

**Abstract**

*Crop simulation models have much potential for assisting in agrotechnology transfer, crop management decision-making, climatic assessment, and in the synthesis of research results. For these reasons, it is important to continue to develop and improve models for predicting the growth and yield of groundnut (Arachis hypogaea). In this paper, we briefly review approaches for modeling growth and yield of groundnut. Then we illustrate major areas of improvement in the PNUTGRO crop growth model after evaluating PNUTGRO V1.02 versus additional data sets from Florida and India. New areas of improvement include: 1) addition of a hedgerow photosynthesis submodel to improve response to row spacing, sowing density, and growth habit; 2) addition of the Penman equation to incorporate vapor pressure deficit and windspeed to estimate evapotranspiration for arid regions; 3) modification of functions for prediction of crop development; and 4) modification of the effects of stress environments such as high temperature and vapor pressure deficit on partitioning.*

**Résumé**

*Modélisations de la croissance et du rendement de l'arachide—à la pointe de la technique: Des modèles de simulation de culture ont beaucoup de potentiel pour aider au transfert d'agrotechnologie, à la prise de décision sur la gestion des cultures, à l'évaluation climatique et à la synthèse des résultats de recherches. Pour ces motifs, il est important de poursuivre les efforts pour développer et améliorer les modèles de production de la croissance et du rendement de l'arachide (Arachis hypogaea). Dans cette communication, nous passons brièvement en revue les approches de modélisation de la croissance et du rendement de l'arachide. Ensuite nous illustrons les principales zones d'amélioration du modèle de croissance de culture PNUTGRO après avoir évalué le PNUTGRO V1.02, contre les jeux additionnels de données de Floride et d'Inde. De nouvelles zones d'amélioration comprennent: 1) l'addition d'un sous-modèle de photosynthèse pour améliorer la réponse à l'espacement des rangées, à la densité des semis et leurs habitudes de croissance; 2) l'addition de l'équation Penman pour incorporer le déficit de pression d'eau et la vitesse du vent pour évaluer l'évapotranspiration dans les régions arides; 3) la modification de fonction pour prédire le développement des cultures; 4) la modification des effets des environnements de stress comme les fortes températures et le déficit de pression d'eau sur la répartition.*

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Groundnut (*Arachis hypogaea*) models have been developed by several groups for different purposes. The first was developed in the early 1970s by W.G. Duncan at the University of Florida for use as a physiological research tool. It was used to evaluate genetic traits influencing yield potential of groundnut (Duncan et al. 1978). Subsequently, Young et al. (1979) published a groundnut growth model based on photosynthesis, growth, and respiration in response to daily environment. In the early 1980s, our group at the University of Florida became interested in dual-purpose uses of crop models for research understanding and crop-management. We initially adapted the SOYGRO model (Wilkerson et al. 1983) to predict growth and yield of groundnut (Boote et al. 1983, 1986). Since that time, we have conducted additional experiments for testing the model. In addition, 4 years of on-farm model testing were conducted to evaluate how well PNUTGRO performs in producer fields under their management practices (Boote et al. 1989a).

Like most crop models, PNUTGRO is process-oriented and considers crop carbon balance, crop nitrogen balance, and soil-plant water balance. In this approach, state variables are the amounts, masses, or numbers of tissues whereas rate variables are the rates of input, transformation, and loss from state variable pools. For example, the crop carbon balance includes daily inputs from photosynthesis, conversion and condensation of carbon (C) into crop tissues, C losses due to abscised parts, and C losses due to growth and maintenance respiration. Crop nitrogen balance considers daily N assimilation, internal mobilization and re-use of N, and N loss in abscised parts. Crop water balance includes infiltration of rainfall and irrigation, soil evaporation, root uptake of water, drainage of water through the root zone, and crop transpiration.

The PNUTGRO model dynamically responds to daily weather inputs (temperature, radiation, rainfall, as well as windspeed and relative humidity if available), soil-water deficit, cultural practices, and cultivar choice. In addition to weather inputs, the model requires soil characterization traits that describe water-holding capacities, runoff, and drainage aspects. Cultural conditions such as sowing date, row spacing, sowing density, harvest date, and cultivar choice can be specified. Different cultivar traits can be simulated. Screen outputs, graphical outputs, and file outputs are available to evaluate outcomes. PNUTGRO is one of a number of models available in the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project. These models have stan-

dardized inputs and outputs. PNUTGRO is coded in FORTRAN and runs on most microcomputers.

## Description of PNUTGRO Model Features – Old and New

For a more comprehensive overall description of the PNUTGRO model, readers are referred to the paper by Boote et al. (1986). The basic state variable equation approach for crop carbon and nitrogen balance has not been changed. Although C input from photosynthesis is now computed differently, the approaches for dry matter partitioning, growth conversion efficiency, growth respiration, maintenance respiration, and tissue abscission/senescence losses are basically the same. Growth respiration and efficiency of conversion of glucose to plant tissue are computed following the approach of Penning de Vries and van Laar (1982, pp. 123–125). This requires approximate estimates of tissue composition in six types of compounds: protein, lipid, lignin, carbohydrate-cellulose, organic acids, and minerals (summarized by Boote et al. 1986). Maintenance respiration is likewise unchanged, and depends on temperature, crop photosynthesis rate, and on current crop biomass (less oil and protein stored in the seed). Prediction of vegetative and reproductive development is basically the same, although the effects of temperature on development have been changed. The prediction of vegetative and reproductive stages are important, because they describe the crop calendar upon which to predict the partitioning of dry matter to leaf, stem, root, shell, and seed. Partitioning among leaf, stem, and root are dependent on V-stage progression (and water deficit) until flowering. As reproductive development progresses, new sinks (gynophores, podwalls, and seeds) are formed, and assimilate is increasingly partitioned to these tissues rather than to vegetative growth. At the beginning peg (R2) stage, PNUTGRO begins to add new classes or cohorts of reproductive sinks on a daily basis. Fruits of each cohort increase in physiological age and pass through slow and rapid shell growth phases, and at a stage part way through the rapid shell growth phase, seeds in each fruit begin their rapid growth phase. Thus, reproductive “sink” demand comprises many individual reproductive tissues, all of different ages, each having a potential assimilate demand as limited by temperature. The priority for assimilate is seeds first (in order of age), then rapid shell growth, then shells in their slow growth phase, then addition of new gynophores, and lastly, vegetative tissues. A genetic limit of fractional parti-

tioning to pods (XFRUIT) is defined to account for the fact that some groundnut cultivars are indeterminate and continue to grow vegetatively even during rapid seed-filling. Mobilization of protein (C and N) from vegetative tissue begins when seeds begin to grow. The maximum rate of protein mobilization depends on the rate of reproductive development. To the extent that mobilized protein is available, some seeds grow with a reduced conversion cost. The remaining seeds grow with a conversion cost that includes C for nitrate reduction (cost of  $N_2$ -fixation is assumed to be the same). As protein is mobilized, leaf photosynthesis and maintenance respiration are reduced and some leaves are abscised. Maturation of this indeterminate crop is problematic since foliage remains green even though growth of progressive cohorts of individual seeds ceases when they reach the limits of their individual pod cavities (maximum shelling percentage). Currently, harvest maturity is called at a given accumulation of physiological days (thermal accumulator).

Other features of PNUTGRO, such as soil water balance, root growth, root water uptake, and stress effects on leaf senescence are unchanged (see Boote et al. 1986).

