SIMULATION OF WATER USE EFFICIENCY TO TACKLE THE DROUGHT

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ABSTRACT

Rainfed environments are characterised by unpredictable and highly variable seasonal rainfall and hence highly variable yields. Water use efficiency (WUE, yield per unit of water use) is commonly used for agricultural production with limited water resources. Expertise working towards the water resources need to address the multitudinous aspects in which cropping systems and amounts, timing and methods of irrigation, and fertilizer applications may be changed to improve WUE while maintaining yield and harvest quality goals. Since experimentation cannot address all scenarios accurate simulation models may fill in the gaps. Crop simulation models are used widely to predict crop growth and development in studies of the impact of climatic change. The present paper explains the model for WUE for an underutilised crop, bambara groundnut under drought as a sub-module of BAMGRO main model (Karunaratne, 2009). This quantitative model explains the root growth, root distribution and water uptake on daily basis under variable climatic conditions. The model links the size and distribution of root system to the capture of water over the growing period. The model was calibrated using glasshouse experimental data, Nottingham, UK and published information. It was validated against 2 years of independent data sets (2007, 2008) from Nottingham and field site at Notwane, Botswana. Although the limited information on root growth is available, validation of soil moisture against glass house and field reported satisfactory results.

INTRODUCTION

Although global biomass resources are vast and underutilised, over the coming decades, in the face of a growing population and a changing climate, there is likely to be increased pressure on plant resources for food, fuel and other plant products as we move from an oil-based to a bio-based economy. The consequences are the increase in pressure on global agricultural productivity. Plant biologists, agronomists, crop modellers and breeders should therefore consider the future of crop production in a changing climate.

The marginal nature and adverse climatic conditions in the world's arable lands challenge the existence of major crop species. Around the world, species that are little used, or which were grown traditionally but have fallen into disuse, are being brought out of the shadows and put to use, especially in the hands of the poor. Over 7,000 plant species have been grown or collected for food. But worldwide, less than 150 have been commercialised and just three crops - maize, wheat and rice - supply half of our daily proteins and calories. Yet a large number of crops that are now overlooked have the potential to play a much more important role in sustaining livelihoods and enhancing environmental health. The underutilised crops are surely the crops of the future (http://www.cropsforthefuture.org/) that will survive under extreme climatic conditions. 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 in subsistence agricultural systems in, despite the lack of any major research effort until recently. 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.

The unpredictable variability of climate especially with erratic distribution of annual rainfall in sub-Saharan Africa routinely causes severe yield losses. The undoubted importance of water conditions for crop growth and development has been identified on many occasions (Roose and Flower 2004). The rate of water uptake by the root system and the factors affecting the process of root growth are of fundamental interest in determining economic yield of a crop.

The drought tolerance capabilities of bambara groundnut have been characterised in many instances with commonly used growth indices such as, Leaf Area Index (LAI), Total Dry Matter (TDM) and yield (Collinson et al., 1996; Mwale et al., 2007a). Since monitoring root growth and distribution is both labour-intensive and expensive, attempts have been made to develop models to simulate the water use by the root system (King et al. 2003; Manschadi et al. 1998). Thus research work has prioritised the quantification of environmental factors through suitable experimental and modelling approaches. Physiologically-based mechanistic crop models are frequently employed to

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estimate crop yields in variable climate studies, as they attempt to represent the major processes of crop environmental response.

The first dynamic crop model of bambara groundnut, BAMnut (Bannayan, 2001) followed the approaches of the CERES, family of models in which soil profile is divided into 3 layers and the root system restricted to the top and second layer. BAMFOOD project model (Cornelissen, 2005) used the water routine of the PALM model (Matthews, 2005) since no data were available on soil water content in the experiments used. It calculates the ratio between water supply and potential transpiration. The water supply component is influenced by the actual water content of the soil layers and the depth and distribution of the root system.

The present model, BAMGRO uses a simple approach to simulate the root growth, root distribution and soil water uptake of the crop under variable climatic conditions using the starting framework of wheat root model applied for pre anthesis period described by King et al., (2003) and modified for whole crop cycle in bambara groundnut. The model was primarily calibrated with glasshouse experiment (Tropical Crops Research Unit-2003), Nottingham, UK and validated for glasshouse experiments (TCRU-2007, 2008) and field experiment in Notwane, Botswana (2007-2008 season).

