MODELLING THE RESPONSE OF BAMBARA GROUNDNUT: A KEY UNDERUTILISED CROP IN AGRICULTURAL SYSTEMS

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ABSTRACT

Bambara groundnut (*Vigna subterranea* (L.) Verdc) is an indigenous legume that is still cultivated in subsistence agricultural systems in sub-Saharan Africa, despite any major research effort until recently. The crop is cultivated from local landraces as until now there are no true varieties of the species bred for specific traits. The variable and hostile climates in the region mean that annual yields of most rainfed crops including bambara groundnut are far below their agronomic or genetic potential. The lack of quantitative information on the eco-physiological responses of the crop to various abiotic factors has resulted in poor decision making on crop management practices especially in relation to sowing date and the selection of appropriate landraces for different locations. The present modelling approaches via BAMGRO and AquaCrop models provide useful predictive information on canopy development, biomass production and yield formation of bambara groundnut landraces under contrasting environments. Two contrasting landraces; Uniswa Red (Swaziland) and S19-3 (Namibia) were used in the present study to evaluate the growth and yield performances under drought, heat and cold stress.

The comparison of model simulations with experimentally observed values demonstrate that canopy development, biomass production and yield are statistically acceptable with a high correlation (r^2; 1:1) with line of identity and lower RMSE. Recent approaches of calibration in FAO-AquaCrop reported that the observed *CC*%, biomass and end of season yield under glasshouse (Nottingham, UK) and field (Africa) can be well explained in model simulations. Further, the extension of the present dynamic model BAMGRO for inclusion of landrace parameters based on molecular genetic estimates is introduced as a novel approach in modelling bambara groundnut. A model that links physiological/trait data and/or molecular genetic estimates of genetic width of a landrace will provide the potential for further improvement of this underutilised species. Further, our multidisciplinary experience with one underutilised crop i.e. bambara groundnut integrated into a global system i.e. AquaCrop can act as a generic basis to model many other underutilised species that can play an important role in the agricultural systems of the future.

INTRODUCTION

The agricultural systems in semi-arid regions of sub-Saharan Africa are normally characterised by extreme climatic conditions. Some of the most resilient crop species such as sorghum (*Sorghum bicolor*. L. Moench), pearl millet (*Pennisetum Americanum*) and cowpea (*Vigna unguiculata*). have originated from this region. Globalization challenges the existence of these indigenous crops with less resilient, but more popular crops like maize (*Zea mays*) and bean (*Vicia faba*), which are higher yielding under favourable climates. In addition, the improved breeding programmes of major crops have widened the gap between the cosmopolitan and traditional crops.

Bambara groundnut (*Vigna subterranea* (L.) Verdc) is one such indigenous legume with significance as a source of protein in sub-Saharan Africa where it is mainly grown by women farmers for the subsistence of their families. Its nutritional composition (protein content is 16-25%) is highly comparable or superior to other legumes (Linnemann and Azam-Ali 1993), providing an important supplement to cereal-based diets. In the absence of established varieties, marginal and subsistence farmers in Africa grow locally selected 'landraces' of bambara groundnut. A landrace is a locally adapted strain of a species selected through traditional methods and not influenced by modern breeding technologies.

The production and consumption of bambara groundnut is mainly confined to semi-arid Africa where very low and erratic distribution of rainfall, losses through run-off, drainage and evaporation result in limited available

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soil moisture for crop growth. According to Azam-Ali and Squire (2002), the agro-ecological niche of bambara groundnut is similar to that of millet and groundnut based on the observations that it appears to be more tolerant of drought conditions than other legumes (Linnemann and Azam-Ali 1993). In spite of the drought tolerant capabilities of bambara groundnut, results reported by Collinson et al. (1996) suggested that canopy expansion, biomass production and yield are reduced under strong drought stress.

Temperature variability is a yield determining factor in many parts of the world including semi-arid Africa where bambara groundnut is normally grown. The wide fluctuations in daily mean temperature in semi-arid Africa necessitate a thorough understanding of the effects of heat and cold stress which may both affect growth and development in the same season. Extremes of temperatures are a major constraint to crop adaptation and productivity; especially when they coincide with drought and critical growth stages of plant development.