## PNUTGRO Model Improvements

One of the limitations of the last PNUTGRO version was its inadequate response to row spacing and sowing density. A hedgerow light interception-canopy photosynthesis model was developed to overcome this inadequacy. Canopy assimilation is predicted on an hourly basis throughout the day using hourly photosynthetic photon flux density (PPFD) values, computed from the daily radiation integral using a full sine-wave function described by Charles-Edwards and Acock (1977). Hourly temperatures are already computed in the PNUTGRO model for phenology. The hedgerow assimilation model has performed well in predicting field-measured gross canopy assimilation on soybean (*Glycine max*) and groundnut in various row spacings (Boote et al. 1988).

### Assimilation by hedgerow canopies

The photosynthesis model was developed by Boote et al. (1988, 1989c) based on a simplification of the hedgerow approach of Gijzen and Goudriaan (1989). The approach considers two classes of leaves, sunlit and shaded. The shadow projected by the canopy is

computed as a function of canopy height (H), canopy width (W), time of day, day of year, latitude, and row azimuth. The canopy envelope is defined in the plane perpendicular to the row direction and is assumed to have a height, a width, and an effective curvature of the canopy that is equivalent to a half circle with radius equal to half of the width. Light interception, photosynthesis, and LAI are restricted to the fraction of the soil surface shaded by the canopy, which is a function of the shadow projection, row spacing, and plant spacing in the row. Effects of plant spacing in the row and light reflectance from the soil are also included.

Total hourly incoming PPFD is distributed into a direct component and diffuse component dependent on solar elevation. The PPFD absorbed by sunlit and shaded LAI is computed as described by Spitters (1986). A proportion of the direct beam PPFD is converted to diffuse light within the canopy by scattering processes. Absorption of skylight (diffuse component) is computed following an approach from Goudriaan (1977, pp. 59–63) that uses the path width (alley between hedges), the height and width of the hedgerow, LAI, and a diffuse extinction coefficient of 0.8. Goudriaan's approach assumed that diffuse irradiance originates from a uniformly overcast sky. The average flux of PPFD absorbed by the shaded leaves comes from absorbed skylight and from direct beam converted to diffuse within the canopy. The flux absorbed by sunlit leaves includes diffuse plus direct beam.

**Leaf level photosynthesis.** Hourly leaf photosynthesis of sunlit and shaded classes of leaves is computed using the asymptotic exponential equation defined by a maximum light-saturated rate ( $P_{max}$ ) and quantum efficiency (QE). The leaf photosynthesis parameters,  $P_{max}$  and QE, are influenced by temperature and leaf N. With the  $P_{max}$  and QE parameters, we model leaf photosynthesis response of sunlit and shaded leaves to light, air temperature, and leaf N at each hour of the day, and sum over all leaf area in sunlit and shaded classes to compute hourly canopy assimilation. Hourly assimilation is accumulated to give daily rates. Since soil water and evapotranspiration are computed on a daily basis, water deficit affects daily photosynthesis outside of the hourly loop in the same manner as the present PNUTGRO model.

**Photosynthesis response to temperature.** The relative response of  $P_{max}$  to temperature increases lin-

early from 5° to 25°C (to relative rate of 0.9), achieves an optimum of 1.0 between 28° to 34°C, and declines above 34°C. The QE declines gradually with increasing temperature using an equation that mimics the response reported by Ehleringer and Bjorkman (1977) with a QE = 0.0524 mol mol<sup>-1</sup> at 30°C. The present equations are valid only for current ambient concentrations of CO<sub>2</sub> and O<sub>2</sub>.

#### Photosynthesis response to leaf N concentration.

Data on canopy photosynthesis versus average canopy leaf N concentration (Bourgeois 1989) were used to solve for the shape of leaf photosynthesis decline with N mobilization. Leaf Pmax response to N is modeled with a half parabola described by a minimum N concentration (Nbase = 2.45% N) at which photosynthesis is zero, and an N concentration (Nopt = 5.00% N) at which photosynthesis is maximum. With this new function, there was an improved fit to the late-season decline in canopy photosynthesis for the Florunner cultivar at Gainesville (Fig. 1). Over that same period, N concentration of foliage declined from 4.3 to 3.0%. These changes improved model fit and reduced late-season dry matter accumulation in pod and total crop compared to PNUTGRO V1.02.

**Height-width prediction.** The hedgerow photosynthesis submodel requires the prediction of canopy geometry. We assumed groundnut has a half circular cross-section perpendicular to the row that can be described by the apparent canopy height and the apparent canopy width. The rate of height and width increase is proportional to the rate of V-stage increase, which in turn is dependent on temperature and water deficit. A "lookup" function was added to the crop parameter file to describe internode length relative to progressive V-stage development. Internode length is additionally dependent on temperature, water deficit, solar irradiance, and photoperiod.

We initially calibrated the rate of vegetative node progression using the Florida data sets. We found it necessary to make minor code changes to allow more rapid node development for the first five nodes expressed. Next, we calibrated the increase in height and width over time with 14 data sets for Florunner in which height and width measurements were taken (Fig. 2). This calibration resulted in an internode length versus V-stage algorithm added to the crop parameter file. A comparison of eight cultivars for V-stage progression at Gainesville in 1990 showed that cultivars do not differ significantly in V-stage progression until late in reproductive growth. The

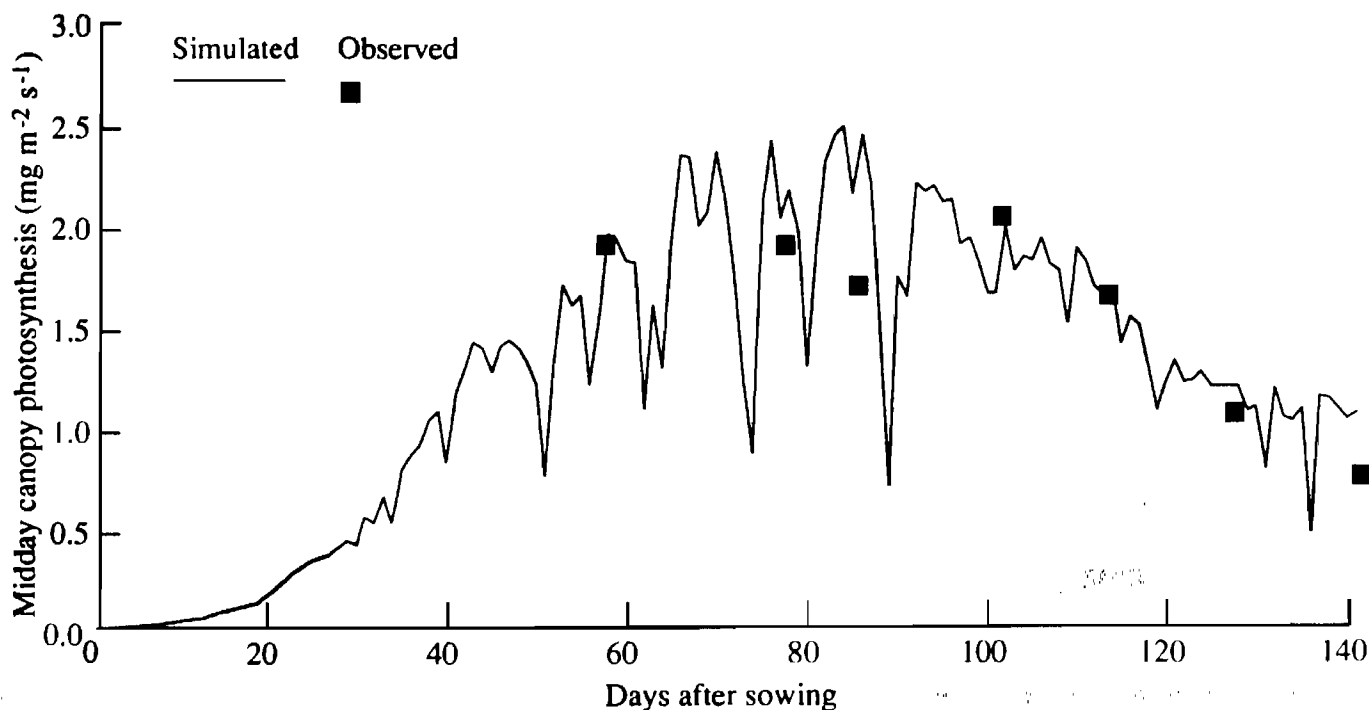


Figure 1. Simulated and observed gross canopy assimilation rate at midday for Florunner during 1986 at Gainesville, showing the effect of declining N mobilization as the crop matured. (Source: Bourgeois 1989.)

