

## Madhuram: A Simulation Model for Sweet Potato Growth

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**Abstract:** In this paper a process model for simulating the growth of sweet potato has been proposed. Vegetative developmental days (VDD) and reproductive developmental days (RDD) were calculated to predict crop phenology. Crop growth was divided into three phases, i.e., the first phase from planting to tuber initiation, the middle phase from tuber initiation to the beginning of tuber bulking and the final phase from the beginning of tuber bulking to harvest. Vine growth rates in terms of RDD were worked out for all the phases. Leaf production was assumed to be related to the length of life of individual leaves and the average leaf area was assumed to be inversely related to the number of leaves retained. A new algorithm for predicting branching events was developed. Solar radiation and photosynthesis were calculated using standard methods. Part of the photosynthates produced was used for providing energy for the maintenance and growth processes. The remaining was allocated to leaves, stem and tubers in proportion to their growth rate. The model predicted yields were in good agreement with the corresponding observed values in most of the cases. Prediction of number tubers was also reasonably accurate. However, prediction of number of leaves and branching deviated considerably from the observed value.

**Key words:** Sweet potato . computer simulation . crop simulation

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### INTRODUCTION

Sweet potato is grown in nearly all parts of the tropical and sub tropical world and in warmer areas of temperate regions. The crop has been a staple food crop for many tropical communities for centuries and it continues to be an important source of food in many poor countries. Sweet potato is rich in carbohydrate [1] and vitamins [2]. This paper describes a growth simulation model development for sweet potato, which predicts the crop phenology in response to environmental factors and computes total dry matter production and its distribution. Parameters of three sweet potato varieties Sree Arun, Sree Bhadra and Sree Rethna were estimated for evaluating the model. Usefulness of this model for computing the impact of stress effect due to water, potassium and nitrogen deficit/ deficiency on final yield is also discussed in this paper.

**Background:** Several studies have been reported on the relationship between plant parts and sweet potato tuber yield [3, 4]. Bourke [5] showed the dependence of tuber yield on total plant dry matter. Earlier studies indicated that distribution of assimilate to the tuber is more

important than total photosynthate production in determining the final tuber yield [6, 7]. According to Bouwkamp [8], sweet potato crop might be either source or sink limited, depending on the cultivar, environment or canopy management. [9] observed that the formation of storage roots of sweet potato in the field did not retard the vine growth but proceeded concurrently with the growth of the tops. They also noted the effect of environmental factors on the growth of sweet potato. Increase in storage root growth with fluctuating temperatures was attributed to the increase in the rate of translocation of carbohydrates from the tops to the roots and the influence on mineral nutrition and water uptake. [10] identified mean tuber weight and number of tubers as the most important yield components in sweet potato. Another conclusion from their study was that the variation in yield occurred in sweet potato due to the influence of season, planting material and tuber development. The realization of tuber yield after tuber initiation, depends on the capacity of the shoot system to produce assimilate and the development of the tubers to produce a sink for such assimilate [11]. [12] showed that long days enhanced the shoot development and retarded the tuber growth and vice versa for short day. They also observed a

similar inverse relationship between day length and number of branches. Short days were found to promote tuber bulking. Sweet potato was identified as a short day plant with a critical photoperiod of 13 h [13]. According to [14], short days retard shoot growth and enhance tuber development. [15] observed that early tuber initiation, high rate of tuber bulking, long period of tuber bulking and large number of tubers were important in increasing the tuber yield of sweet potato.

Though there does not exist a simulation model for sweet potato growth, growth simulation models are available for other tuber crops. GUMCAS model [16] of cassava described the growth of cassava reasonably well. In this model, phenological development of the crop was calculated in terms of developmental day. For computing developmental day, a vegetative clock, which is a function of temperature and a reproductive clock, which is a function of temperature and photoperiod, were assumed.

Relationships between environmental parameters (day length, temperature, solar radiation, moisture content and relative humidity), growth parameters and development of sweet potato are modeled in this work. The final model was obtained by combining all these sub-models and was then used for simulating the growth of the plant under different environments. The proposed model also computes both the potential (stress free) tuber yield of sweet potato in a given environment and also the yield in the presence of stresses created by the shortage of water, potassium and nitrogen and when there is no stress.

## MATERIALS AND METHODS

**Structure of the model:** With this background, we propose a growth simulation model (Fig. 1) for sweet potato and the environmental driving variables of the model are:

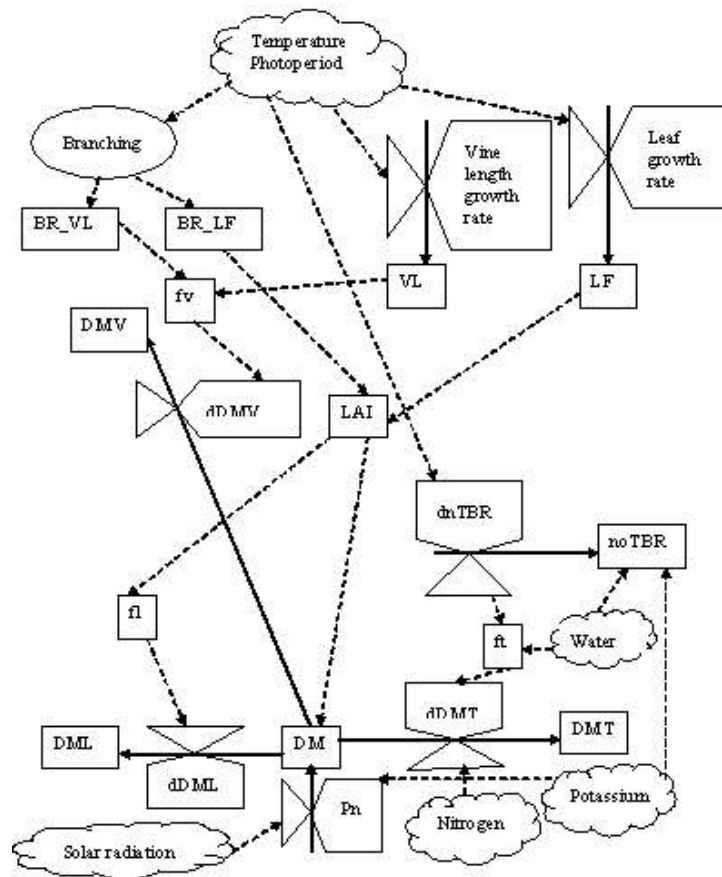


Fig. 1: Relational diagram illustrating the relationship of environmental factors with growth and production of sweet potato. Boxes represent state variables, valves are rate variables, oval is the auxiliary variable and clouds are the driving variables and other environmental variables. Solid lines and broken lines represent the flow of matter and information respectively

- Maximum temperature (°C)
- Minimum temperature (°C)
- Sunshine hours (h)
- Maximum relative humidity (%)
- Minimum relative humidity (%) and
- Soil moisture content (mm)

**Crop phenology:** The phenology of sub model explains the relationships between different plant parts and the environmental variables during the development of sweet potato. Growth phases of sweet potato are different as compared to other flowering crops. Its growth is divided into three phases [13].

