (days)	Observed (days)
Emergence	11	10	10	09
Anthesis	52	52	45	45
First pod	69	69	64	63
First seed	72	72	67	67
Physiological maturity	142	142	139	139
Harvest maturity	142	142	139	139

Table 8
Overall model performance statistics for the landraces UniswaRed and S19-3 with experimental data under fully irrigated conditions for the 2003 experiment grown at 28°C and the 2006 experiment grown at 23°C and 33°C.

Variable Name	Observed Mean	Simulated Mean	Observed SD	Simulated SD	Mean Diff.	RMSE	d-Stat.
SLA ($cm^2\ g^{-1}$)	235.60	226.85	48.35	25.33	-8.78	94.91	0.45
Pod HI	0.18	0.21	0.13	0.14	0.02	0.05	0.96
Leaf weight ($kg\ ha^{-1}$)	1182.50	1006.67	736.07	641.69	-175.67	362.19	0.89
Stem weight ($kg\ ha^{-1}$)	1088.50	1133.17	709.53	794.88	44.50	475.56	0.86
LAI	2.08	2.06	1.32	1.30	-0.20	0.38	0.96
Tops weight ($kg\ ha^{-1}$)	3071.67	2930.83	2330.10	2311.79	-140.83	628.92	0.98
Pod weight ($kg\ ha^{-1}$)	1209.50	1260.50	1035.95	1036.61	51.0	288.71	0.96

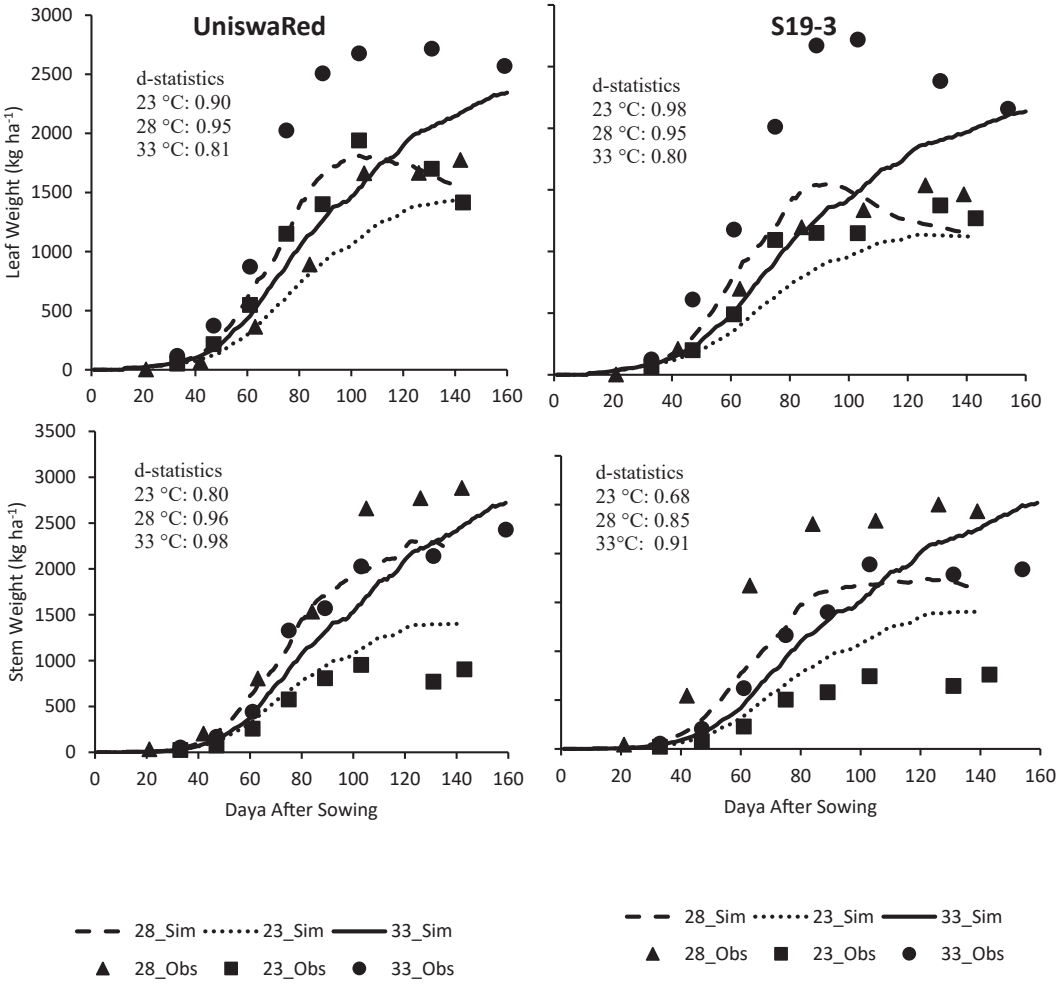

Fig. 2. Simulated (lines, and observed (points) leaf weight and stem weight over time course for the landraces UniswaRed and S19–3 grown under optimum (28°C ±5) temperature in 2003, low (23°C ±5), and high (33°C ±5) temperatures in 2006 experiments.