V-stage progression of Robut 33-1 (and TMV 2, data not shown) was not different from Florunner (Fig. 3). Height increase likewise did not differ among these

three cultivars (data not shown), although width increase was less for TMV 2 and Robut 33-1 compared to Florunner (Fig. 2).

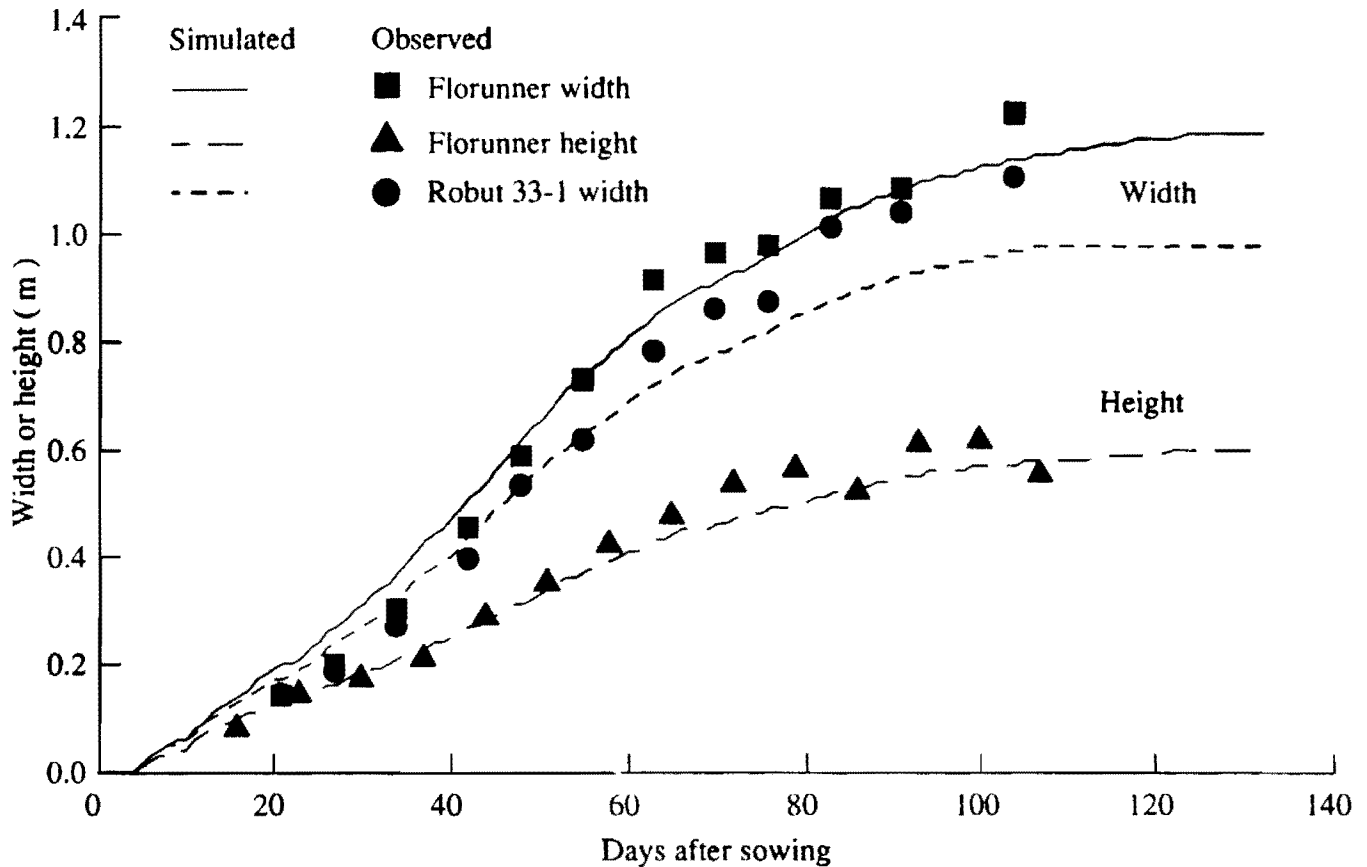


Figure 2. Simulated and observed canopy width and height of Florunner and Robut 33-1 during 1990 at Gainesville. (There was no difference in height between cultivars, hence data for height of Robut 33-1 not plotted.)

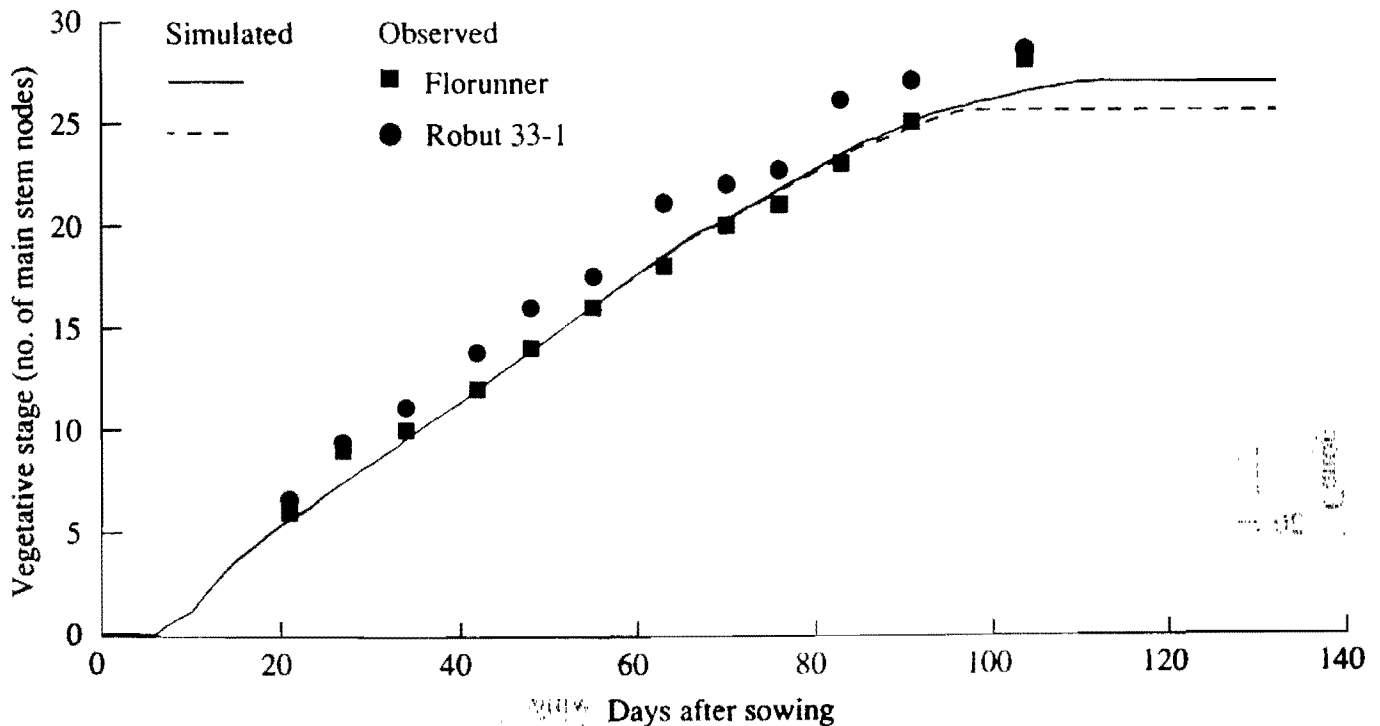


Figure 3. Simulated and observed vegetative stage (main stem node number) of Florunner and Robut 33-1 during 1990 at Gainesville.