To explore the potential growth and yield of bambara groundnut landraces in various agro-ecological regions and to evaluate the possibilities of transferring them to a different locations, it is vital to understand how crop processes are influenced by major environmental factors. The numerous permutations of abiotic factors that may affect growth and development mean that research has prioritised the quantification of key environmental factors through the use of suitable modelling approaches.

The heuristic value of a crop model for determining growth and yield are well established (Sinclair and Seligman, 1996). The broader goal of a crop model is to simulate and explain crop development, growth and yield as functions of environment, management and genetically controlled characteristics.

In this paper, the response of bambara groundnut is presented through the use of a new crop model (BAMGRO) integrated into the UN-Food and Agriculture Organisation (FAO) AquaCrop model (http://www.fao.org/nr/water/AquaCrop.html).

BAMGRO is based on the established CROPGRO model (Boote et al. 2002a) and collectively both BAMGRO and AquaCrop simulate responses to abiotic stress with special reference to drought, heat and cold. Subsequently approaches for linking molecular information within BAMGRO/AquaCrop are outlined.

A crop simulation model for an agronomically and nutritionally variable crop like bambara groundnut will provide the framework for scientific cooperation to rapidly integrate new knowledge and prioritise future research on an under-researched and underutilised species. This new approach to model bambara groundnut responses to major abiotic stress factors provides a platform for easily incorporating other biotic and abiotic factors and extending the model to more landraces and ultimately varieties of the crop. These modelling approaches linked with integrated research have useful lessons for the modelling of other underutilised crops and their potential for future agricultural systems.

MODEL DATA SETS

Briefly, datasets from glasshouse experiments in Sutton Bonington Campus, University of Nottingham, UK (Tropical Crops Research Unit; TCRU) in 2002 and 2006 were used to calibrate BAMGRO. The FAO-AquaCrop model was calibrated for bambara groundnut using all the data sets from glasshouse, UK (2002, 2006, 2007, 2008) and field observations in Swaziland to represent different growing conditions.

The details of experimental design, plant sampling procedures, irrigation treatments and standard measurements for TCRU-2002 experiment have been previously explained in Mwale et al., (2007a). BAMGRO was validated using independent datasets from 2 years of Glasshouse experiments, Nottingham, UK (TCRU-2007, TCRU-2008) and field experiments in Swaziland.

Over the summer months of 2006, 2007 and 2008 (April to September), two contrasting bambara groundnut landraces; Uniswa Red (Swaziland) and S19-3 (Namibia) were grown in five glasshouses with each house having one Uniswa Red and one S19-3 plot under controlled temperature regimes. Two temperatures 23±5 ^{0}C (LT) and 33±5 ^{0}C (HT) were imposed in the five glasshouses. Soil moisture in each house was non-limiting with weekly irrigation to field capacity until harvesting in 2006, up to 77 DAS in 2007 and up to 33 DAS in 2008. The treatments were allocated according to a split-plot design that combined two bambara groundnut landraces (Uniswa Red, S19-3) and two different temperature regimes (LT, HT) with each treatment replicated twice and thrice at low and high temperature, respectively, due to limited number of glasshouses.

As described by Cornelissen (2005), from December 2002 to May 2003 a set of Swaziland and Botswana landraces were grown in field sites in Swaziland (Malkerns and Luve) and Uniswa Red was selected for the present validation of BAMGRO as it is common to the landraces grown in glasshouse conditions at Nottingham, UK. During the experimental period Malkerns reported well distributed rainfall thus suggesting no water limitation while the crop experienced a severe drought stress in the Luve field site.

MODEL DESCRIPTION

Summarised details of BAMGRO and AquaCrop models are described below.

BAMGRO Model

BAMGRO is intended to predict the performance of different landraces under variable climates. Bambara groundnut is an indeterminate crop so leaf production can occur from emergence until maturity, depending on the supply of assimilates available and the effects of stress due to drought and temperature. Also, a fraction of produced leaves is removed from the plants as dead leaves due to senescence. Therefore, the rate of daily increment in actual leaf number (*LN*) can be explained as the balance between rate of new leaf production (LN_{new}) and rate of leaf senescence (LN_{dead}) as in Equation (1).

$$\frac{dLN}{dt} = LN_{new} - LN_{dead} \quad (1)$$

Thereby the leaf area expansion (*LA*) is calculated as a function of rate of leaf production and landrace coefficient *a* according to Equation (2).