Therefore the objective of the present study were to simulate (1) root growth and root distribution, (2) the water uptake by the root system and (3) the soil water balance of the profile under variable climates in controlled environments and in the field.

MODEL DATA SETS

Briefly, datasets from glasshouse experiments in University of Nottingham, UK (TCRU) in 2003 and published information in King et al., (2003) were used to calibrate BAMGRO. The model was validated against independent data sets from Nottingham, UK (TCRU-2007, TCRU-2008) and field site in Notwane, Botswana.

The details of experimental design, plant sampling procedures, irrigation treatments and standard measurements for TCRU-2003 experiment have been previously explained in Mwale et al. (2007a) and TCRU-2007, TCRU-2008) and field experiments in Botswana in Karunaratne et al. (2010a 2010b).

Over the summer months of 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 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.

During 2007 and 2008 growing season in TCRU experiments, soil moisture content in the soil profile was monitored in all plots using a PR2 probe. The PR2 probe measures the soil moisture at 10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm. Each plot has four access tubes, the average of the access tubes readings represent the mean amount of water in the soil for each plot. Measurements were taken weekly starting from 55 DAS. Unfortunately during TCRU- 2007 experiment, the PR2 broke down after 119 DAS so the measurements are unavailable between 119 and 168 DAS.

The experimental farm, Notwane (Botswana College of Agriculture) performed field experiments for set of landraces at three sowing dates: December 21, January 18 and February 1 in 2006/2007 growing season where a range of environmental conditions were considered. The experiment was conducted in a single split plot with three sowing dates in main plots and the landraces in sub plots, replicated four times. Neutron probe was used to determine the soil moisture content in the profile (up to 100 cm depth) of Botswana field experiments (2007-2008). However this paper explains the model validation results for Uniswa Red sown in December 2007 only.

MODEL DESCRIPTION

The BAMGRO-soil water module uses daily time-steps to simulate root growth, root distribution, root water uptake and soil water balance from sowing until maturity for different bambara groundnut landraces. A summarised detail of soil water module is described below.

The soil is represented as a one dimensional profile; it is homogeneous horizontally and consists of a number of soil layers. The total soil depth is assumed to be 1.5 m, divided into 15 soil layers each of 10 cm depth. This model computes the daily changes to root length and balance of soil moisture content for each soil layer due to rainfall and irrigation, vertical drainage, soil surface evaporation and root water uptake processes.

The root distribution is simulated according to Gale and Grigal (1987) as in Equation (1)

$$Y = 1 - \beta^d \qquad (1)$$

Where, Y is fraction of root system accumulated from soil surface to depth d and β, parameter to describe root distribution with depth.

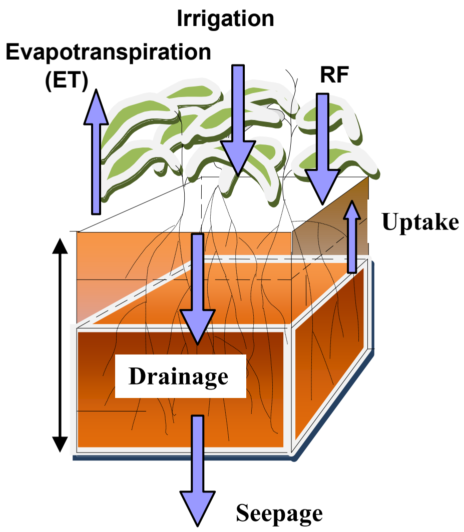


Figure 1: Inward and outward water flows for the different layers considered in the soil water balance.

The BAMGRO model follows the cereal root model (King et al., 2003) to calculate root length density (L_v; cm cm^{-3}). The value of β, σ, *RW* and *Y* (Equation (1)) are used to estimate the root length density of each 10 cm layer of the soil profile at each stage of crop growth according to Equation (3). King et al., (2003) reported that total root length (*L* m) is related to root dry weight (*RW* g m^{-2}) by the specific root weight (σ g km^{-1}). According to experimental evidence the value of σ significantly varies among landraces.

$$L_v = (Y_d - Y_{d-10}) \times \frac{RW}{\sigma} \qquad (2)$$

Where, L_v is root length density at 10 cm of soil layer at depth *d* (cm cm^{-3}); Y_d, cumulative fraction of roots at depth *d*; Y_{d-10}, cumulative root fraction at depth (*d-10*); *RW*, root weight (g m^{-2} d^{-1}) and σ, specific root weight (g km^{-1}).