**Different growth habits of groundnut.** Experience with a wide range of genotypes showed the need to account for differences in growth habit: erect bunch type, spreading bunch, or spreading runner type. Simple modifiers were added to the GENETICS.PN9 file to describe genotypes for their relative canopy width or height (RWIDTH or RHIGH), compared to a tall spreading runner type (Florunner standard of 1.0). With this function, we were able to correctly account for the reduced light interception associated with smaller canopy size of erect spanish cultivars such as Chico and Tamnut. Although cultivars differed in crop growth rate because of differences in light interception, we found that radiation use efficiency was not significantly different among eight cultivars during vegetative growth (Ma 1991).

**Light interception.** With the height and width function calibrated to 14 Florunner data sets and accounting for growth habit, we were able to successfully predict light interception by the crop (Fig. 4).

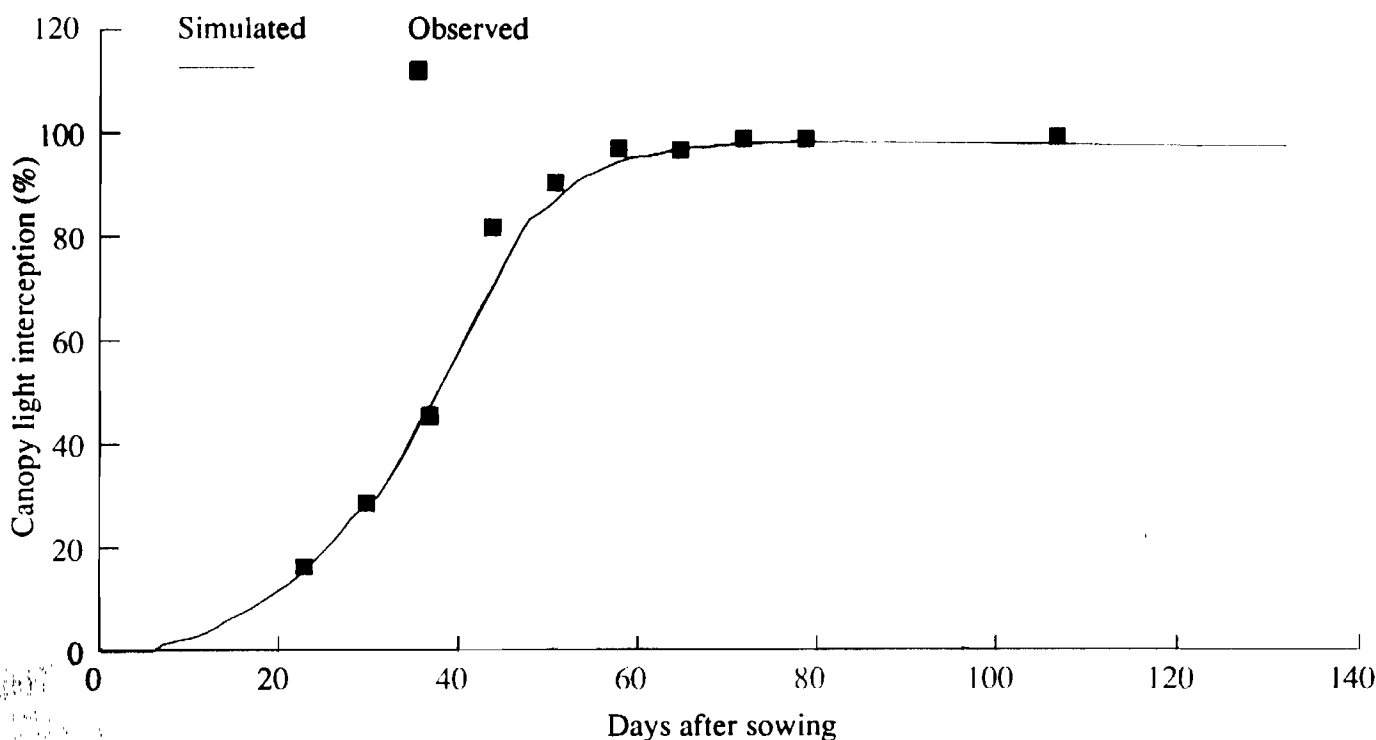
**Simulated response to row spacing.** To illustrate the sensitivity of PNUTGRO with the hedgerow photosynthesis submodel, we simulated pod yield response (Fig. 5) for the Robut 33-1 cultivar to row spacings from 0.15 to 3.00 m using 1987 weather data from ICRISAT Center (courtesy, P. Singh). The sowing

density per unit land area was held constant at 32.5 plants  $m^{-2}$ . The response appears reasonable, but will require validation with experimental data.

### Penman evapotranspiration option

The Penman method of computing potential evapotranspiration ( $E_0$ ) was added as an option in PNUTGRO. By specifying the Penman function, the FAO version of the Penman ET equation as described by Jensen et al. (1990) is used to compute  $E_0$  through a subroutine call from the soil water balance module. Otherwise, the Priestley-Taylor method that was previously used in PNUTGRO is used. Users can select these methods alternately in the sensitivity analysis mode.

Because the Penman method requires windspeed and humidity data, the weather input subroutine was modified to read daily wind movement ( $km\ d^{-1}$ ) and dew point temperature ( $^{\circ}C$ ). Thus, if wind movement and dew point temperature (or humidity) data are available, users must add these data to the IBSNAT standard format weather data files. Because these data are unavailable for many locations, defaults are specified in the crop parameter file for windspeed and for the value to subtract from the daily minimum temperature to estimate the day's dew point temperature.



**Figure 4.** Simulated and observed light interception by Florunner during 1990 at Gainesville. (Source: Observed points from Ma 1990.)