- Initial phase of extensive growth of fibrous roots. During this phase vines have only moderate growth rate.
- Middle phase where vines grow extensively and fast. Tubers are initiated and there is a tremendous increase in leaf area.
- Final phase where tuber bulking occurs. Very little growth of vines and fibrous roots. Initially leaf area stays constant and then decreases.

Under tropical conditions first phase last for almost four weeks and the second phase lasts up to about seven weeks after planting. Very little tuber initiation occurs after seven weeks [17].

Phenological development of the crop is calculated on each day in terms of developmental days (Dd). The Dd is calculated using the method followed by [16]. Photoperiodic effect (?) is calculated using the empirical formula which was developed by cubic curve fitting on the data taken from [18]:

$$\phi = 0.0029088DL_i^3 - 0.13662DL_i^2 + 1.898447DL_i - 6.981968 \quad (1)$$

where  $DL_i$  is the day length (h) and  $i$  is the number of days after planting (DAP). Critical photoperiod for sweet potato is taken as 13 h. Optimum temperature for the growth of sweet potato ( $T_{opt}$ ) is taken as 25°C [18]. The base temperature for the growth of sweet potato ( $T_{base}$ ) is calculated as 8.1°C. The highest temperature at which sweet potato grows ( $T_{high}$ ) is taken as 38°C [11].

**Calculation of Dd:** Hourly increments in developmental time (HD, DD/day) are calculated according to:

$$T_d \leq T_{base}, T_d \geq T_{high} : HD = 0$$

$$T_{base} < T_d \leq T_{opt} : HD = \frac{T_d - T_{base}}{T_{opt} - T_{base}} \quad (2)$$

$$T_{opt} < T_d \leq T_{high} : HD = \frac{T_{high} - T_d}{T_{high} - T_{opt}}$$

where,

$$T_d = \frac{T_{min} + T_{max}}{2} + (T_{max} - T_{min}) \times \cos(0.2618(h - 14))/2 \quad (3)$$

where,  $h$  = time of the day,  $T_{min}$  and  $T_{max}$  = Minimum and maximum temperature of the day.

$$Rv = f(T_{min}, T_{max}) = \sum_{h=1}^{24} (HD/24)$$

Sweet potato is an indeterminate crop. The plant continues to produce branches and leaves even after flowering. So throughout the life of the crop, two types of developmental days are calculated.

- Vegetative Development Day (VDD): Here only vegetative clock [16] is considered for calculating Dd. VDD is the sum of vegetative development rates ( $Rv$ ) till date.
- Reproductive Development Day (RDD): RDD is calculated as the sum of reproductive development rates ( $Rr$ ) till date. This is computed using the same method as in [16] by modifying  $Rv$  with  $\phi$ , as:

$$Rr = Rv \times \phi \quad (4)$$

**Tuber initiation:** The end of first phase of the growth is marked by the beginning of tuber initiation. Tubers are found to be initiated when RDD i.e.,  $SRr$  reaches a particular value ( $ntbr$ ). This value was computed to be same for all varieties.

**Production of tubers:** Once the first tuber is initiated further production of tubers is continued till the end of the middle phase. The end of middle phase is marked by the beginning of tuber bulking. The Value of  $SRr$ , after the production of one tuber, should reach at least  $tbr\_gap$ , before the next tuber is produced. This value is computed separately for the three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna*.

**Tuber bulking:** [17] reported that tuber initiation happens after four weeks and tuber bulking after seven weeks of planting under tropical conditions. [19] suggested that under non tropical conditions, first phase lasts up to 9.5 weeks after planting and the second

phase from 9.5 weeks to 16 weeks after planting. From these data the DAP on which tuber bulking starts (DAP<sub>tb</sub>) is calculated as:

$$DAP_{tb} = \frac{DAP_{ti}}{ti} \times tb \quad (5)$$

where, DAP<sub>ti</sub> = DAP on which tuber initiation happens, ti = 4 and 9.5 weeks after planting under tropical and non tropical conditions respectively, tb = 7 and 16 weeks after planting under tropical and non tropical conditions respectively.

**Vine growth:** Vine growth is more vigorous in the middle growth phase compared to the initial and final growth phases. Vine length (VL) was calculated as a function of phenological growth rate. This growth is further modified in terms of dry matter accumulated in vines.

$$dVL_i = dVL_i' \times \frac{(DMV_{i-1} - DMV_{i-2})}{(DMV_{i-2} - DMV_{i-3})} \quad (6)$$

where, dVL<sub>i</sub> = increase in VL on i DAP, DMV<sub>i-1</sub>, DMV<sub>i-2</sub> and DMV<sub>i-3</sub> = Dry matter in vines on i-1, i-2 and i-3 DAP respectively,

$$dVL_i' = \frac{vlen2}{\sum_{i=0}^n R_i}, i > 1 = vlen1 \times R_i, i=0 \quad (7)$$

where, R<sub>i</sub> = growth rate of reproductive clock on i DAP,

**Number of leaves:** Leaves are the main source of assimilates which is utilized for the growth of the plant and for increasing the tuber weight. The number of leaves (LF) produced depends on the rate of leaf production during this period and the length of life of individual leaves. Sweet potato continues to produce leaves till the harvest [20]. The number of leaves per plant at any point of time varies widely among cultivars [21].

In this study, the number of leaves per plant is calculated in terms of the phenological growth rate as well as the dry matter accumulated to the leaves.

$$dLF_i = \frac{R_i \times lfactor + \frac{\left(\frac{DML_i - DML_{i-1}}{DML_{i-1} - DML_{i-2}}\right) \times \left(\frac{LA_{i-1} - LA_{i-2}}{ALA_{i-2}}\right)}{noBR_i}}{2} \quad (8)$$

where, dLF<sub>i</sub> = increase in LF on i DAP, DML<sub>i</sub>, DML<sub>i-1</sub> and DML<sub>i-2</sub> = Dry matter in leaves on i, i-1 and i-2 DAP

respectively, LA<sub>i-1</sub> and LA<sub>i-2</sub> = Leaf area on i-1 and i-2 DAP respectively, ALA<sub>i-2</sub> = Average leaf area on i-2 DAP, noBR<sub>i</sub> = number of branches on i DAP. lfactor is a cultivar dependent constant.

**Leaf duration:** In this study, the life of individual leaves of sweet potato was worked out empirically as 30 RDD and using this value, leaf falling was simulated.

