



Cotton Phenology and Growth Processes: Model Development

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ABSTRACT

In cotton, phenology and leaf area development are major determinants of final yield, and are substantially affected by temperature when other conditions are optimum. Here the rate functions for various phenological events and leaf area development are presented, providing appropriate information how to develop physiologically-based subroutines for those processes as functions of temperature.

Introduction

Over the last two decades, crop simulation modeling has become a major research tool in production agriculture for resource management. If models encompass current knowledge and integrate crop responses to a range of environmental factors, they can provide opportunities to optimize crop management practices. Cultural and management practices only alter the crop's physical and chemical environment. The modeling literature has at least two types of models: simple and mechanistic models. Simple models are easy to use, but fail to encapsulate present knowledge and often need fine tuning across environments. Complex models are needed to capture the state-of-the-current-scientific knowledge to test hypotheses, to describe and understand complex systems and to compare weather and management scenarios. Unfortunately, complex models are expensive to develop and may require information that is not readily available. Many crop models, however, are only at an early stage of development because 1) they do not fully capture either the existing knowledge or 2) there are real knowledge gaps in our understanding of how plants respond to their physical environment. Unless existing mechanistic models use known science, it is difficult to identify knowledge voids. This paper presents analysis of modeling various facets of cotton phenology and leaf area development as a function of temperature.

Rates of Crop Maturity

Cotton is indeterminate in growth habit; the main-stem apex continuously initiating leaves and axillary buds. The axillary buds on the lower nodes develop into vegetative or monopodial branches if conditions are favourable. The axillary buds in the upper nodes, normally above node five, develop into fruiting or sympodial branches. Vegetative branches behave much like the main-stem producing both vegetative

and fruiting branches. Fruiting branches, on the other hand, initiate one true leaf and then terminate as a flower. Branch elongation is accomplished by growth of axillary buds producing a sympodial zigzag structure (Mauney, 1984; Mutsaers, 1983a; Reddy *et al.*, 1997a). An understanding of the morphological and physiological characteristics of the crop are needed to comprehend and model cotton responses to its environment, and to quantify its responses to temperature, water, and nutrient supply. It is necessary to describe the plant as a whole and each facet of growth at the organ level.

Cotton development stages such as germination, floral initiation, square development, flower formation and boll developments are fairly distinguishable, have predictable periods. Considering current world cotton production areas and the temperatures to which the crop is normally exposed, data sets and response functions that represent a wide range of temperatures are needed. The number of days between emergence and first square and the daily rate of development (reciprocal of days) for the same period is presented as an example in Fig. 1. Corresponding regression parameters are also presented in Table 1 for plants grown under non-limiting water and nutrient conditions. Similarly, parameters for rates of square to flower formation and boll maturation are also presented in the Table 1. The response functions for rates of development for various stages are different and are not parallel. This makes the models that use a whole growing period or harvest date as a single entity less accurate. Also, these functions show that models based on heat summations do not adequately represent cotton phenology under a wide range of temperature conditions. Of course, species and cultivars do differ slightly in the rates of certain development and need adjustments to these rate functions presented here.

Using the daily developmental rate concept, the number of days required to reach an event for the

average temperature of each day can be calculated. The daily developmental values can be added together until the cumulative value is 1.0 or greater when the event should occur. A similar procedure can be used to estimate the timing of other developmental events. Such an exercise can be readily done with a record of the crop's planting and emergence dates, and daily temperature records. This calculation allows one to maintain a reasonably quantitative estimate of the crop's status and is reasonably independent of location or calendar dates. Water and nutrient deficiencies seem to have little direct effect on these developmental processes unless the deficits are extreme.

Leaf Area Development

Leaf area development is a key factor for light interception and carbon assimilation in crops. To mechanistically simulate leaf area development throughout the season, it is essential to estimate potential leaf expansion rates and then decrement these potential rates with stress factors such as water and nutrient deficiencies. Leaf area development can be treated as a combination of several processes such as leaf emergence rates on the main axis and on branches, rate and duration of expansion and life expectancy of individual leaves. Leaf emergence and duration of leaf expansion are primarily governed by temperature and slightly modulated by nutrient supply (Reddy *et al.*, 1997a; Hodges *et al.*, 1998). Leaf expansion rates are equally sensitive to temperature, water and nutrient supply.

Leaf emergence rates of main-stem and fruiting branches determine the number of leaves produced and canopy development, and therefore, help to determine interception of photosynthetically active radiation. The rate of leaf appearance is defined as the time from one leaf unfolding to the next leaf unfolding on the main-stem or on branches. We define a leaf to be unfolded when three main veins are visible. Defined in this way, leaf appearance can be used as a discrete event. The rates of leaf appearance on the main-stem and fruiting branches are functions of temperature when water and nutrients are not limiting (Table 2). Similar to the approach described earlier, daily unfolding rates can be accumulated until the cumulative value of one was reached, and that can be used to predict a newly unfolded leaf either on the main-stem or on fruiting branches. The rate of leaf formation on fruiting branches is considerably slower than on the main-stem, because the branch primordium develops a flower and an axillary meristem must be developed from which the next leaf and internode and flower is produced. Thus, the ratio of main-stem and fruiting branch leaf unfolding interval are not constant at different temperatures. Pre-fruiting leaves, nodes 1 to 5, unfold much slower