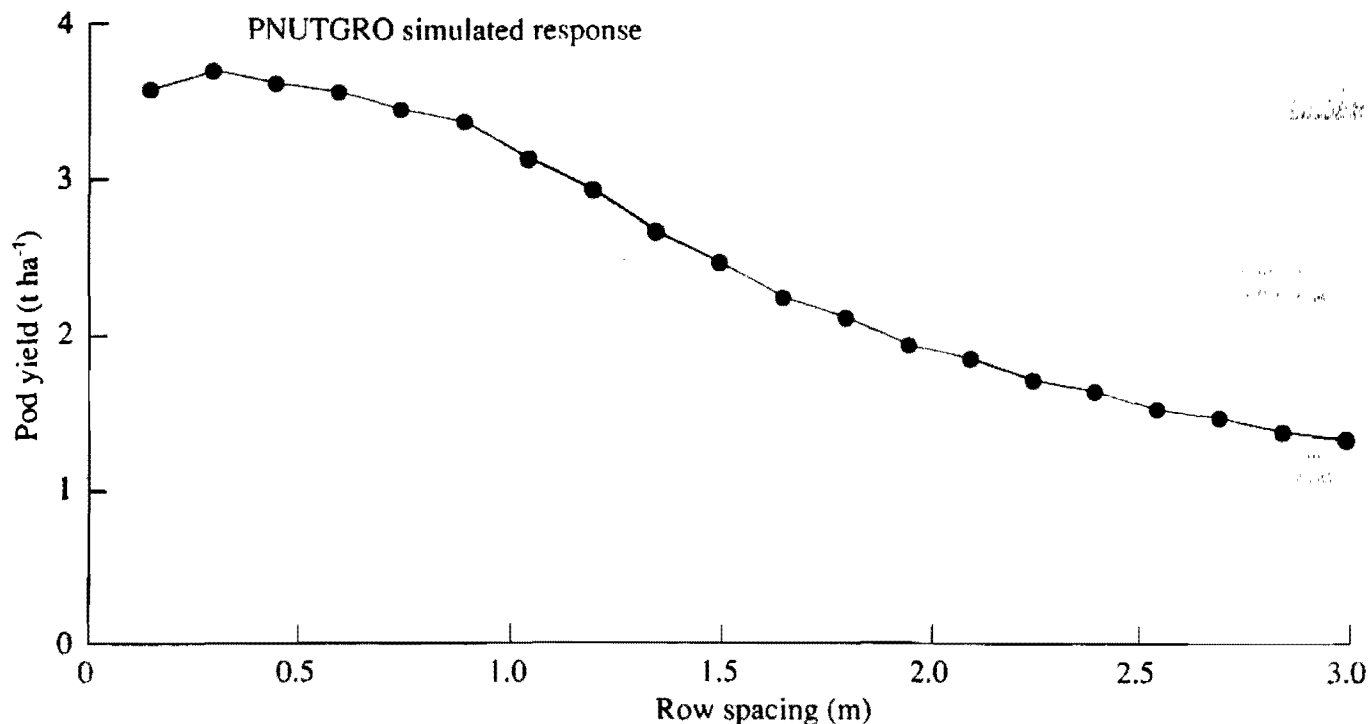


Figure 5. Simulated pod yield in response to row spacing for Robut 33-1 in 1987 at ICRISAT Center. The number of plants per unit area was constant at 32.5 plants m<sup>-2</sup>.

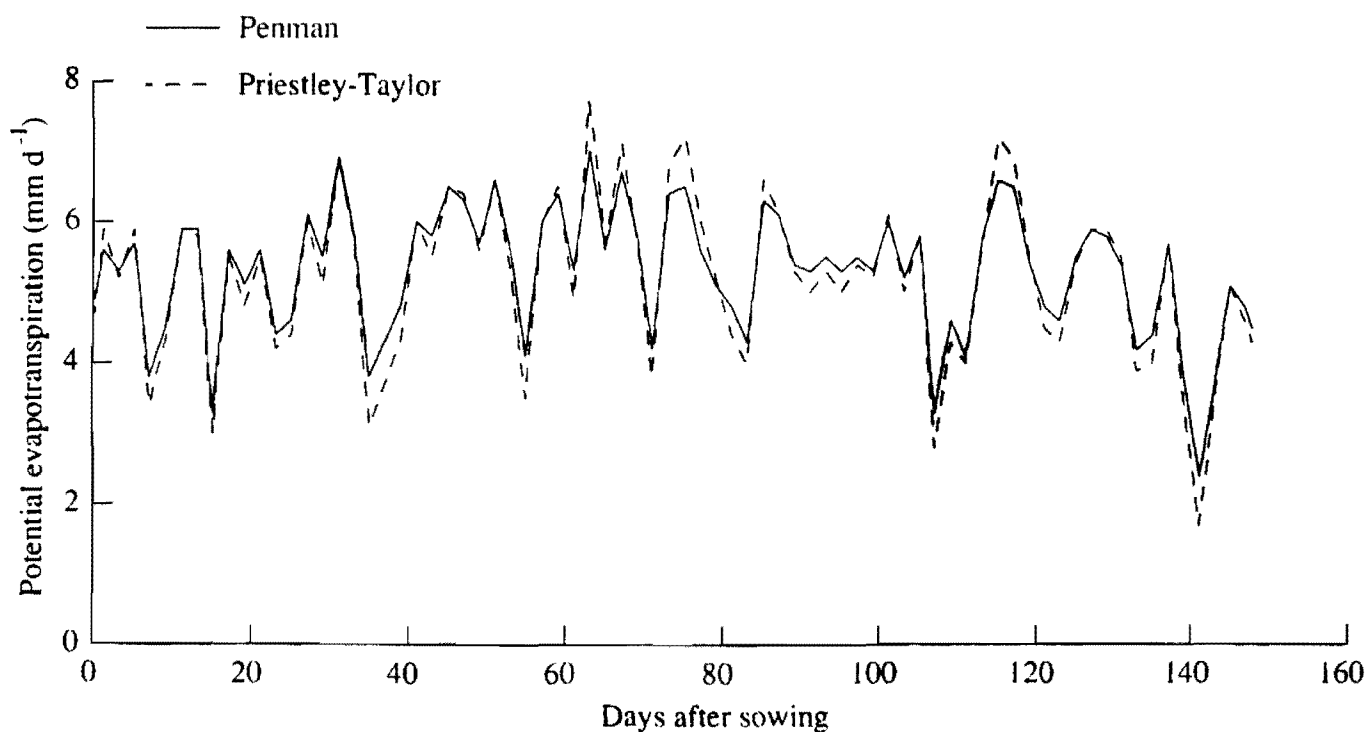


Figure 6. Potential evapotranspiration for Florunner predicted by the Penman and Priestley-Taylor functions during 1981 at Gainesville.

In humid areas, this value is usually between 0.0 and 1.0°C.

With a default windspeed of 2 m s<sup>-1</sup> and the default method for estimating dew point temperature, the Penman ET function produced very similar ET to

the Priestley-Taylor function in Gainesville (Fig. 6) and actually created less ET in midsummer at the Hisar location in India. Unless actual windspeed and humidity are available, there is no advantage in using the Penman function.

The prediction of crop development and ontogeny is important because the onset of new organs dictates where assimilate is partitioned. The new version predicts the progressive development of vegetative and reproductive stages of groundnut as defined by Boote (1982). The V and R development stages are used in the model to influence height-width increase, partitioning among plant parts, pod addition, seed addition, and the beginning of N remobilization.

In version V1.02 of PNUTGRO (Boote et al. 1989b), a broken linear function ( $T_{base} = 11$ ,  $T_{opt} = 28$ ,  $T_{opt2} = 32$ , and  $T_{max} = 55$ ) was used to describe both vegetative and reproductive development. Experience with Florida and India data showed this function to be inadequate for reproductive development; simulated reproductive development proceeded too slowly at moderate temperature and too rapidly at high temperature. In particular, maturity was unrealistically delayed in late fall. We propose that reproductive response to temperature differs from that of vegetative development in at least two ways: 1) there is a curvilinear component in the response to temperature as shown by Bagnall and King (1991a), and 2) the base and optimum temperature for reproductive development may shift to lower values as the crop sets pods.

Based on limited data on the Florunner cultivar in Florida (17 observations on days to flower), we also concluded that progress toward flowering has a non-linear component and is better fitted by the full sine function than by linear, broken linear, or the Bagnall and King parabolic function. In fact, fit by all models was improved if developmental rate was allowed to be reduced at high temperature. Fitted values for the full sine function gave a  $T_{base}$  of 14.5°C and  $T_{opt}$  of 26.5°C and standard deviation of 2.71 days. Because our data did not span far enough into the range of cool temperatures, we did not trust the solved  $T_{base}$  for general use, we decided to keep the  $T_{base}$  of 11°C and  $T_{opt}$  of 28°C as consistent with Ong (1986) and Fortanier (1957).