$$LA = a \times LN \quad (2)$$

Actual increase in dry matter (DM_{actual}) is calculated from the minimum of two potential growth rates (Equation (3)), one determined by intercepted radiation (Light Limited Growth-*LLG*, Equation (4)) and the other by soil water supply (Water Limited Growth-*WLG*, Equation (5)).

$$DM_{actual} = \min(LLG, WLG) \quad (3)$$

$$LLG = PAR \times S_i \times \varepsilon_s \times \left(1 - \exp^{-k \times LAI}\right) \quad (4)$$

$$WLG = \frac{\left(U_{soil} \times TE\right)}{SD} \quad (5)$$

Where, S_i is short wave solar radiation (MJ day^{-1} m^{-2}), *PAR* is Photosynthetically Active Radiation (50% of S_i) ε_s is efficiency of conversion of this solar radiation (g MJ^{-1}), *LAI* is leaf area index, *k* is light extinction coefficient, U_{soil} is potential rate of water uptake by roots in profile (mm d^{-1}), *TE* is transpiration efficiency (g mm^{-1}) and *SD* is, saturation deficit (k Pa).

Dry matter (DM_{actual}) partitioning gives priority to above ground parts (leaves and stems) during vegetative growth and towards pods during reproductive phase. At the end of each simulated day, remaining biomass is directed towards roots based on the requirement of the roots that is adjusted according to growth phase and stress condition. Pod formation (*PN*) and pod filling (*PW*) are considered as two independent processes during the reproductive phase and contribute towards the pod yield.

To model the effect of soil moisture stress (*WSTRESS*) on growth and development, a relationship *WLG* (Equation (5)) and *LLG* (Equation (4)) is considered. The value varies from zero to one where one represents no stress and zero represents maximum stress.

When the crop is exposed to a range of temperatures within the boundary line of base (T_{base}) and ceiling (T_{high}) temperatures, it results in potential temperature stress and the stress index (*TSTRESS*) ranges between zero and one like in *WSTRESS*.

AquaCrop Model

AquaCrop is a water-driven crop-model aiming at simulating yield response to water of herbaceous crops. AquaCrop describes crop foliage development in terms of canopy cover (*CC*, Figure 1) and not via *LAI*. This distinctive feature introduces a significant simplification, allowing the user to enter actual values of CC even estimated by eye.

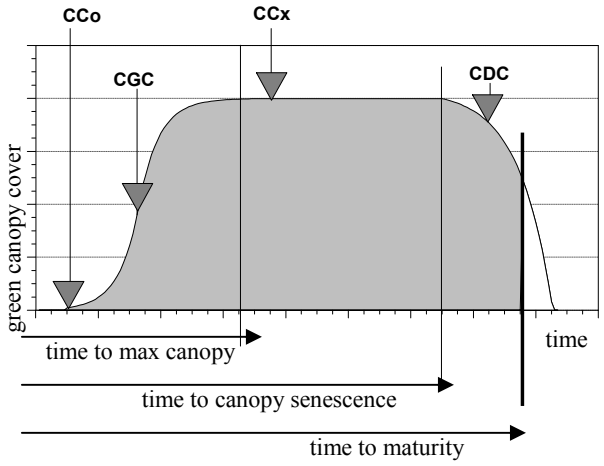

Figure 1: Green canopy cover development described by four parameters: initial canopy cover at the time of crop emergence (*CCo*), canopy growth coefficient (*CGC*), expected maximum canopy cover (*CCx*), canopy decline coefficient (*CDC*)

Canopy cover is used for the computation of transpiration. Using Water Productivity (*WP*), AquaCrop calculates above-ground biomass production from transpiration (*Tr*) and reference evapotranspiration (*ETo*) (Equation (6)).

$$m_i = WP \times \frac{Tr_i}{ETo_i}) \quad (6)$$

Where, m_i is the daily above-ground biomass production, Tr_i is the daily crop transpiration, ETo_i is the

daily reference evapotranspiration, and WP* is the normalized water productivity.

The model is based on the conservative behavior of *WP* (de Wit 1958, Hsiao and Bradford, 1983, Steduto et al. 2007), that is the constancy to the relationship between biomass production and transpiration. The normalization of *WP* for climate (atmospheric evaporative demand, ET_o, and concentration of the bulk atmosphere, CO_2) makes AquaCrop applicable to diverse location and seasons, including future climate scenarios.