than the fruiting leaves for reasons unknown (Reddy *et al.*, 1997b). Leaf unfolding intervals, generally referred to in the literature as phyllochron intervals, were not different from the square appearance intervals (Hesketh *et al.*, 1972; Reddy *et al.*, 1993a; 1997a). Squares normally appear when the leaf at a given node unfolds. Defined in this way, the leaf response rate functions can be used to predict square intervals. Once the leaves are formed, their expansion durations are functions of temperature (Table 2) irrespective of their position (Reddy *et al.*, 1993b).

Once leaves unfold, the potential rates of leaf expansion can be calculated from the relative leaf expansion rate (RLER) as a function of days after leaf unfolding at any given temperature. These functions can be calculated from daily measurements of leaf area for each leaf on plants grown under a range of temperature conditions. The RLER decreases with age. The linearly-extrapolated intercepts provide estimates of the maximum RLER ($\text{cm}^2 \text{cm}^{-2}$) on day one. The maximum RLER and slopes of the RLER with age for each leaf ($\text{cm}^2 \text{cm}^{-2} \text{d}^{-1}$) are functions of temperature when other conditions are not limiting (Reddy *et al.*, 1997a).

The intercepts and slopes for leaves are inversely related and change progressively with temperature. The effect of temperature on leaf area is the net result of both temperature effects on duration and rate of leaf expansion. The following equations describe the rate parameters (Y) for leaves as functions of temperature: maximum RLER ($\text{cm}^2 \text{cm}^{-2}$):

$$Y = -0.03390 + 0.02041 * X; R^2 = 0.95$$

and reduction in slope of RLER ($\text{cm}^2 \text{cm}^{-2} \text{d}^{-1}$):

$$Y = 0.01341 - 0.001879 * X; R^2 = 0.98,$$

where X is average temperature for the time increment used.

Modeling leaf area development needs, leaf sizes at leaf unfolding. Potential leaf area at leaf unfolding increases progressively at higher positions on the main-stem until first square is formed. After the first square was initiated, the initial leaf area decreases at higher positions on the main-stem. The following equations describe initial leaf areas (Y, cm^2) as functions of main-stem nodes:

$$\text{leaves 1 to 6: } Y = 6.061 + 1.8069 * X; R^2 = 0.91,$$

$$\text{leaves 7 and up: } Y = 18.3812 - 0.523 * X; R^2 = 0.95$$

Where X is the main-stem node number.

Temperature also affects initial leaf sizes. Leaf area at leaf unfolding for leaves 10 to 12 increased as temperature increased to about 27° to 30°C and declined at higher temperatures (Reddy *et al.*, 1997a).

The following equation estimates leaf area at leaf unfolding (Y , cm^2) as a function of temperature:

$$Y = 18.599 + 2.186 * X - 0.0381 * X^2; R^2 = 0.62,$$

where X is average temperature.

The initial branch leaf area decreased linearly with number of nodes on the branches and was consistent with mature leaf area by position on the branch (Mutsaers, 1983a; 1983b). That relationship suggests that leaf area was largely determined by the number of cells formed before the leaf began to expand. The following equation describes initial leaf area (Y , cm^2) as a function of branch node number (Reddy *et al.*, 1997a):

$$Y = 13.457 - 1.179 * X; R^2 = 0.98,$$

where X is branch node number.

To date, factors controlling leaf longevity or leaf senescence are poorly understood and are not amenable to predictive modeling, and in fact most existing cotton models use an empirical function to abscise a leaf. However, this may be improved by predicting physiological effectiveness of a leaf. Sassenroth-Cole *et al.* (1996) found cotton leaves decreased their photosynthetic rates linearly as they aged whether they were in full sun or shaded. In less than 30 days after unfolding, or less than 14 days after reaching their maximum size, the leaves were only at 50% of their maximum photosynthetic capacity. In reality, the leaves produced early are shaded in well-developed canopies so that they contribute little as they age because of both their decreased physiological effectiveness and low light environment.

Summary and Conclusions

The data presented should be useful for building a mechanistic cotton model. Accurate prediction of phenology and leaf area development is needed both by simple and more physiologically-sound mechanistic models. The influence of various stress factors on leaf area development and phenology is needed to accurately predict cotton growth and yield in a production environment. Models that are assembled properly will be sources of archiving and synthesizing existing knowledge about the performance of crops in a complex system. As we learn more about complex systems, models will become important tools for turning information into useful knowledge. Growers can use that knowledge to improve their management decisions.