Potential water extraction from the soil by roots equals potential transpiration. Its magnitude depends on the depth and density of the root system, and on the available soil water. This maximum uptake rate can be realized in a soil that is at *FC* and fully exploited by roots. When either soil moisture or root density is below optimum the actual water uptake is reduced relative to potential. Following (King et al., 2003), a generic function (Equation (4)) is used to predict water uptake as a fraction of total available water which is potentially available to uptake over the day. Thereby the potential water uptake for each 10 cm soil layer is estimated by Equation (4) based on the maximum available water in each layer on a daily basis.

$$U_{pot(t)} = \theta \times \left(1 - Exp\left(-k_w \times L_v\right)\right) \times E \qquad (3)$$

Where, k_w is 'root water capture coefficient' (cm^2); L_v, root length density of the soil layer (cm cm^{-3}); *E*, water capture parameter; θ, fraction of available water in soil layer and $U_{pot(t)}$, change in potential water uptake in layer *i* (cm d^{-1}).

The root water capture coefficient (k_w) is related to the resource uptake physiology especially molecular mechanism of water and nutrient transport across membranes and soil water transport mechanisms (King et al., 2003). Due to the lack of available data BAMGRO uses the value of two for k_w, similar to the value used for dry land barley (Gregory and Brown, 1989) and wheat (King et al., 2003). However, BAMGRO reduces k_w when the crop is exposed to temperatures below optimum ($T_{mean} < T_{opt}$).

The potential uptake by the whole root system is the accumulated capture by roots in each layer (1 to 15), assuming maximum possible rooting depth (1.5 m).

$$U_{pot(soil)} = \sum_{1}^{15} \frac{dU_{pot(i)}}{dt} \qquad (4)$$

Then actual water uptake is calculated using the potential values as given by Equation (4) considering Water Limited Growth (*WLG*) as in Equation (5) and Light Limited Growth (*LLG*). The actual water uptake from individual layer is calculated as a proportion of $U_{pot(soil)}$ and U_{actual} (Equation (7)).

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

$$U_{actual} = \left(\min\left(\frac{LLG}{WLG}\right),1\right) \times U_{pot(soil)} \qquad (6)$$

$$U_i = \left(\frac{U_{actual}}{U_{soil}}\right) \times U_{pot(i)} \qquad (7)$$

Where, U_{actual} is actual rate of water uptake by roots in profile (mm d^{-1}); $U_{pot(soil)}$, potential rate of water uptake by roots in profile (mm d^{-1}); U_i, actual rate of water uptake by roots in layer *i* (mm d^{-1}) and *TE*, transpiration efficiency (g mm^{-1}).

As mentioned earlier, the model assumes 15 soil layers of 10 cm. Soil moisture is calculated separately for each of these (Figure 1). Layer 1 is the topmost layer dealing with calculation of potential evaporation from soil, addition from rainfall and irrigation, water extraction from crop component and vertical drainage. The subsequent layers deal with water extraction from roots and vertical drainage.

To estimate infiltration the model takes the simplified approach in which the top layer takes up water until it is at field capacity. Subsequent water is added directly to the second layer (Equation (9)). The drainage component and FC_l are estimated according to Equation (9) and (10) respectively.

$$\frac{dWATER_1}{dt} = IRRI + RAIN - DR_1 - EVAPO - UP_1 \quad (8)$$

$$DR_1 = \max((WATER_1 - FC_1), 0) \quad (9)$$

$$FC_1 = FC_{soil} \times d_1 \quad (10)$$

Where, $WATER_1$ is soil moisture in layer 1(mm); *IRRI*, irrigation (mm d^{-1}); *RAIN*, precipitation (mm d^{-1}); UP_1, actual water uptake by roots in layer 1(mm d^{-1}); DR_1, drainage in layer 1(mm d^{-1}); d_1, depth of layer soil layer (cm) and FC_1, field capacity in layer 1 (cm).