AquaCrop does not calculate the partitioning of biomass to various organs, but simply adopts the Harvest Index (*HI*) to simulate the portion of above-ground biomass stored into the grains (yield). This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes.

AquaCrop simulates water stress in terms of its effects on leaf growth, stomata conductance, canopy senescence, and *HI*. With the exception of *HI*, these effects are manifested through individual stress coefficients (K_s). K_s varies from one (no stress) to zero (the stress effect is maximum), and it is function of water content in the root zone.

Temperature plays a role in influencing crop development, when the Growing Degree Days (*GDD*) mode is chosen. Biomass production might be hampered when the air temperature is too cool, through a temperature stress coefficient (K_s). In addition, cold or heat stress at flowering might induce a reduction in *HI*.

Proposed Genetic Linkage Model

A new approach has been initiated within the BAMLINK project (Sean Mayes), University of Nottingham, UK (Mathematics in Plant Sciences Study Group http://cpib.info/study2008/programme.shtml) to link existing genetic marker and physiological data as a test case using the BAMGRO/AquaCropmodel to evaluate the effect of genetic variability *per se* on physiological traits. It will provide information on how much intra-landrace genetic viability contributes to each trait, or to 'traits' more generally.

Large marker datasets are currently in development It is likely that intra-landrace genetic variability will actually be a variable in the model that is built, in the first instance. This model would be able to derive results which estimate the required amount of genetic 'width' data to optimally inform the physiological data, for a number of scenarios. A partial validation will be carried out with existing (limited) data.

In order to assess model performances and provide an objective evaluation of the "closeness" of simulated (*S*) vs. measured (*M*) values, a number of indicators are used. Visual observations provide comparisons for either over or under estimations. Coefficient of determination with 1:1 line is the conventional r^2 statistic, applied to the line of identity (r^2; 1:1) (Equation (7).

$$r^2 = \left(\frac{\sum \left(M_i - \overline{M}\right)^2 - \sum \left(M_i - S_i\right)}{\sum \left(Mi - \overline{M}\right)^2} \right) \qquad (7)$$

SIMULATION RESULTS

BAMGRO Model

The model comparison for pooled data from glasshouse experiments, Nottingham and field experiments in Swaziland on *LAI*, Total Dry Matter (*TDM*) and yield (Y) over the season for each landrace correlated well with measured values. The statistical evaluation of the model reported that *LAI* is well correlated with the line of identity indicating acceptable correlation coefficients (r^2; 1:1 line) for S19-3 (0.83) and Uniswa Red (0.78). Similarly, yield simulation of BAMGRO was statistically acceptable with higher correlations (r^2; 1:1 line for S19-3 (0.87) and Uniswa Red (0.61)) and less than 0.5 t ha^{-1} of RMSE value.

AquaCrop Model.

The linear regression of simulated vs. measured canopy cover (*CC*) shows an over- and under estimation of not more than 3%, which is much less than the degree of error in measuring the data at field level. Further, the slope of the regression line (0.91) and the intercept (2.97) are not significantly different to the slope (1.0) and the intercept (0) of 1:1 line. The canopy cover formation is explained successfully by AquaCrop model indicating high r^2 (0.88). RMSE (15%) was acceptable, considering the degree of error in the data at field level in Africa and the Glasshouse in Nottingham, UK due to the differences in solar radiation intensities.

The linear regression of simulated vs. measured biomass shows a very small over-estimation at the early stage. However the slope of the regression line (0.95) and the intercept (0.23) are not significantly different to the slope (1.0) and the intercept (0) of 1:1 line. Biomass production is explained successfully by AquaCrop indicating high r^2 (0.78). RMSE (0.78 t/ha) was acceptable

Simulation of end of season yield can be considered satisfactory with relatively higher R^2 (0.72), with RMSE (0.36 t/ha) lower than half ton/ha (data not shown). AquaCrop version 2.9 was used for the present calibration and version 3.0 provides more mechanistic approaches to overcome the problems associated with yield simulation in version 2.9. Therefore better results can be obtained by most recent version 3.0.