**Leaf area:** Leaf area varies widely among cultivars and at different growth periods depending on the number of leaves retained on the stem and their size [21]. The following empirical equation 9, shows the relationship between average leaf area (ALA) and LF.

$$ALA = \frac{lfactor}{\log(LF)} \quad (9)$$

An initial ALA (larea) is assumed for each cultivar till at least three leaves are formed. lfactor is a parameter specific to cultivars. Leaf area index (LAI) can be computed as:

$$LAI = \frac{ALA \times LF}{spacing} \quad (10)$$

where, spacing is the product of distance between rows and the distance between plants within the rows.

**Branching:** [12] observed an inverse relationship between day length and number of branches produced (BR). SR<sub>r</sub> required for branch initiation (br<sub>l</sub>) and the SR<sub>r</sub> between branching events (br<sub>gap</sub>) are calculated for the varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna*. The steps followed for predicting branching are:

- Initialise: BR=0.
- Determine DAP on which branching is initiated (DAP<sub>brl</sub>); BR=1; DAP on which branching happens (brday) = DAP
- Calculate the number of days required between two branching events (brgap) as:

$$brgap = \frac{DAP_{brl}}{brl} \times br\_gap \quad (11)$$

- BR=BR+1; if  $\sum_{i=brday}^{brday+brgap} R_i \geq br\_gap$  and (DAP-brday) ≤ brgap,  
brday = brday+1; if  $\sum_{i=brday}^{brday+brgap} R_i \geq br\_gap$  and (DAP-brday) > brgap,

- $BR=BR_i$ ; if  $\sum_{i=brday}^{brday+brgap} R_i < br\_gap$ .

Length of the branches and the number of leaves on it are assumed to increase at the same rate as that of the main stem. Since short days promote the growth rate of the crop as well as the production of branches, branching event is predicted when the crop grows at a rate higher than that of the expected rate.

**Calculation of solar radiation:** Solar radiation absorbed by the plant was calculated using the method suggested by [22]. Direct and diffused solar radiations are calculated separately.

**Calculation of photosynthesis:** Rate of leaf photosynthesis (PL,  $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ ) is calculated using the equation 12 [18] as:

$$PL = PLMX \left( 1 - \exp \left( - \frac{PLEA \times PAR}{PLMX} \right) \right) \quad (12)$$

where, PLEA = initial light use efficiency ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1} (\text{Jm}^{-2} \text{ s}^{-1})^{-1}$ ), PLMX = Maximum rate of leaf photosynthesis ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ h}^{-1}$ ), PAR = Photosynthetically active radiation which is about 50% of the solar radiation received.

PL was computed separately for direct and diffused irradiance. PLEA and PLMX are specific to cultivars and they vary with temperature. Effects of temperature on PLEA and PLMX are explained by equations 13 and 14 respectively, which were developed by least square curve fitting on the data from [18].

$$PLEA = -0.000187 \text{TMEAN}_i^2 - 0.001 \text{TMEAN}_i + 0.519 \quad (13)$$

$$PLMX = PLMX_{\text{opt}} \left( \frac{-0.001501 \text{TMEAN}_i^2 +}{0.069 \text{TMEAN}_i + 0.137} \right) \quad (14)$$

where,  $PLMX_{\text{opt}}$  = PLMX at  $25^\circ\text{C}$  (this is a varietal parameter),  $\text{TMEAN}_i$  is the mean temperature of on  $i^{\text{th}}$  DAP which is calculated using the method suggested by [23].

Daily gross canopy photosynthesis is calculated from the leaf photosynthesis rate using equation 15 [22].

$$P_c = L_s \cdot PL_s + L_d \cdot PL_d \quad (15)$$

where,  $L_s$  and  $L_d$  are components of LAI in direct and diffused sunlight respectively,  $PL_s$  and  $PL_d$  are components of PL in direct and diffused sunlight respectively

A fraction of the daily gross photosynthate is used for the maintenance process in the plants. This process includes resynthesis of degraded proteins and maintenance of ion-gradients across cell membranes. The energy for this process is derived from the photosynthates by maintenance respiration. Maintenance coefficient 'm' represents the daily maintenance respiration rate ( $\text{Kg CH}_2\text{O ha}^{-1} \text{ d}^{-1}$ ) and the equation 16 represents its variation with temperature [24].

$$m = 2^{(\text{TMEAN}_i - 20)/10} \cdot R_m \quad (16)$$

where,  $R_m = m$  at  $20^\circ\text{C}$ .

Another fraction of the dry matter will be converted into structural parts and the efficiency of converting substrate to structure is called growth efficiency (Y) and its value is assumed to be constant in this model. Proportion of the gross photosynthate allocated to the shoot process (?) is assumed to be 80% in this model. Daily net canopy photosynthesis is calculated using [22].

$$P_{n_{ce}} = P_g (1 - \eta(1 - Y)) - Y \cdot m \cdot \frac{L}{\xi} \quad (17)$$

where,  $P_{n_{ce}}$  = Daily net canopy photosynthesis ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1}$ ),  $P_g$  = Daily gross canopy photosynthesis ( $\text{Kg CO}_2 \text{ ha}^{-1} \text{ d}^{-1}$ ),  $L$  = LAI,  $\eta$  = Leaf area ratio ( $\text{m}^2$  (g dry weight in  $\text{CO}_2$  equivalents) $^{-1}$ ).  $P_{n_{ce}}$  computed using equation 17 is converted into Kg dry weight with the help of the equation given by [22].

$$P_n = \frac{P_{n_{ce}}}{1.65} \quad (18)$$

where,  $P_n$  = Daily net canopy photosynthesis ( $\text{Kg ha}^{-1} \text{ d}^{-1}$ ).

**Partitioning:** Photosynthates remaining after the maintenance and growth processes will be stored in different parts and storage organs. Growth rate of individual parts of the plant provides a measure of their competitive ability as sink [25]. In sweet potato, competition between stems and leaves for the available supply of assimilates continues for a long period.

Growth rate of each plant part is computed in terms of increase in leaf area, for estimating the photosynthate allocated to them. Growth rate of vines ( $fv_i$ ) on  $i^{\text{th}}$  DAP is calculated using equation 19 as the product of increase in leaf area and dry matter accumulated in vines per increase in leaf area on  $i^{\text{th}}$  DAP.

$$fv_i = (LA_i - LA_{i-1}) \times wt\_vl \quad (19)$$

where,  $LA_i$  and  $LA_{i-1}$  = Leaf area on  $i$  and  $i-1$  DAP respectively,  $wt\_vl$  is a cultivar dependent constant.