If the soil moisture in the adjacent upper layer exceeds its *FC* the excess water flows to the subsequent layer of the soil profile. The major component in soil water balance in layers 2 to 15 is due to the uptake of water by the crop (Figure 2). In addition, excess water is directed to the next lower layer as the drainage fraction as explained in layer 1 (Equation (9)). The soil water balance in layer 2 to 15 is given by Equation (11).

$$\frac{dWATER_i}{dt} = DR_i - DR_{i+1} - UP_i \quad (11)$$

Where, $WATER_i$, is soil moisture in layer *i* (mm); UP_i, actual water uptake by roots in layer *i* (mm d^{-1}) and DR_i, drainage in layer *i* (mm d^{-1}).

SIMULATION RESULTS

The model was validated only for soil moisture due to the unavailability of root growth data. Mainly the model was compared with experimental soil moisture data sets from glasshouse experiments in 2007 and 2008 and the Botswana 2007/2008 season. The available soil moisture is assumed to be the net remaining after water uptake, vertical drainage and evapotraspiration. Therefore the simulation results of root growth and distribution though the profiles are shown as they are connected to soil water uptake component (Figures 2 and 3) at LT and HT in 2007 and 2008 respectively.

Comparison between simulated and observed soil moisture content (mm) for four soil layers (layer 1, 10 cm; layer 2, 20 cm; layer 3, 30 cm; layer 10, 100 cm) in glasshouse experiments during summer months of 2007 and 2008 are shown in Figure 2 and 3 respectively for UniswaRed.

The model was able to simulate the reduction in soil moisture content (mm) correctly due to the drought (2007, 77 DAS; 2008, 33 DAS). However the predicted soil moisture content (mm) in deeper layers was heavily under estimated, particularly under high temperature (33 ± 5 ^{0}C) thus indicating over estimation of losses of the water from the layer 10 (100 cm). A similar trend was observed for the variation of soil moisture content (mm) for S19-3 (data not shown). However the model generally over estimated the soil moisture content in the 2008 glasshouse experiment in which the drought was imposed at 33 DAS.

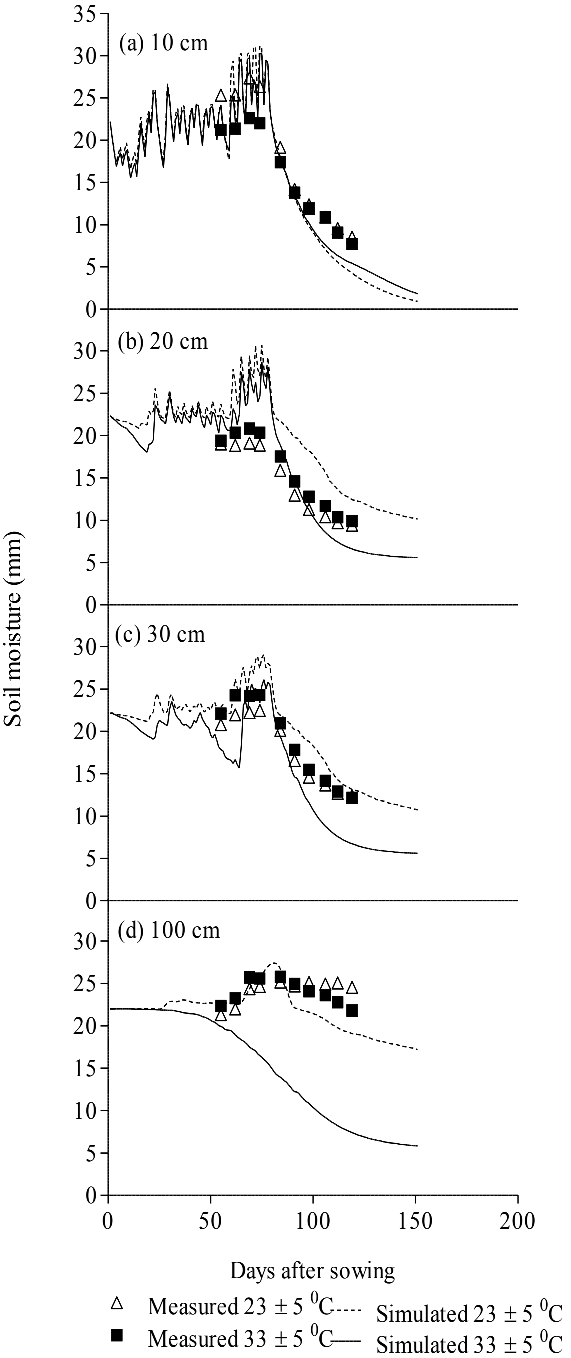
BAMGRO-soil water module simulates the soil moisture variation the soil profile of field sites in Notwane, Botswana with less deviation from measured values (MAE is ± 22.8 mm) (Figure 4). However, there is an over estimation especially towards the end of the growing season.