Simulated LAI agreed well with observed values at optimum, low and high temperatures (Table 8) for the two landraces and the three temperature regimes (Fig. 4) with reported d-statistics greater than 0.95 for all treatments. The two landraces had a relatively similar performance for LAI, although UniswaRed has relatively later onset of reproductive growth pattern, with later flowering (EM-FL = 40.8 ptd) and pod growth compared to S19–3 (EM-FL = 35.0 ptd).

The crop biomass was well simulated for UniswaRed and S19–3 for 2003 and 2006 (Fig. 5, d-statistics >0.96) for all temperatures. The 2006 season was longer and more delayed at either cooler or warmer temperatures compared to the 2003 growing season. The two landraces, UniswaRed and S19–3, had a relatively similar performance for biomass, although S19–3, which has been reported as early maturity, was earlier for pod growth (FL-SH = 12 ptd, FL-SD = 11.0 ptd) and was somewhat more determinate (XFRUIT of 0.91 vs. 0.87). UniswaRed was assigned a higher leaf photosynthesis (LFMAX of 1.24 compared to S19–3 at 1.18) during the calibration. Fig. 6 illustrates simulated and observed pod weight for the two landraces and three temperatures regimes for all six

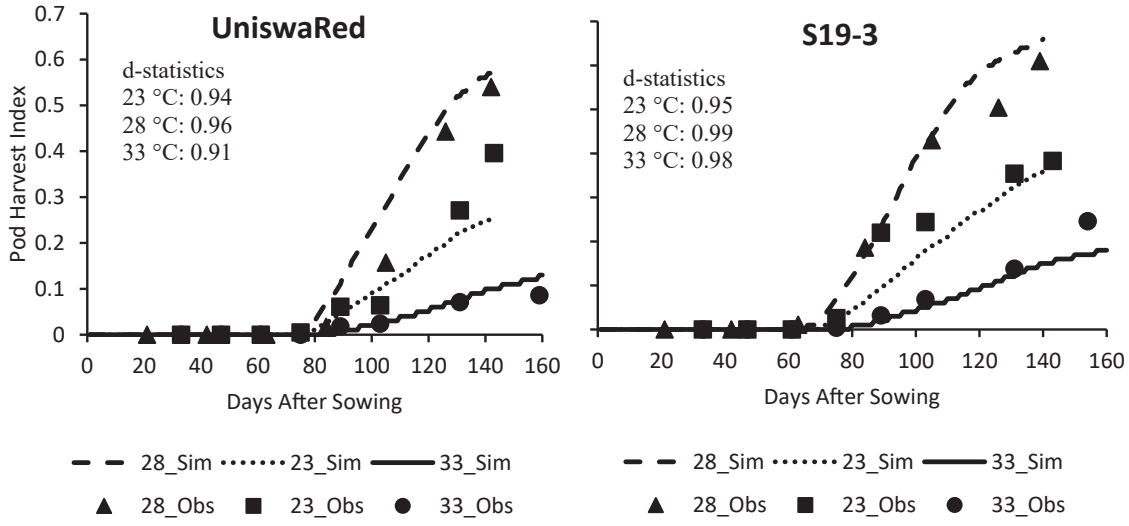

Fig. 3. Simulated and observed (points) pod harvest index over time course for the landraces UniswaRed and S19–3 grown under optimum (28°C ±5) temperature in 2003, low (23°C ±5), and high (33°C ±5) temperatures in 2006 experiments.