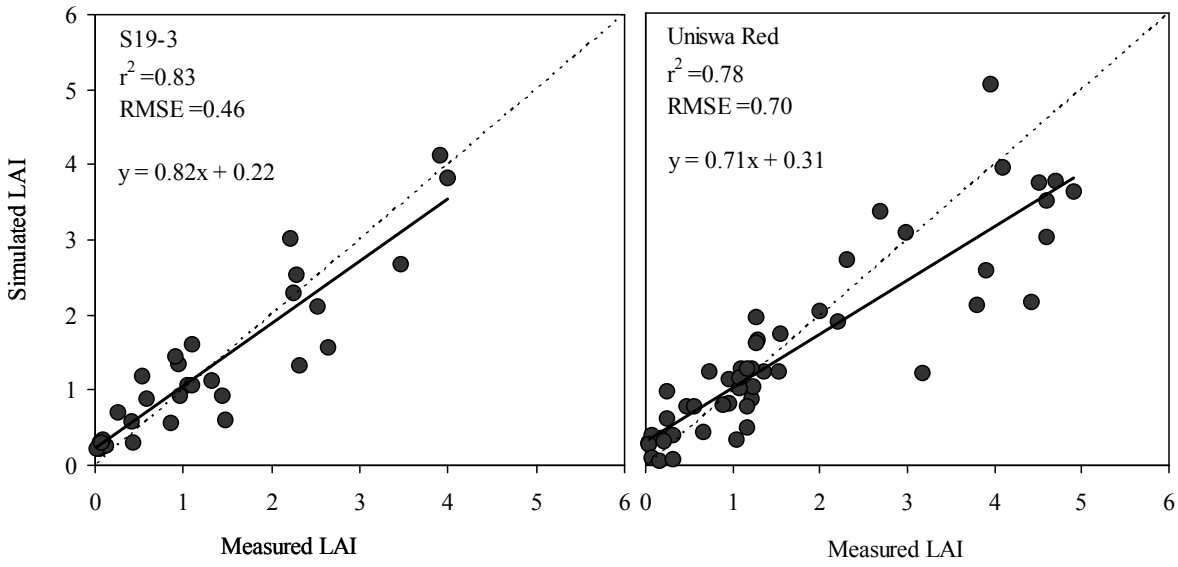

Figure 2. Comparison between measured and simulated *LAI* for Uniswa red and S19-3 in glasshouse experiments, Nottingham, UK and field sites in Swaziland. Model data sets were provided by Ibraheem Alshareef, Stanley Noah and R.Cornelissen.

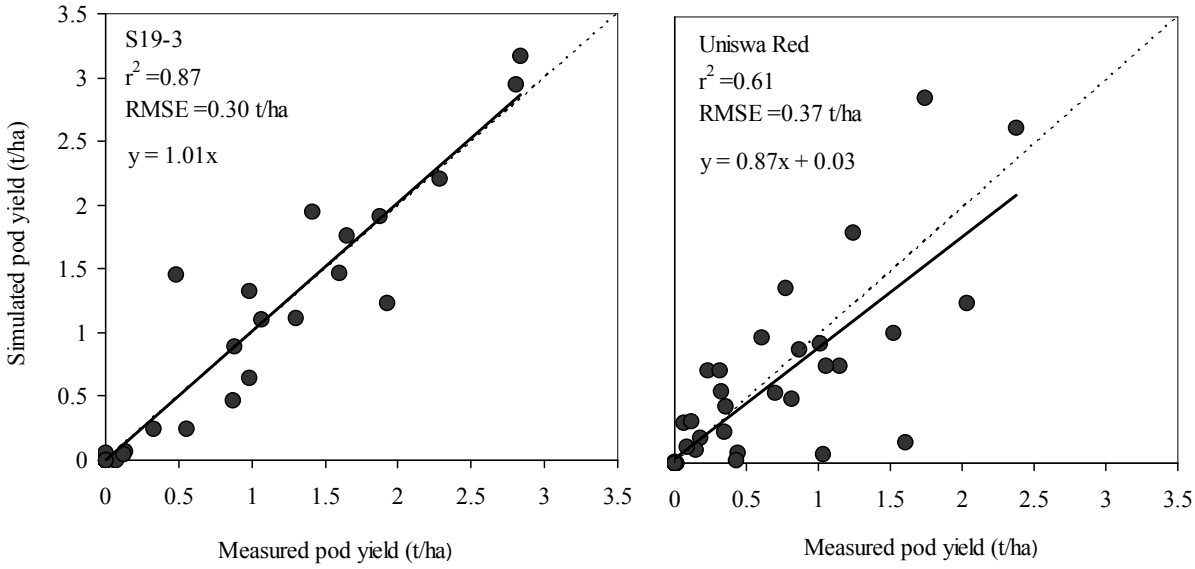

Figure 3. Comparison between measured and simulated pod yield for Uniswa red and S19-3 in Glasshouse experiments, Nottingham, UK and field sites in Swaziland. Model data sets were provided by Ibraheem Alshareef, Stanley Noah and R.Cornelissen.