The new version of PNUTGRO uses three temperature functions for crop development: 1) the previous broken linear function for V-stage progression, 2) the full sine function for reproductive development until seed growth begins at the R4-R5 stage, using a  $T_{base} = 11$ °C and  $T_{opt} = 28$ °C, with slower development above 28°C, and 3) the full sine function from beginning seed growth to maturity with  $T_{base} = 5$ °C and  $T_{opt} = 26$ °C. There is still insufficient information on how temperature affects rate of reproductive progress of groundnut during seed filling.

It is important to test crop models over a wide range of environments. In testing PNUTGRO with 11 growth analyses on the Florunner cultivar in Florida, we found model misfits in some of the years/environments. Since the cultivar was the same and soil type was common across years (10 sets on the same research location/soil type), we could not attribute differences to genotype or soil type, but were forced to look closely at weather effects. It is too easy (and often incorrect) to attribute differences to a new cultivar and/or a new soil fertility factor when, in fact, the cultivar or soil may not differ.

An evaluation of weather associated with poor predictions of reproductive growth in Florida suggested that pod addition and intensity of partitioning to pods were slowed down by either high temperature or high vapor pressure deficits. The same situation (slower pod growth, greater vegetative growth) was observed for hot, arid environments in India (Haryana and Punjab as contrasted to Tamil Nadu). Gramme Hammer (personal communication, 1990) has also observed an association of lower partitioning (rate of increase in harvest index) and prolonged vegetative growth at higher temperature. Thus, we developed an algorithm to allow daily maximum temperature ( $T_{max}$ ) and/or long days to reduce partitioning (XFRUIT) and pod addition rate (PODVAR). The  $T_{max}$  was used rather than hourly or mean temperature because days with high  $T_{max}$  frequently had lower minimum temperatures, thus creating little difference in average temperature. This function was calibrated to the 11 research data sets and several on-farm data sets of Florunner. The best fit resulted with a function that reduced partitioning and pod addition when  $T_{max}$  was greater than 33°C, with a linear decline in relative rate to 0.4 at 46°C. This change also forced a slight re-calibration in the standard values for XFRUIT and PODVAR because these now become defined when  $T_{max}$  is less than 33°C. The XFRUIT value for Florunner increased from 0.85 to 0.90 and PODVAR increased from 15.0 to 16.0 pods  $m^{-2} day^{-1}$ . XFRUIT and PODVAR both affect rate of pod addition, but XFRUIT additionally defines the maximum fraction of daily plant assimilate that is allocated to pod growth.

The temperature effect also worked well for the Indian data sets, but we additionally added a photoperiod effect on rate of pod addition and partitioning for the Robut 33-1 and TMV 2 cultivars, which resulted in a better fit to data spanning north to south in India and spanning from early to late summer sowing.



Long days were shown by Bagnall and King (1991b) to reduce flower, peg, and pod numbers on Robut 33-1.

We also evaluated effects of dry pegging zone soil and low plant turgor on pod addition. We developed a function to compute the fraction of water available in a variable depth of topsoil. The best depth was about 20 cm. Shallower depths were unstable for computing pegging zone soil water content because of unrealistically rapid evaporation from the soil surface. The best function was a relative pod addition rate of 0.0 to 1.0 as soil water availability increased from 0.01 to 0.25, and a rate of 1.0 above that point. In the pod addition function, we took the minimum of this function or the SWFAC (ratio of root water supply to potential climatic transpiration). This function resulted in slight delays in rate of pod addition for several drought treatments, while creating minimal effect on well-irrigated treatments. The effect of this function was intentionally made weak since recent evidence suggests that Florunner and Robut 33-1 will produce pods in air-dry soil although at a slower rate.

Water deficit effects (SWFAC) were further allowed to delay progression toward the following reproductive stages: beginning peg (R2), beginning pod (R3), and beginning seed (R4-5). There were only small effects from these changes with the Florida data sets.

For the Florida data sets, the hedgerow version of Pnutgro predicted less water deficit during early season than the previous version and did not correctly predict the relative drought effects, even with the addition of the Penman ET equation. We compared predicted to observed root length density for four Florida data sets and concluded that the model was overpredicting the total root length density (RLD) and that the predicted profile distribution placed too much RLD at depth. A comparison of partitioning to a 1984 data set suggested that relative partitioning to root mass was correct up to 42 days. Thus, we took the simple approach to reduce RFAC1, root length per unit mass, from 6550 to 4550 cm g<sup>-1</sup>. To better predict the observed profile, the RLD function for Florida sandy soils was changed to produce more RLD in the upper 30 cm and approximately one-third less RLD below 30 cm as compared to the previous function. With these changes, better fits to rainfed treatments were obtained and effects of drought were more realistically simulated. It is unfortunate but realistic that minor changes in rooting in deeper layers have an important impact on ability to predict drought consequences.

## Automatic sowing for strategy evaluation

In simulating groundnut production for several years to estimate the variability in production due to weather uncertainty, it is not realistic to sow the crop on the same day each year. The soil may be too dry on the intended sowing day (or too wet) and thus sowing would have to be delayed. An option for the strategy evaluation mode was added to delay sowing beyond the input sowing date, if soil water in the top 30 cm is too low or too high (less than 50% or greater than 100% of available soil water). In the latter case (greater than 100%), sowing is delayed because soil water is above the drained upper limit.

## Scheduled harvest date

Physiological maturity in groundnut is not as clearly defined nor as discrete as in other crops such as *Glycine max* and *Zea mays*. Pod addition is more gradual in groundnut than in other crops, vegetative growth continues during the seed growth phase, and there are pods of various ages when the crop is harvested. In the field, abscission of mature pods will occur if harvest is delayed too long (the current model does not account for pod losses). As a result, predicting harvest date is very difficult, and harvested yield depends on this date to a large extent. To provide a more straightforward comparison with observed harvest data, an option was added to Pnutgro to force harvest on the date that the experimental crop was actually harvested. Otherwise, the model stops when the simulated maturity is achieved. For strategy evaluation runs, the model always stops at the simulated date of maturity.

## Pnutgro Simulations in Florida and in India

The predictions of pod and total crop growth were quite successful for well-managed research plots at Gainesville, Florida (Fig. 7), where fertility was good and optimum pest-control practices were followed. Most of these treatments were irrigated, so the Florida data did not span far into stressful environments. For the India data, we found a wider range of environments including greater drought stress. Drought at ICRISAT Center in 1987 greatly reduced dry matter accumulation in total crop and pod of Robut 33-1 compared to the irrigated treatment (Fig. 8). Crop and