DISCUSSION

The BAMGRO-soil water module provides a framework for predicting root growth, water uptake and soil water balance for bambara groundnut landraces grown under drought stress conditions. Generally the model over estimates the soil moisture content in upper soil layers and it is heavily under estimated at deeper layers. There are several possibilities for these discrepancies.

According to the model, the vertical distribution of roots (*Y*) as described by β, can influence the water uptake capacity of the crop. The general over estimation of the simulation results from the present study indicates that the parameter values used for β are higher. As this was derived from the crop grown at optimum temperature condition (28 ± 5 ^{0}C), a general reduction of β can be hypothesised under heat and cold stress. However, this has not been considered within the model due to the lack of information on changes of β under different temperature stress conditions. In addition, the use of a single value of β from sowing to harvesting, does not consider the root distribution with age. The value used for (k_w) is also not very specific to bambara groundnut and this may contribute towards the poor correlation of model simulations with the measured data. In addition, several soil physical factors influence root growth and distribution that are not considered in BAMGRO (eg. hydraulic conductivity, soil porosity).

The model clearly indicates the relationship of root length density (L_v) and water uptake (Equation (6). However the variation of L_v under drought, heat and cold stress for bambara groundnut is unknown. This provides a weak link within the model. Husain et al. (1990) indicates that both L_v and rooting depth of faba bean (*Vicia faba* L.) grown under drought stress were significantly higher than regularly irrigated crops. A study focussed on investigation of L_v and water uptake revealed that some cereal species consistently had five to ten times the total root length of grain legumes and a higher correlation with maximum rooting depth than the root length density (Hamblin, 1987).