Growth rate of leaves ( $fl_i$ ) on  $i^{th}$  DAP is calculated using equation 20, as the product of increase in leaf area and dry matter accumulated in leaves per increase in leaf area on  $i^{th}$  DAP.

$$fl_i = (LA_i - LA_{i-1}) \times wt\_la \quad (20)$$

where,  $wt\_la$  is a cultivar dependent constant. Growth rate of tubers ( $ft_i$ ) on  $i^{th}$  DAP is calculated using equation 21

$$ft_i = \frac{DMT_{i-1}}{nTBR_{i-1}} \times dnTBR_i \quad (21)$$

=  $(LA_i - LA_{i-1}) \times wt\_ntbr$ , if number of tubers on  $i$  DAP > 0 and that on  $i-1$  DAP = 0

where,

$$dnTBR_i = Rr_i \times TBR_K \times WS$$

$$nTBR_{i-1} = \sum Rr_{i-1} \times TBR_K \times WS,$$

$Rr_{i-1}$  = growth rate of reproductive clock on  $(i-1)^{th}$  DAP,  $TBR_K$  = Effect of stress due to potassium shortage on number of tubers,  $DMT_{i-1}$  = Dry matter in tubers on  $i-1^{th}$  DAP,  $wt\_ntbr$  is a cultivar dependent constant.

Dry matter stored in vines ( $dDMV_i$ ), leaves ( $dDML_i$ ) and tubers ( $dDMT_i$ ) on  $i^{th}$  DAP are estimated using the equations 22, 24 and 26 respectively.

$$dDMV_i = \frac{fv_i}{tdm_i} Pn_i, \quad \text{if } tdm_i > 0 \quad (22)$$

where,  $dDMV_i$  = Dry matter allocated to stem on  $i^{th}$  DAP,  $tdm_i = fv_i + fl_i + ft_i$ ,  $Pn_i$  = Net photosynthetic rate on  $i^{th}$  DAP.

$$DMV_i = DMV_{i-1} + dDMV_i, \quad \text{if } i > 0 \quad (23)$$

where,  $DMV_i$  and  $DMV_{i-1}$  = Dry matter in vine and branches on  $i^{th}$  and  $(i-1)^{th}$  DAP respectively.

$$dDML_i = \frac{fl_i}{tdm_i} Pn_i, \quad \text{if } tdm_i > 0 \quad (24)$$

where,  $dDML_i$  = Drymatter allocated to leaves on  $i^{th}$  DAP.

$$DML_i = DML_{i-1} + dDML_i, \quad \text{if } i > 0 \quad (25)$$

$DML_i$  and  $DML_{i-1}$  = Dry matter in leaves on  $i^{th}$  and  $(i-1)^{th}$  DAP respectively.

$$dDMT_i = \frac{ft_i}{tdm_i} Pn_i, \quad \text{if } tdm_i > 0 \quad (26)$$

where,  $dDMT_i$  = Drymatter allocated to tubers on  $i^{th}$  DAP.

$$DMT_i = DMT_{i-1} + dDMT_i, \quad \text{if } i > 0 \quad (27)$$

where,  $DMT_i$  and  $DMT_{i-1}$  = Dry matter in tubers on  $i^{th}$  and  $(i-1)^{th}$  DAP respectively.

**Water stress on crop growth:** The effect of water stress on crop growth is computed using the method suggested by [26]. Since the data on wind speed is not commonly available, Priestly-Taylor method is used in this model for calculating reference evapotranspiration ( $ET_0$ ). Water stress (WS) is calculated using [26]:

$$WS = \frac{wtr - dep}{wtr - RAW} \quad (28)$$

where,  $wtr$  = water available in the soil (mm),  $dep$  = water depleted from root zone (mm),  $RAW$  = readily available water (mm),  $wtr$  was calculated using the formula [26]:

$$wtr = 1000 \times (FC - PWP) \times root\_depth \quad (29)$$

where,  $FC$  = field capacity,  $PWP$  = permanent wilting point,  $root\_depth$  = maximum effective root depth.  $raw$  was calculated using the formula [26]:

$$raw = wtr \times dep\_fctr \quad (30)$$

where,

$$dep\_fctr = P_{table} + 0.04(5 - ET_c) \quad (31)$$

where,  $P_{table}$  = water depletion factor at no stress,  $ET_c$  = crop evapo transpiration.  $ET_c$  was calculated as:

$$ET_c = ET_0 \times cropfactor \quad (32)$$

$dep$  was calculated using the formula:

$$dep = dep1 - (rfall - roff) - irrigation - capillaryrise + ET_c + percolation \quad (33)$$

where,  $depl$ =water content in the root zone at the end of the previous day,  $r_{fall}$ =precipitation,  $r_{off}$ =runoff from the soil surface,  $irrigation$ =net irrigation depth that infiltrates the soil,  $capillaryrise$ =capillary rise from the groundwater table,  $ET_c$ =crop evapotranspiration,  $percolation$ =water loss out of the root zone by deep percolation.

WS is multiplied with  $Rr_i$  before summing it to check whether  $tbr\_gap$  is reached which marks the production of a tuber in the middle phase.

**Potassium stress on crop growth:** The most important macro element for sweet potato is potassium which is beneficial to the principal physiological processes [1]. Potassium fertilizers increase the number of tubers of sweet potato [27]. Potassium increases the rate of photosynthesis as well as the translocation of the photosynthates [20]. Equation 34 is formulated to estimate the effect of potassium stress on tuber production. They are developed with the assumption that, when there is no potassium application there are  $TBR_{K0}$  number of tubers at 90 DAP. Ninety DAP is selected in this case because the short duration high yielding varieties are usually ready for harvest at 90 DAP under tropical condition. Another assumption is that when more potassium is added it increases the number of tubers linearly till the maximum possible values  $TBR_{KM}$  is reached.  $KM_{TBR}$  is the quantity of potassium which is required to attain  $TBR_{KM}$ . Values of the parameters  $TBR_{KM}$ ,  $KM_{TBR}$  and  $TBR_{K0}$  are estimated using the data from [28].

$$TBR_K = \frac{\left( \left( \frac{TBR_{KM} - TBR_{K0}}{KM_{TBR}} \right) K + TBR_{K0} \right)}{TBR_{KM}} \quad (34)$$

**Nitrogen stress on crop growth:** Nitrogen is a valuable component for the development of aerial parts of sweet potato [1]. Increasing nitrogen application increases the size of individual leaves [29]. Nitrogen potassium mixture is important for increasing the number and weight of tubers.