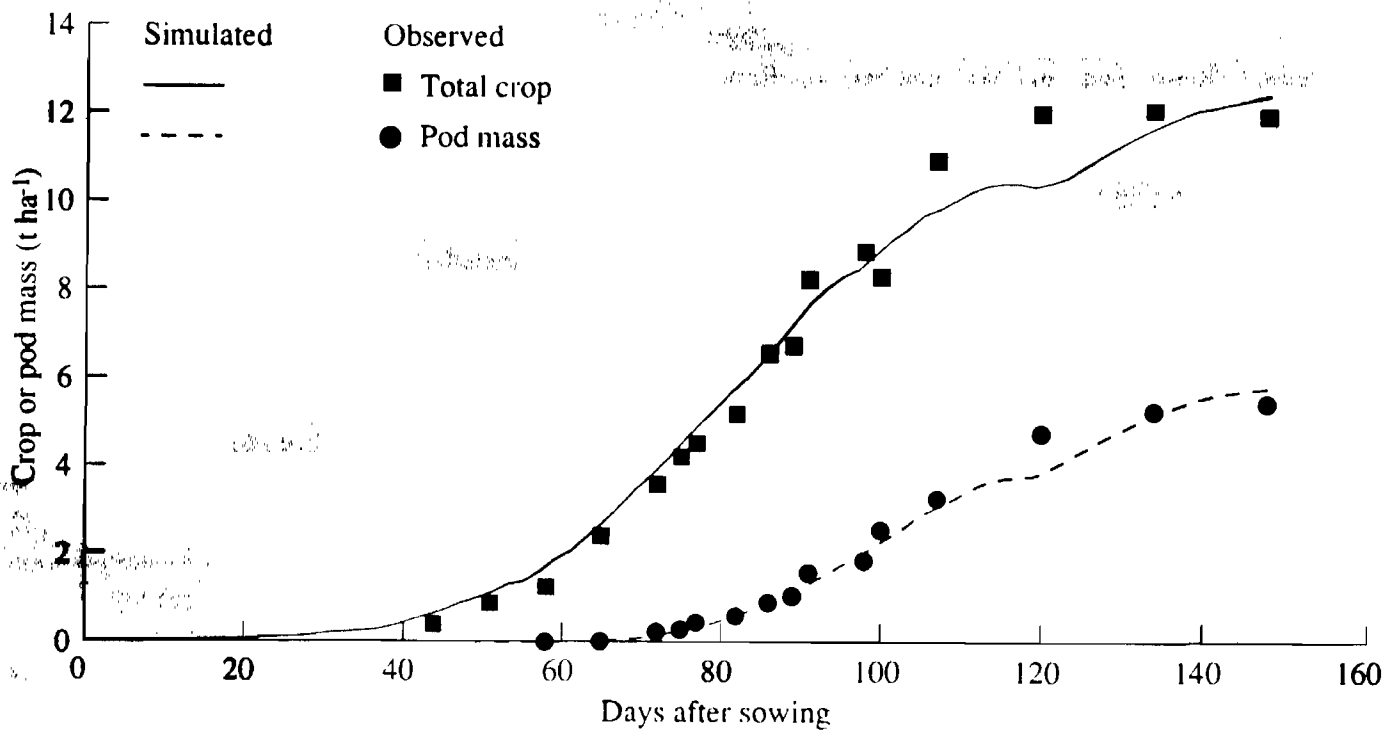


Figure 7. Total crop biomass and pod mass for Florunner in 1981 at Gainesville.

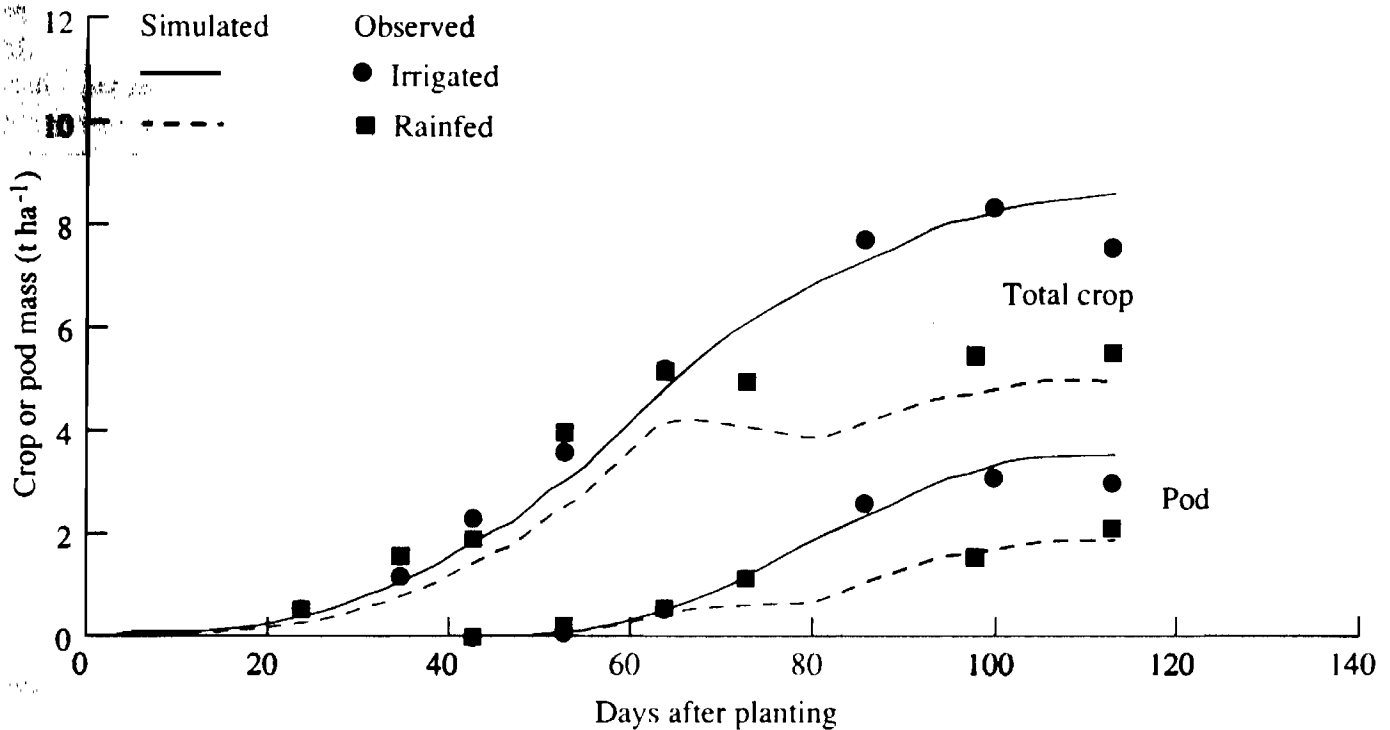


Figure 8. Total crop biomass and pod mass for irrigated and rainfed Robut 33-1 grown in 1987 at ICRISAT Center.

pod growth of Robut 33-1 were also reduced for the rainfed treatment at Anand, India, in 1987 (Fig. 9). The apparent good model fits in these three examples must be tempered by the fact that we calibrated the Florunner cultivar (one common set of genetic traits) for 11 Florida data sets, and the Robut 33-1 cultivar

for 19 data sets over 7 sites. The soil fertility (site) factor was set at 1.00 for Gainesville, 0.94 for ICRISAT Center, and 1.05 for Anand. After the calibration for Robut 33-1 (19 growth analyses over 6 sites), the PNTGRO model was able to account for 71% of the pod yield variation (Fig. 10). At the Ludhiana site (5