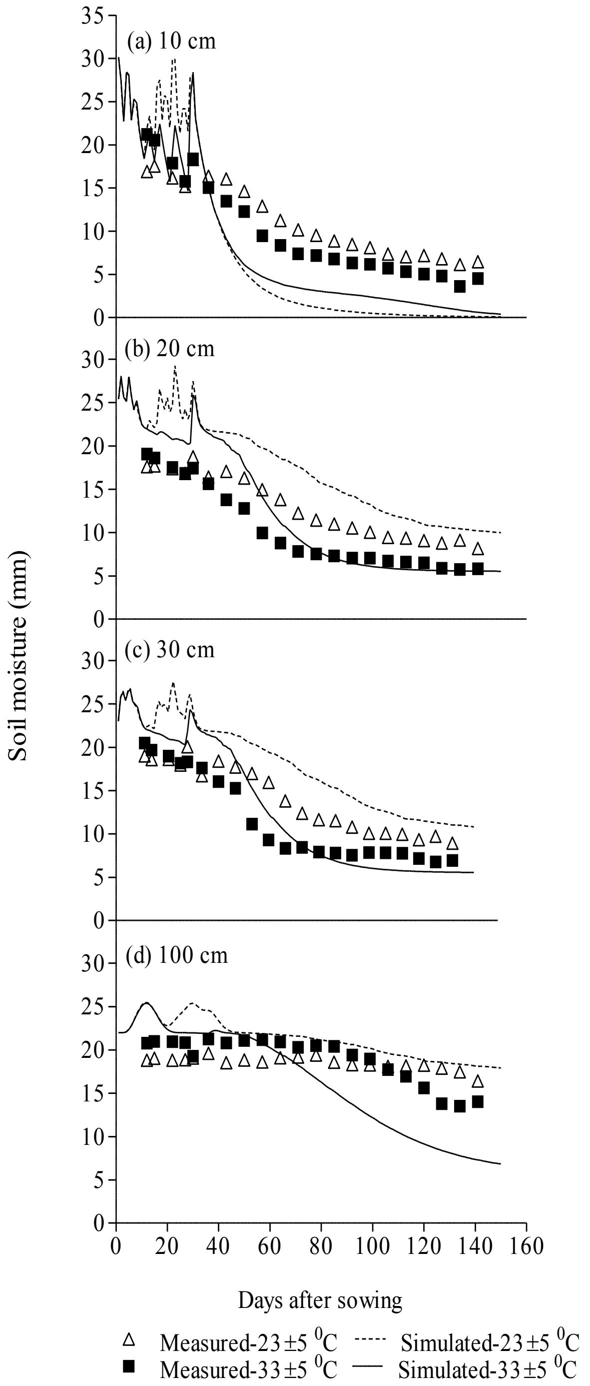


Figure 2. Soil moisture variation with days after sowing at top 10 cm (a), 20 cm (b), 30cm (c) and 100 cm (d) layers for Uniswa Red grown under 23 ± 5^0 C and 33 ± 5 ^{0}C in Glasshouse experiments during 2007. Model data sets were provided by Ibraheem Alshareef.

Figure 3. Soil moisture variation with days after sowing at top 10 cm (a), 20 cm (b), 30cm (c) and 100 cm (d) layers for Uniswa Red grown under 23 ± 5 ^{0}C and 33 ± 5 ^{0}C in Glasshouse experiments during 2008. Model data sets were provided by Stanley Noah.

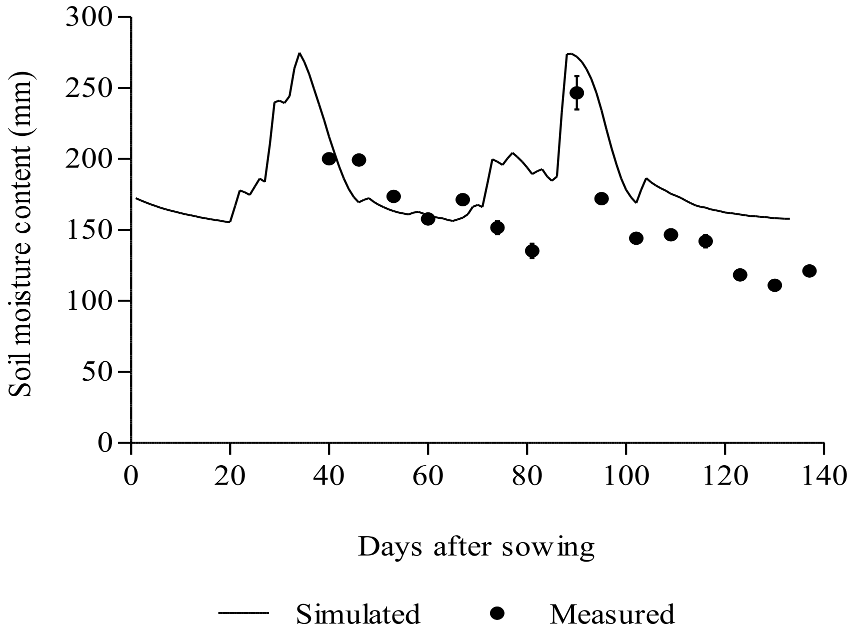


Figure 4. Soil moisture variation of Uniswa Red with days after sowing through the soil profile in Botswana field site during the growing season 2007-2008. The soil moisture was measured using neutron probe. Model data sets were provided by, Abu Sasey Botswana College of Agriculture, Botswana).

CONCLUSIONS AND FUTURE WORK

A model for simulation of root growth, distribution and plant water uptake developed by this study is a modified approach of a simple wheat model. The functions and relationships were derived from the glasshouse experiments at TCRU, University of Nottingham, UK. The testing the model performance was primarily done with the experimental observations from glasshouse experiments with early and late drought and field trials in Botswana. BAMGRO-soil water model predicts the soil water content for two bambara groundnut landraces (Uniswa Red, S19-3) realistically but needs further improvement in calibration of k_w, β and ε_s.

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