Nitrogen stress on mean tuber weight ( $TWT_N$ ) is given by equation 35. As in the case of potassium stress, this equation is developed with the assumption that, when there is no nitrogen application there is a mean tuber weight of  $TWT_{N0}$ . Similar to potassium, another assumption made here is that, when more nitrogen is added it increases the mean tuber weight linearly till the maximum possible value  $TWT_{NM}$  is reached.  $NM_{TWT}$  is the quantity of nitrogen, which is required to attain  $TWT_{NM}$ . Values of the parameters  $TWT_{NM}$ ,  $NM_{TWT}$  and  $TWT_{N0}$  are computed using the data from [7].

$$TWT_N = \frac{\left( \left( \frac{TWT_{NM} - TWT_{N0}}{NM_{TWT}} \right) N + TWT_{N0} \right)}{TWT_{NM}} \quad (35)$$

**Estimation of parameter values:** The parameters required to simulate the growth of sweet potato were estimated by conducting a field experiment at Mitraniketan, Thiruvananthapuram, India, which is situated at 8.5°N latitude. Soil type at the site is clayey. Three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna* were planted in Randomised block design with three replications. *Sree Arun* is a spreading variety of 90-100 days duration, with an average yield of 20-28 T/ha. *Sree Bhadra* is a semi-spreading variety of 90-95 days duration, with an average yield of 20-27 T/ha. The variety *Sree Rethna* is of spreading type and 90-100 days duration. Its average yield is about 20-26 T/ha. Vine cuttings of 15 cm length were planted in rows taken 60 cm apart. Plant to plant spacing followed was 25 cm within each row. As a control measure against sweet potato weevil, cuttings were dipped in 0.05% monocrotophos and kept for 10 minutes before planting. Agro techniques recommended by Central Tuber Crops Research Institute (CTCRI), Thiruvananthapuram, India were followed. Vine cuttings were planted on 22 May 2004, 4 June 2004, 24 September 2004, 7 October 2004 and 3 November 2004. Fertilizers were applied at the recommended dose of 50 Kg N, 25Kg  $P_2O_5$  and 50 Kg  $K_2O$  per hectare. Half of the recommended dose of N and  $K_2O$  and full  $P_2O_5$  were applied as basal dose and the remaining dose was top dressed one month after planting. Destructive samplings were done to collect data on following plant attributes.

- Vine length
- Number of leaves
- Leaf area
- Number of flowers
- Number of tubers
- Fresh and dry weights of vine, leaves and tubers
- Length of branches and
- Number of leaves in branches

Sampling schedule is given in Table 1.

**Model evaluation:** To evaluate the performance of developed model, field experiments were carried out at Mitraniketan, Thiruvananthapuram for three seasons using three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna*. Data were collected from CTCRI, Thiruvananthapuram and Regional centre (RC) of CTCRI, Bhubaneswr also to test the performance of the model. Weather data of each of the site were also collected.

Table 1: Sampling schedule of the field experiment to estimate crop parameters

Date of planting	Sampling dates	Harvest date
22.05.2004	04.06.2004, 18.06.2004, 03.07.2004 and 10.08.2004	17.09.2004
04.06.2004	18.06.2004, 03.07.2004 and 10.08.2004	23.09.2004
24.09.2004	06.10.2004, 03.11.2004, 25.11.2004 and 09.12.2004	05.01.2005
07.10.2004	03.11.2004, 25.11.2004, 09.12.2004 and 05.01.2005	28.01.2005
03.11.2004	25.11.2004, 09.12.2004 and 05.01.2005	28.01.2005

- Mitraniketan, Thiruvananthapuram: For testing the model, an experiment field was conducted in the same site to estimate the crop parameters. The same agro techniques were followed. Three sets of data were collected for each variety by planting the crop in three different dates, 18 June 2004, 4 July 2004 and 24 July 2004. Three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna* were planted. Data collection was done on 101<sup>st</sup>, 90<sup>th</sup> and 101<sup>st</sup> days after planting respectively.
- CTCRI, Thiruvananthapuram: The second site was CTCRI, Thiruvananthapuram, India, which is located at 8.5°N latitude. Soil type at the site was clayey. Data were collected from the same three varieties, which were kept in the institute germplasm collection. Agro techniques recommended by CTCRI were followed for raising the crops. The planting was done on 21 January 2006 and data were collected when the plants were 116 days old. Data on plant attributes were collected similar to data collection done for *Mitraniketan, Thiruvananthapuram*.
- RC of CTCRI, Bhubaneswar: The third site was Regional centre of CTCRI, Bhubaneswar, India, which was located at 21.25°N latitude. Soil type at the site was sandy loam. Data were collected from the varieties *Sree Arun* and *Sree Bhadra* which were kept in the institute germplasm collection. The crop was raised as per the agro techniques of CTCRI. The planting was done on 5 September 2005 and data were collected on 124<sup>th</sup> day. Data on plant attributes were collected similar to data collection done for *Mitraniketan, Thiruvananthapuram*.

## RESULTS

**Estimation of parameter values:** Required parameter values for the model development were computed based on the data collected as given below:

**ntbr:** Since the field experiment was conducted under tropical condition,  $SRr_i$  for four weeks after planting was worked out with maximum temperature on  $i^{\text{th}}$  day ( $TMAX_i$ ) and the minimum temperature on  $i^{\text{th}}$  day

( $TMIN_i$ ) of 32°C and 23°C respectively and obtained the value of ntbr as:

$$ntbr = \sum_{i=1}^{4 \times 7} Rr_i \quad (36)$$

**tbr\_gap:** The varietal character tbr\_gap, was computed separately for the three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna*, using the equation:

$$tbr\_gap = \frac{tblk - ntbr}{noTBR} \quad (37)$$

where, tblk =  $SRr_i$  for seven weeks after planting with  $TMAX_i$  and  $TMIN_i$  of 32°C and 23°C respectively, noTBR = Number of tubers produced by the plant.

**vlen1 and vlen2:** The parameters vlen1 and vlen2 were computed using the equations 38 and 39.

$$vlen1 = \frac{VL_i}{\sum_{i=1}^n Rr_i} \quad (38)$$

where,  $VL_i$  = VL on  $i^{\text{th}}$  DAP,  $Rr_i$  =  $Rr$  on  $i^{\text{th}}$  DAP,  $n$  = number of days.

$$vlen2 = \frac{VL_i}{\log \left( \sum_{i=1}^{mn} Rr_i \right)} \quad (39)$$

where,  $Rr_i$  =  $Rr$  on  $i^{\text{th}}$  DAP,  $mn$  = number of days. *lfactor*, *lafactor* and *larea*: Value of the parameter lfactor and lafactor were estimated using equations.

$$lfactor = \frac{LF_i}{\sum_{i=1}^n Rr_i} \quad (40)$$

where,  $LF_i$  = LF on  $i^{\text{th}}$  DAP.