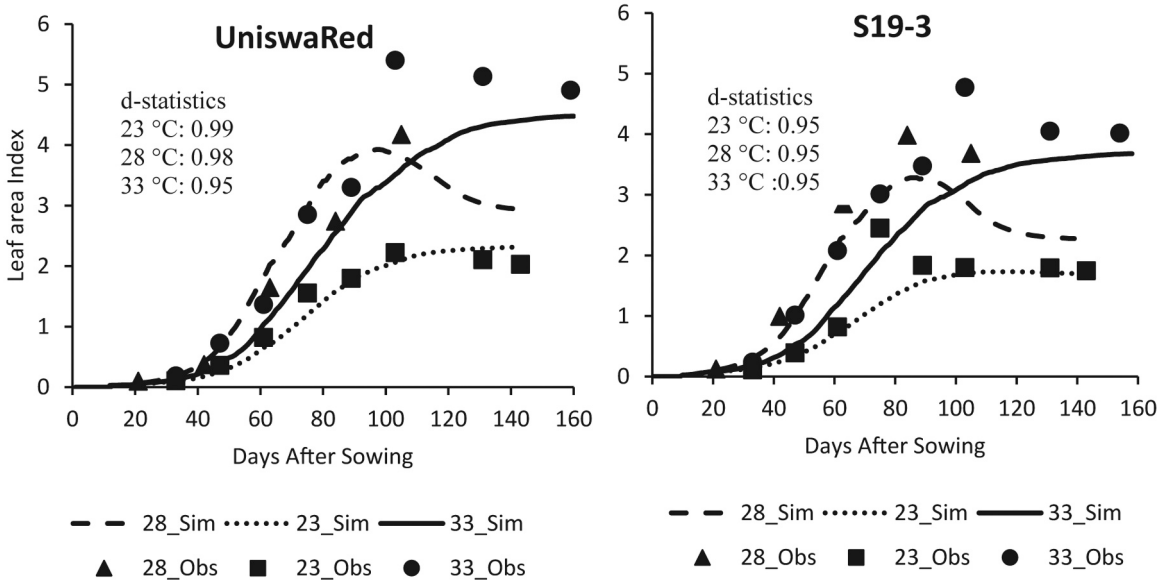

Fig. 4. Simulated (lines,) and observed (points) leaf area index (LAI) over time course for the landraces UniswaRed and S19–3 grown under optimum (28°C ±5) temperature in 2003, low (23°C ±5), and high (33°C ±5) temperatures in 2006 experiments.

treatments.

Overall, the crop grown under optimum temperature (28°C ±5) had the highest pod mass with d-statistics greater than 0.99 compared to the crop grown under low (23°C ±5, d-statistics of 0.99) and high (33° C ±5, d-statistics of 0.89) temperatures for the two landraces with relatively higher yield for S19–3 (Fig. 6). The low temperature growing condition resulted in the second highest pod yield, whereas the high temperature resulted in the lowest pod yield. Landrace S19–3 had a higher pod yield compared to the UnswaRed landrace across the three temperature treatments with a threshing percentage (THRESH) of 90.8 % compared to 89.8 % for UniswaRed. However, the difference for THRESH was small and would have a minor effect on yield. The seed filling duration of individual seeds (SFDUR) had to be increased to 48 ptd to prevent artificial "termination" of single seed growth and the increase resulted in an increase in final seed yield.

The present model adaptation applies for two landraces originating from two zones in semi-arid Africa, i.e, UniswaRed from Swaziland and S19–3 from Namibia. According to the experimental evidence of Mwale (2005), the Namibian landrace S19–3 was reported to have a faster rate of development and produced a reasonable number of pods under high temperature condition. In contrast, UniswaRed is slow growing landrace and has lower values for many growth variables compared to S19–3. Also, the Swaziland landrace, UniswaRed has a lower pod formation when grown under high temperature (33°C ± 5), highlighting the negative effect of heat stress on pod formation. These differences between the two landraces in response to temperature can be explained as agro-ecological adaptation origins in semi-arid Africa (Karunaratne, 2009, Karunaratne, 2011). The total amount of rainfall, the daily mean temperature, and the length of the growing season in these countries appear to be closely related to the growth and developmental performances of the landraces. Based on the climates of Swaziland and Namibia, it is suggested that Bambara groundnut has a wide climatic