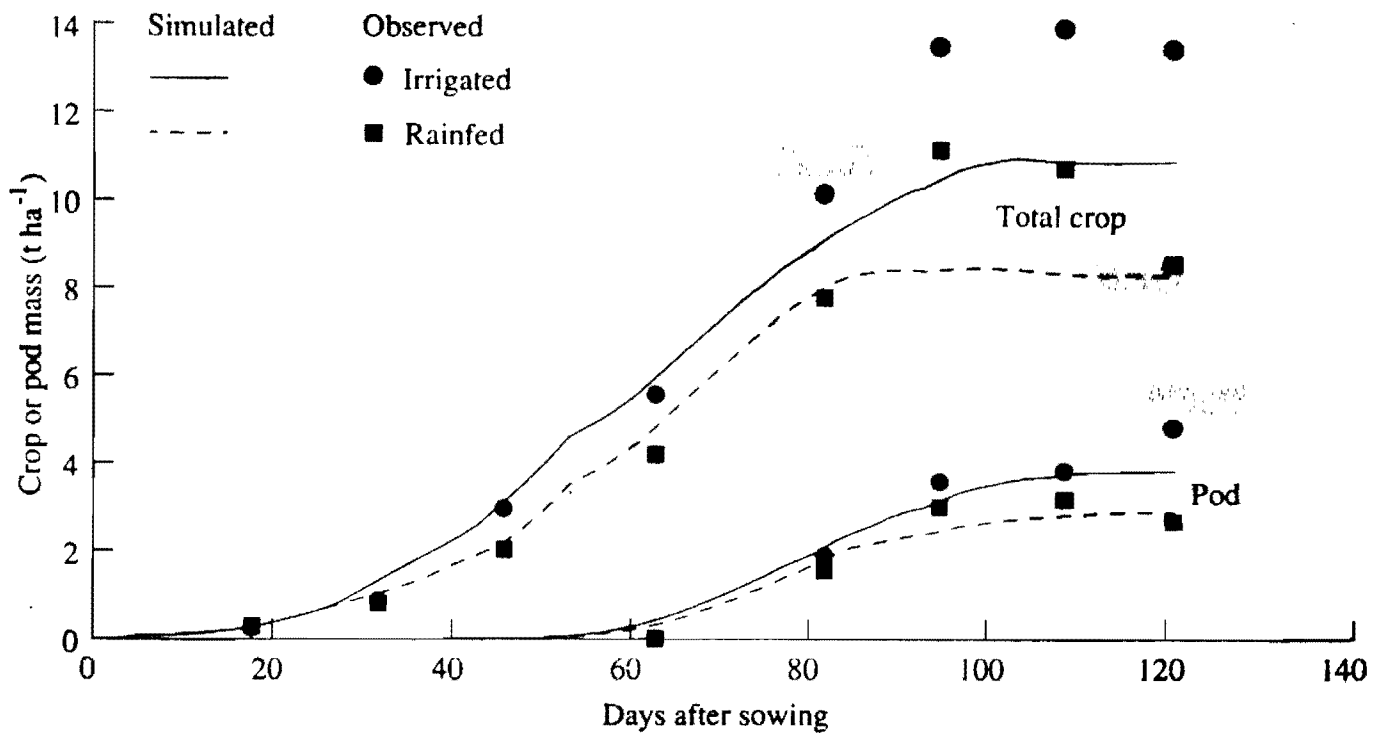


Figure 9. Total crop biomass and pod mass for irrigated and rainfed Robut 33-1 grown in 1987 at Anand, India.

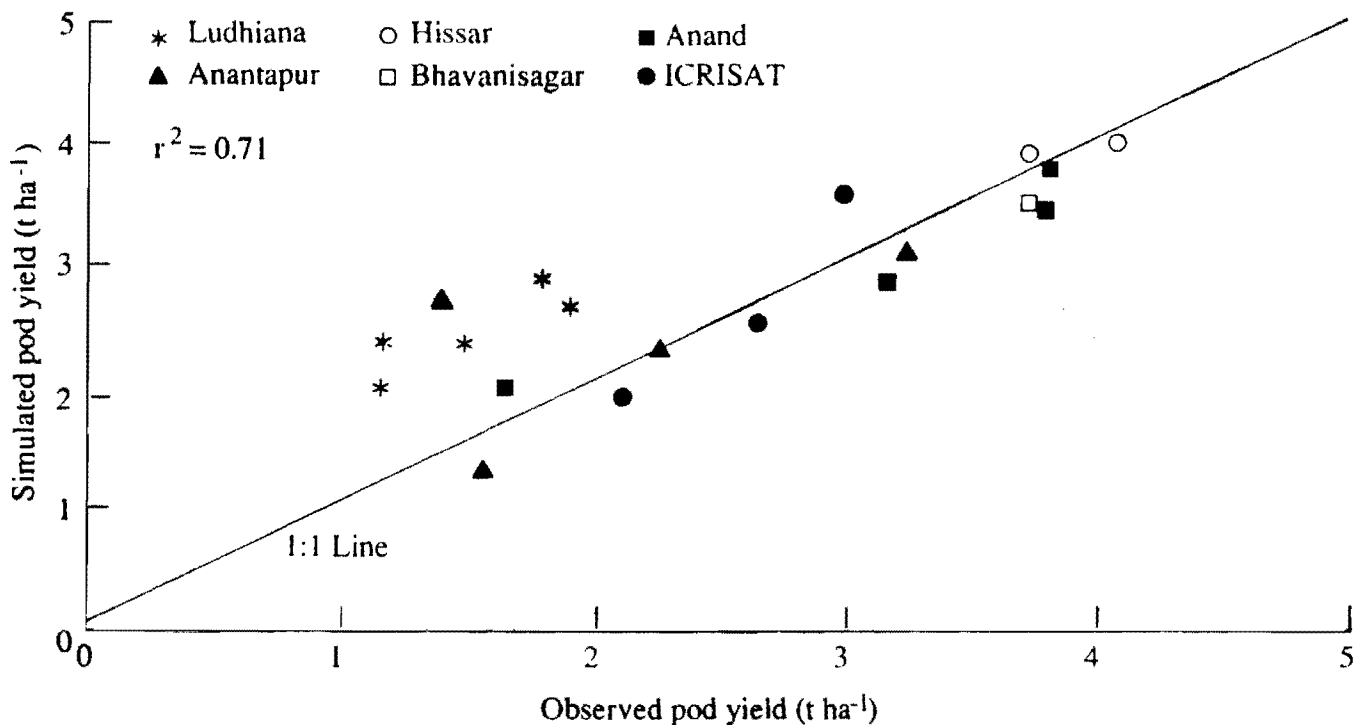


Figure 10. Simulated versus observed final pod yield for Robut 33-1 grown in 19 treatments at 6 sites in India in 1987.

of 19 data sets), the model over-estimated pod yield even though it was correct on biomass accumulation. There appeared to be a problem with partitioning to pods at that site. Serious over-estimation of rainfed yield at Anantapur was attributed to uncertainty of

initial soil water below 45 cm and unknown probability of roots below that depth. The more important test of PNUTGRO predictability is still to come when we validate the new version against new data (1988–1991) for the same locations, without changing cultivar or soil traits.

## Potential yields, actual yields, and limitations from pests and infertility

It is important to realize that PNUTGRO is programmed to respond to climatic and soil water limitations, but that it does not presently consider pest or soil fertility limitations. (This is true of most crop models.) Our on-farm experience with groundnut producers in Florida over the past 4 years has shown that many grower fields do not achieve the climatic production potential because of diseases, insects, nematodes, and other soilborne pests. Similarly, we found many situations in the India data in which actual growth and yield were less than the predicted (climatic potential) growth and yield. In many cases, climate was probably not a limiting factor, but poor growth may have been associated with low fertility, soilborne pests, and poor foliar disease and insect control. We are not sure how well these factors were controlled in the India data sets. Actually, this comparison of actual growth and yield to potential may provide a useful assessment tool that illustrates how much yield one should have obtained if there were no disease or insect pests and if there were no soil fertility limitations. In this way, models can be used to highlight nonclimatic limitations to yield. They can give researchers a target yield that should be attainable, provided soil and pest limitations can be discovered and then minimized.

## Work in Progress

Work in progress includes efforts to add effects of soil phosphorus to all IBSNAT models, and soil N processes to the PNUTGRO and SOYGRO models. A future PNUTGRO version will have sensitivity to carbon dioxide for use in global climate change studies. We are developing a generic 'pest coupling' approach for the IBSNAT crop models including PNUTGRO, whereby the observed pest damage can be entered into a file and the model run to evaluate potential yield loss from the pest. This approach requires 'scouting' data inputs, but it does not require mechanistic models of the pests. Lastly, we are attempting to develop a simple primary set of modeled 'genetic' traits so we can mimic growth and yield of different groundnut genotypes. The ability to evaluate hypothetical cultivar traits with the PNUTGRO model is a potentially valuable tool to determine the best adaptation in new climatic regions (Boote and Jones 1988).

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