$$lafactor = \log(LF_i) \times ALA_i \quad (41)$$



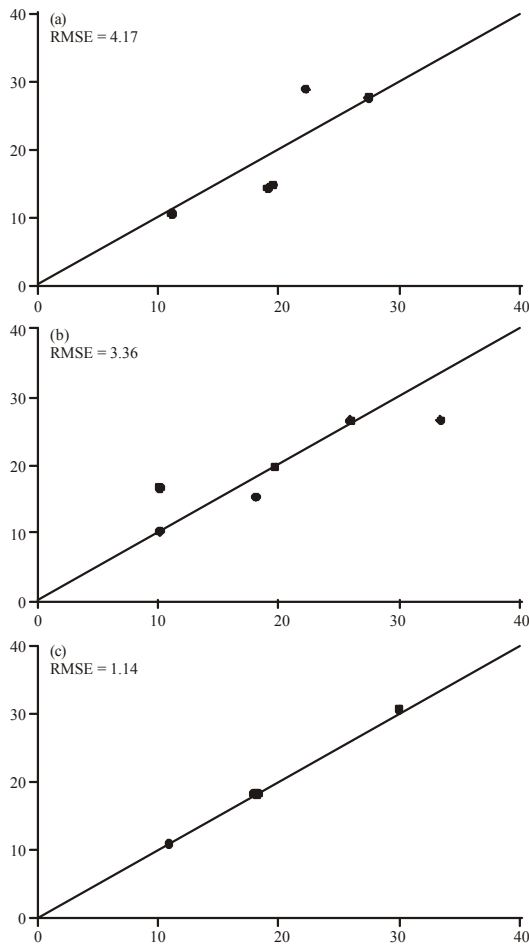


Fig. 2: Observed Vs predicted tuber yield (T/ha) for the varieties (a) *Sree Arun* (b) *Sree Bhadra* and (c) *Sree Rethna*

where,  $ALA_i = ALA$  on  $i^{th}$  DAP.

Value of larea was estimated separately for all the three varieties from field observations.

**br1 and br\_gap:**  $SR_{ri}$  required for branch initiation (br1) and the  $SR_{ri}$  between branching events (br\_gap) were calculated separately for the three varieties from field observations.

**wt\_vl, wt\_la and wt\_ntbr:** Value of these parameters were estimated as follows:

$$wt\_vl = \frac{DMV_i}{LA_i} \quad (42)$$

$$wt\_la = \frac{DML_i}{LA_i} \quad (43)$$

$$wt\_ntbr = \frac{DMT_i}{LA_i} \quad (44)$$

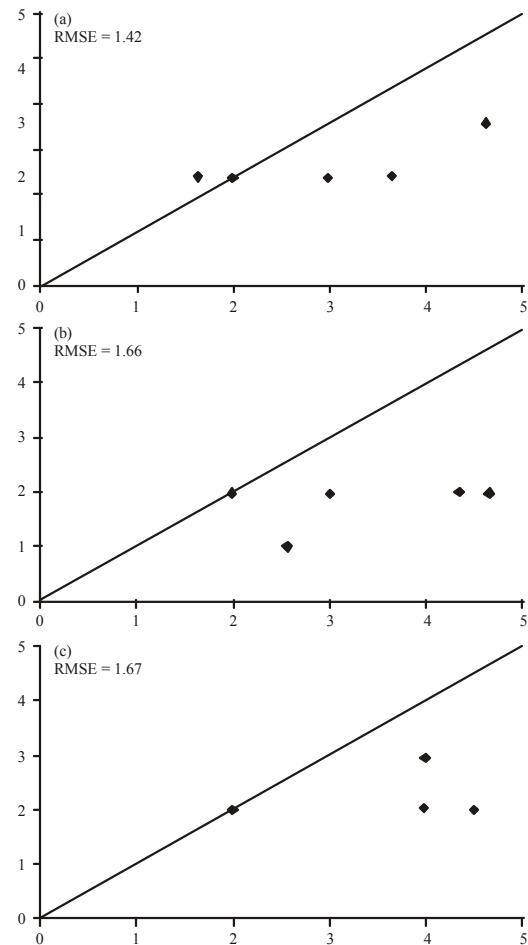


Fig. 3: Observed Vs predicted values of number of tubers for the varieties (a) *Sree Arun* (b) *Sree Bhadra* and (c) *Sree Rethna*

Values of the crop parameters estimated for the three varieties *Sree Arun*, *Sree Bhadra* and *Sree Rethna* are given in Table 2. These values are the average of the five data sets which were collected under different weather conditions.

**Model evaluation:** Using the model, tuber yield of the varieties at each site were computed. In Fig. 2a-2c observed values of tuber yield were plotted against the predicted ones. From these figures, it is observed that the predicted values are reasonably close to the observed values. The number of tubers predicted was plotted against the observed values in Fig. 3a-3c.

The plot of observed Vs predicted for the number of leaves and the number of branches for all the varieties are shown in Fig. 4a-4c and 5a-5c respectively. Predicted values of number of branches deviated considerably from the observed values in many cases.

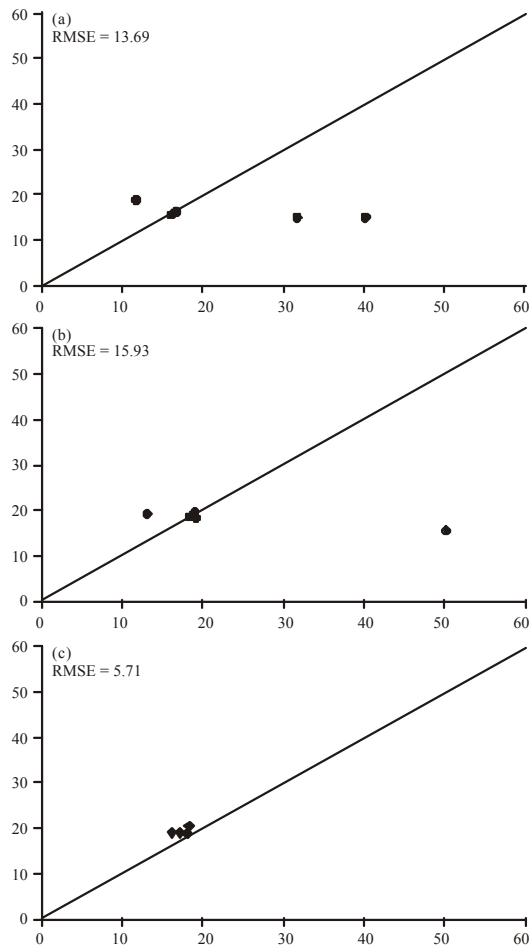


Fig. 4: Observed Vs predicted values of number of leaves for the varieties (a) *Sree Arun* (b) *Sree Bhadra* and (c) *Sree Rethna*

Table 2: Crop parameter values estimated for Sree Arun, Sree Bhadra and Sree Rethna

Parameter	Sree Arun	Sree Bhadra	Sree Rethna
<i>ntbr</i>	12.310	12.310	12.310
<i>tbr_gap</i>	3.164	3.863	2.969
<i>vlen1</i>	4.380	5.460	5.050
<i>vlen2</i>	36.980	46.410	41.520
<i>lafactor</i>	116.00	120.000	123.000
<i>lfactor</i>	0.646	0.725	0.886
<i>br1</i>	4.749	5.329	4.762
<i>br_gap</i>	3.892	3.557	3.129
<i>larea</i>	42.580	43.590	43.940
<i>wt_vl</i>	0.0052	0.00515	0.00953
<i>wt_la</i>	0.00397	0.00534	0.00725
<i>wt_ntbr</i>	0.000382	0.000389	0.000537