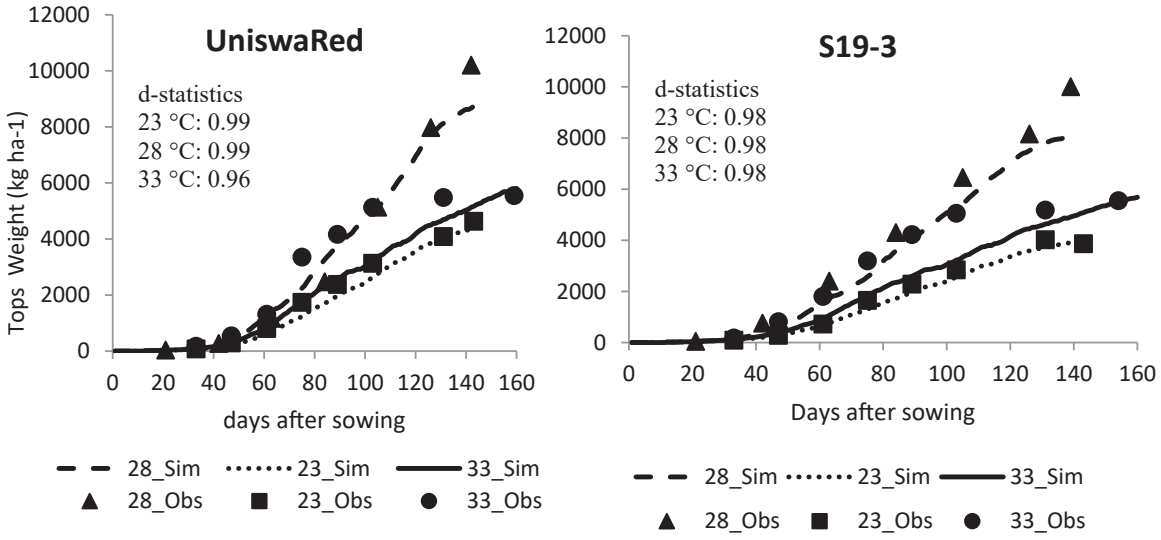

Fig. 5. Simulated (lines) and observed (points) tops weight (kg ha^{-1}) over time course for the landraces UniswaRed and S19–3 grown under optimum (28°C ±5) in 2003 and low (23°C ±5) and high (23°C ±5) temperature conditions in 2006 experiments.

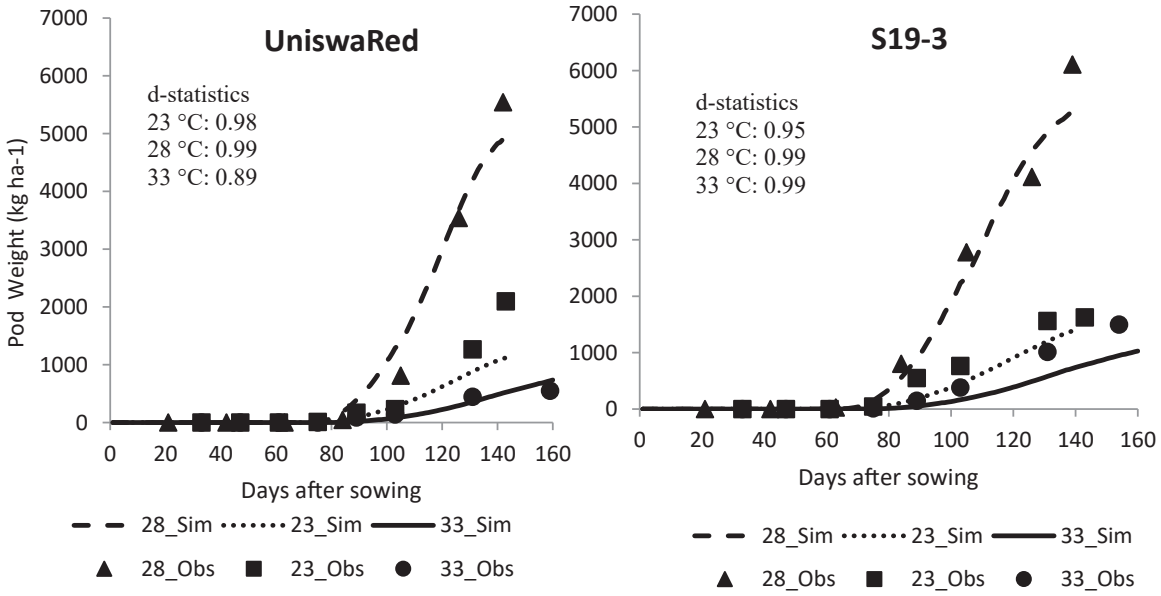

Fig. 6. Simulated (lines) and observed (points) pod weight (kg ha^{-1}) over time course for the landraces UniswaRed AND S19–3 grown under optimum (28°C ±5) temperature in 2003, low (23°C ±5), and high (33°C ±5) temperatures in 2006 experiments.

adaptation.

The new model will benefit from further evaluation and improvement with experimental data for adaptation to different water management regimes, temperature, and CO_2 levels to test the sensitivities of different landraces to key weather variables for different environments. One of the uncertainties of the current model is the need for evaluation under full-sun field conditions, because the data from this study were collected under relatively low light greenhouse conditions. This will provide an avenue for application of the model to estimate the yield variability and evaluation of yield under future climate scenarios. Since uncertainty in climate change projections remains substantial, it is vital to assess the resilience of underutilised crops as potential adaptation options. Bambara groundnut can serve as a potential example for this. Furthermore, the results from the current study have revealed that the model can be used to predict optimal selections of parental germplasm for breeding material suited to different locations for a climate-resilient future using genetically distinct landraces from matched climatic conditions.

5. Conclusions

The CROPGRO module of DSSAT was successfully adapted for Bambara groundnut based on development and growth analyses data from two years of experiments conducted at University of Nottingham Sutton Bonington Campus, UK. The new model showed statistically acceptable simulations for the growth dynamics of Bambara groundnut grown under different temperature conditions. Although further evaluation is necessary under field conditions, the model is suitable to be included in the DSSAT crop modeling system. This will allow for application to test management practices and climate scenarios on the production of Bambara groundnut.

CRediT authorship contribution statement

Ken Boote: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Hoogenboom:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Asha Sajeewani Karunaratne:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127279.

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