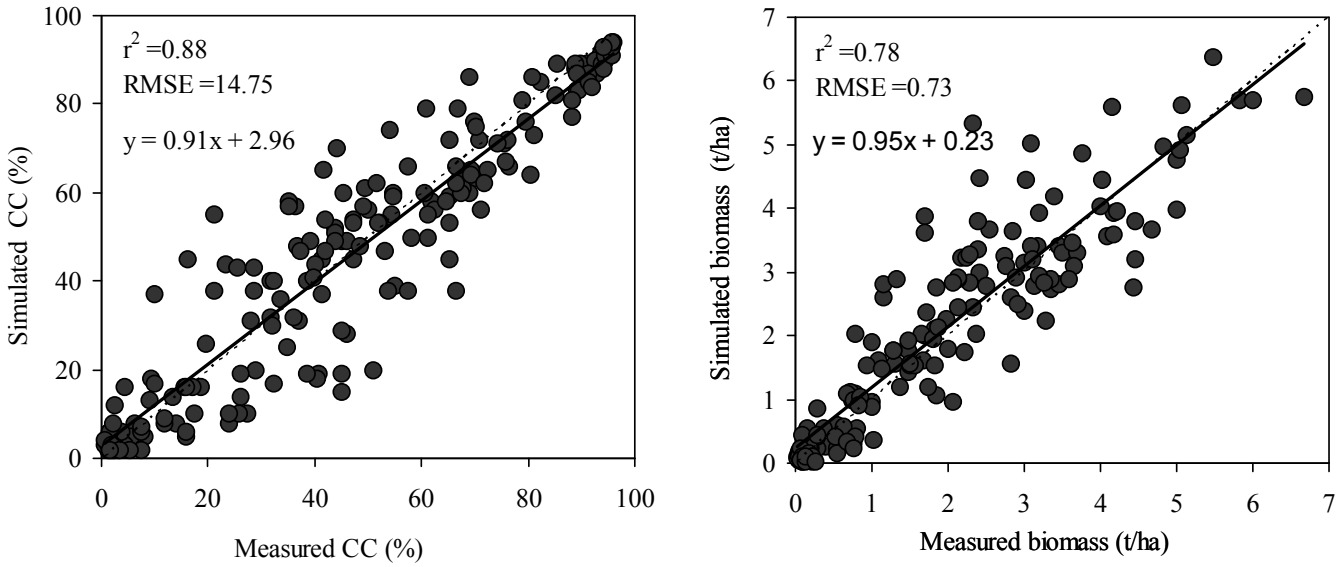

Figure 4. Model calibration results of AquaCrop model for canopy cover (*CC* %) and biomass for four landraces (Uniswa Red, S19-3, DipC and OM1) in glasshouse experiments, Nottingham, UK and field sites in Africa. Model data sets were provided by Ibraheem Alshareef, Stanley Noah, R.Cornelissen (University of Nottingham.

DISCUSSION

The validation of the BAMGRO and calibration of the AquaCrop models show some deviations of model prediction for two different growth conditions (glasshouse and field) under drought, heat and cold stress. Therefore the possible reasons for these discrepancies may be the landrace variability ('genetic width' the differences in quality and quantity of solar radiation during UK summer and in semi-arid Africa and model structure.

CONCLUSIONS AND FUTURE WORK

BAMGRO model validation results for canopy development and yield for the tested two landraces (Uniswa Red and S19-3) are in good agreement with measured values in glasshouse conditions in Nottingham, UK and field sites in Swaziland. However, Uniswa Red reported wider distribution of simulations consistently in *LAI* and yield compared to the Namibian landrace, S19-3 thus providing opportunity for extending the model to genetics.

Bambara groundnut was successfully included in the FAO-AquaCrop phase providing evidence for possibility of inclusion of other underutilised crops in this interface.

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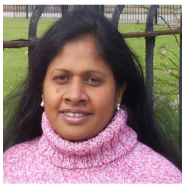

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