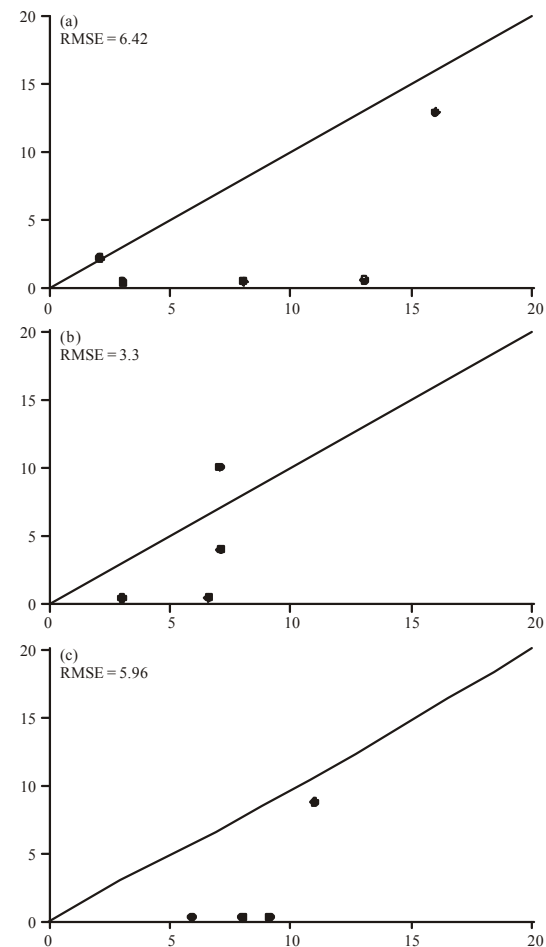


Fig. 5: Observed Vs predicted values of number of branches for the varieties (a) *Sree Arun* (b) *Sree Bhadra* and (c) *Sree Rethna*

**Sensitivity analysis:** An average cultivar was defined for conducting sensitivity analysis. Average of the parameter values estimated for Sree Arun, Sree Bhadra and Sree Rethna were taken as the parameter values of the average cultivar. Sensitivity of the final output (T/ha) to the perturbations in each plant parameter was computed. Sensitivity ( $\beta$ ) (Table 9) was estimated using equation 45 as the ratio of the fractional change in yield to the fractional change in a particular parameter [16].

$$\beta_n = \frac{dY/Y}{dP_n/P_n} \quad (45)$$

where,  $\beta_n$  =  $\beta$  value of the parameter 'n', Y = Default tuber yield when all the parameter values are optimum (Table 6), dY = Yield when parameter value changed – Y,  $P_n$  = Optimum value of the parameter 'n',  $dP_n$  = Parameter value after change -  $P_n$ .

Weather data of Mitraniketan, Thiruvananthapuram during the first season (18 June 2004 to 26 September 2004) was used for making this analysis. Average of the 5% change on either side of the parameter value was used for computing  $\beta$ . Default tuber yield at this site when all the parameters are at optimum level during the season for the average cultivar was computed as 31.05 T/ha.

From Table 9 it is understood that branching is the most sensitive parameter in determining tuber yield. The parameters  $br\_gap$  and  $br\_1$  play a major role in determining the canopy size of the plant and thus important in determining the source potential of the plant. High  $\beta$  values for the parameters  $lafactor$  and  $lfactor$  reiterates the importance of vegetative growth in determining the final yield. Other high ranking sensitive parameters is  $ntbr$ . This parameter is very important for attaining good sink capacity which is the most important factor in determining dry matter production and yield.

## DISCUSSION

MADHURAM model describes the growth of sweet potato reasonably well in the two environments where it was evaluated. Most of the growth processes were modeled using the empirical data.

Factors controlling branching in sweet potato are not well understood and require further research. Inverse relationship between day length and number of branches as reported by [17] was the basis of the branching algorithm used in this model. Reproductive growth rate becomes faster when day length is short and under such situations more branches are produced. But the model predicted values deviated considerably from the observed values. Hence it appears that a better branching algorithm will improve this model to a large extent.

Since tuber initiation is promoted by short day conditions [19],  $ntbr$  is computed as the sum of  $Rr$ 's. From Fig. 3, it appears that the model explains the process of tuber initiation reasonably well.

Source sink relationships are explained well by the model. Dry matter partitioning to tubers are simulated based on the basic idea that the source potential is the more limiting factor in the initial phase and the sink capacity is more important after the formation of the storage roots [1].

Nitrogen and potassium stress on the plant was modeled with a lot of assumptions. Though they influence many growth processes, the most important ones only were included in this model. This is an area where a lot of refinement can be made.

Table 3: Variation in yield at different levels of soil moisture content for Sree Arun, Sree Bhadra and Sree Rethna during the period from 18 June 2004 to 20 September 2004

Soil moisture Content (mm)	Yield (t/ha)		
	Sree Arun	Sree Bhadra	Sree Rethna
2	35.61	35.11	36.73
3	35.87	35.64	40.00
4	35.97	35.86	41.10
5	35.97	35.86	41.46
6	35.97	35.86	41.46
7	35.97	35.86	41.46

Similarly water stress algorithm was included in the model with an assumption that only minimum data are available. Hence Priestly-Taylor method was followed for calculating  $ET_0$ , though better methods are available.

**Simulation scenarios:** This model can be used for understanding the performance of the crop under different soil and environmental conditions. Yield under different levels of stress due to water, K and N can be simulated by this model. Optimum value of inputs like moisture content(mst), K and N at which the tuber yield is maximum can also be found out using this model.

**Water stress on crop growth:** Water stress computed using equation 28, is multiplied with  $Rr_i$  to compute  $dnTBR$  on  $i^{th}$  DAP during the middle phase, by which the rate of tuber production is modified. Table 3 shows the change in tuber yield, under the influence of water stress. The tuber yield (T/ha) were calculated for sweet potato varieties Sree Arun, Sree Bhadra and Sree Rethna which were grown during the period from 18 June 2004 to 20 September 2004 at Mitraniketan Thiruvananthapuram at different levels of moisture content.

To find the value of moisture content (mst) at which YLD is maximum, a quadratic curve is fitted to the yield data obtained at different levels of mst for Sree Arun, Sree Bhadra and Sree Rethna using SYSTAT 9.0.

$$YLD = a \times mst^2 + b \times mst + c \quad (46)$$

where, YLD = Tuber yield (T/ha), a, b and c are empirical coefficients.

Values of a, b and c which were computed for these three varieties are given in Table 4.

Value of mst at which YLD is maximum is found out separately for each variety by differentiating

Table 4: Values of a, b and c computed for Sree Arun, Sree Bhadra and Sree Rethna at Mitraniketan, Thiruvananthapuram during the period from 18 June 2004 to 20 September 2004

Variety	a	b	c
<i>Sree Arun</i>	-0.030	0.333	35.097
<i>Sree Bhadra</i>	-0.063	0.693	34.039
<i>Sree Rethna</i>	-0.379	4.269	30.031

Table 5: Variation in yield at different levels of potassium for Sree Arun, Sree Bhadra and Sree Rethna during the period from 24 July 2004 to 2 November 2004

Quantity of K (Kg/ha)	Yield (T/ha)		
	Sree Arun	Sree Bhadra	Sree Rethna
60	23.54	24.40	28.82
70	23.57	24.43	28.86
80	23.59	24.45	28.89
90	23.57	24.43	28.86
100	23.54	24.40	28.82
110	23.52	24.37	28.78

equation 46 and then solving it by assuming that the value of the first differential is zero when YLD is maximum. Maximum yield due to the effect of moisture content is attained when the moisture content was 5.55, 5.5 and 5.63 mm for Sree Arun, Sree Bhadra and Sree Rethna respectively and the YLD computed at this moisture content were 36.02, 35.94 and 42.05 T/ha respectively.

**Potassium stress on crop growth:** Potassium stress on the production of tubers, which is calculated using equation 34, is multiplied with  $R_i$  to compute  $dnTBR$  on  $i^{th}$  DAP during the middle phase, by which the rate of tuber production is modified. Through the influence on these processes, potassium stress results in a reduction in the final tuber yield. The tuber yield under different levels of K were calculated for sweet potato varieties Sree Arun, Sree Bhadra and Sree Rethna which were grown at Mitraniketan, Thiruvananthapuram during the period from 21 July 2004 to 2 November 2004 are given in Table 5.

To find the quantity of potassium (K) at which YLD is maximum, a quadratic curve is fitted to the yield data obtained at different levels of K for Sree Arun, Sree Bhadra and Sree Rethna using SYSTAT 9.0.

$$YLD = ak \times K^2 + bk \times K + ck \quad (47)$$

where, ak, bk and ck are empirical coefficients. Values of ak, bk and ck which were computed for these three varieties are given in Table 6.

Table 6: Values of ak, bk and ck computed for Sree Arun, Sree Bhadra and Sree Rethna at Mitraniketan, Thiruvananthapuram during the period from 21 July 2004 to 2 November 2004

Variety	ak	bk	ck
<i>Sree Arun</i>	-0.00008	0.013	23.0
<i>Sree Bhadra</i>	-0.00009	0.014	23.9
<i>Sree Rethna</i>	-0.00012	0.020	28.1

Table 7: Variation in yield at different levels of nitrogen for Sree Arun, Sree Bhadra and Sree Rethna during the period from 4 July, 2004 to 1 October, 2004

Quantity of N (Kg/ha)	Yield (t/ha)		
	Sree Arun	Sree Bhadra	Sree Rethna
60	20.91	27.06	24.56
70	22.42	29.03	26.35
80	23.94	31.00	28.13
90	24.01	31.09	28.22
100	22.49	29.12	26.43
110	20.98	27.15	24.65

Value of K at which YLD is maximum was found out separately for each variety as in the case of water stress. Maximum yield due to the effect of potassium is attained when the  $K_2O$  applied was 81.25, 77.78 and 83.33 Kg/ha for Sree Arun, Sree Bhadra and Sree Rethna respectively and the YLD computed at this level of  $K_2O$  were 23.53, 24.44 and 28.93 T/ha respectively.

**Nitrogen stress on crop growth:** Nitrogen stress on the mean tuber weight, which is calculated using equation 35, is multiplied with  $dDMT_i$  to include the influence of nitrogen stress on the tuber yield during the final phase. In this way nitrogen stress reduces the final tuber yield. The tuber yield under different levels of N were calculated for sweet potato varieties Sree Arun, Sree Bhadra and Sree Rethna which were grown at Mitraniketan, Thiruvananthapuram during the period from 4 July, 2004 to 1 October, 2004 are given in Table 7.

To find out the quantity of nitrogen (N) at which YLD is maximum, a quadratic curve is fitted to the yield data obtained at different levels of N for Sree Arun, Sree Bhadra and Sree Rethna using SYSTAT 9.0.

$$YLD = an \times N^2 + bn \times N + cn \quad (48)$$

where, an, bn and cn are empirical coefficients. Values of an, bn and cn which were computed for these three varieties are given in Table 8.

Value of N at which YLD is maximum was found out separately for each variety as in the case of water

Table 8: Values of an, bn and cn computed for Sree Arun, Sree Bhadra and Sree Rethna at Mitraniketan, Thiruvananthapuram during the period from 4 July, 2004 to 1 October, 2004

Variety	an	bn	cn
<i>Sree Arun</i>	-0.00487	0.829	-11.4
<i>Sree Bhadra</i>	-0.00633	1.079	-15.0
<i>Sree Rethna</i>	-0.00574	0.978	-13.6

Table 9: Results of sensitivity analysis of the plant parameters for the average sweet potato cultivar

Parameter	Parameter value	B
<i>ntbr</i>	12.310	0.20934
<i>tbr_gap</i>	3.332	0
<i>vlen1</i>	4.970	0
<i>vlen2</i>	41.640	0
<i>lafactor</i>	119.670	0.731079
<i>lfactor</i>	0.752	0.322061
<i>br1</i>	4.946667	2.074074
<i>br_gap</i>	3.526	2.351047
<i>larea</i>	43.370	0
<i>wt_vl</i>	0.0062	0
<i>wt_la</i>	0.0050	0.074074
<i>wt_ntbr</i>	0.00694	0

stress. Maximum yield due to the effect of nitrogen is attained when the N applied was 85.11, 85.23 and 85.19 Kg/ha for Sree Arun, Sree Bhadra and Sree Rethna respectively and the YLD computed at this level of N were 23.81, 30.98 and 28.06 T/ha respectively.

## CONCLUSION

In this paper we have proposed a model for simulating the growth of sweet potato. This model is built using various sub models/ routes for predicting phenology, productivity and assimilates partitioning. These models were built mainly using the data reported in literature as well as those collected empirically. Important stress factors like water, potassium and nitrogen are also included in the model. Field experiments were conducted at a location for five seasons with three different varieties of sweet potato and the plant parameter values were estimated. Field experiment was also conducted at the same location for another three seasons and data were collected for testing the model predictions. Data were collected from another two sites also for evaluating the model. The values predicted by the model were compared with the field observations. There was a good agreement between the two in respect of tuber yield, number of

leaves produced and the number of tubers produced. However the prediction of number of branches deviated from the observed values. This is the first ever simulation model developed for sweet potato. Assumptions made in this model must be refined and further work should be done to address the real field situation.

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