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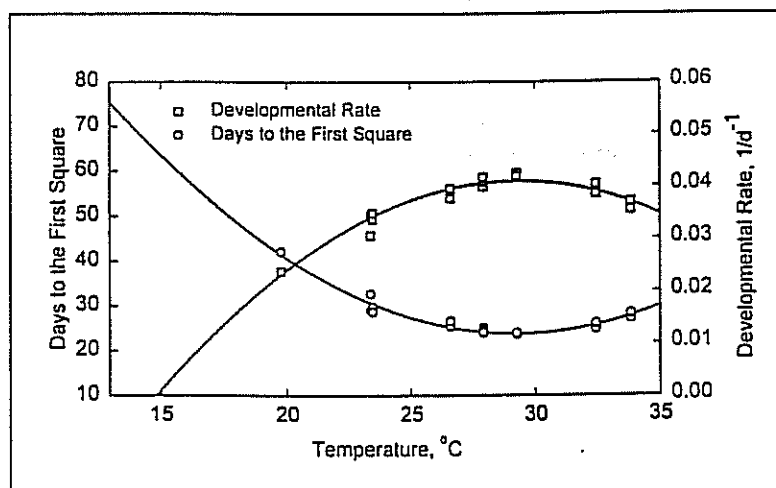
Table 1. Parameters for quadratic equations ($y = a + bx + cx^2$) regressing daily developmental rate (y) for various phenological events as a function of average daily temperature (x) and correlation coefficients (r^2).

Regression parameters				
Parameters	a	b	c	r^2
Emergence to square	-0.1265	0.01142	-0.0001949	0.98
Square to flower	-0.1148	0.00967	-0.0001432	0.94
Flower to open boll	-0.00583	0.0000995	--	0.92

Table 2. Parameters for quadratic equations ($y = a + bx + cx^2$) regressing daily developmental rate (y) for various leaf developmental events as a function of average daily temperature (x) and correlation coefficients (r^2).

Regression parameters				
Parameters	a	B	c	r^2
Main-stem leaf emergence rates	-0.6698	0.0570	-0.0006765	0.94
Brance leaf emergence rates	-0.3645	0.03389	-0.005199	0.84
Leaf expansion duration rate	-0.09365	0.01070	-0.0001697	0.95

Figure 1. Influence of temperature on the development of first square from emergence in cotton and rate of development. The rate of development is calculated as an inverse of duration; i.e. one over days at given temperatures.



Source: Reddy *et al.*, 1997

Modeling and Validating Cotton Leaf Area Development and Stem Elongation

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Abstract

The demand for mechanistic crop simulation models has increased in recent years due to an explosion of site-specific management techniques. Realistic crop models that encompass current knowledge and integrate crop responses to a range of environmental factors can provide opportunities to optimize crop management practices. The cotton simulation model, GOSSYM, is one of the most successful models used in cotton management. It is being continuously updated as new knowledge becomes available. Recently, new stem extension and leaf area expansion subroutines were developed and incorporated into the model. Potential stem and leaf area growth rates were calculated as functions of temperature. Actual stem and leaf growth rates were simulated using an environmental productivity index concept for several environmental conditions such as water and nitrogen stresses and mepiquat chloride (MC or PIX), a plant growth regulator used to regulate cotton vegetative growth in cotton, particularly stem growth and leaf area development. The modified model was validated for its accuracy from data sets collected across several cotton growing areas. The new model with the leaf and stem growth algorithms showed an improvement in estimating plant height and node count over the previous version of the model by 52% for plant height, 55% for mainstem nodes and 13% for lint yield.

INTRODUCTION

The need for predictive crop models has increased in recent years, as new technologies such as site-specific crop management are becoming a major tool in production agriculture for resource management. User-friendly simple crop models fail to encapsulate present knowledge and often require fine-tuning across environments. Mechanistic models capturing current knowledge will be useful to test hypotheses, describe and understand complex systems, and compare weather and management scenarios. Unfortunately, complex models are expensive to develop and may need information that is not readily available.

A good photosynthesis model is highly desirable in modeling because the amount of carbon produced controls mass accretion of various organs, and finally yields. Photosynthesis is dependent on the light intercepted by row crops and is often expressed in many crop models by Beer's law. This relationship is defined as: $I = I_0 e^{-kL}$, where I is the light intercepted by a canopy of leaf area index, L , I_0 is the incident radiation at the top of the canopy, and k is the canopy extinction coefficient. Leaf area development and stem and branch elongation patterns are key factors for light interception and thus carbon assimilation. To mechanistically simulate leaf area development and plant height throughout the season, it is essential to estimate potential leaf/stem expansion rates need to be estimated and then decremented by incorporating effects of stress factors such as water and nutrient deficiencies.

Cotton (*Gossypium hirsutum* L.), the fifth most economically important crop in the world, is typically grown on more than 5 million hectares in the USA (Reddy et al., 2000). Of the different cotton development models that have been proposed and published, the GOSSYM model is the most comprehensive being used in commercial agriculture to aid in crop management decisions (Jallas, 1998). However, GOSSYM uses

a simple plant height and row spacing function to determine daily light interception (Baker and Meyer, 1966). Although it may appear that such a simple relationship should be replaced by a more mechanistic one that is more in line with Beer's Law, this approach to light interception has worked well and has been validated by Kharche (1984) in the field conditions.

GOSSYM simulates plant height based on the ages of the top three main stem nodes. Plant height increments are calculated from the age of the top main stem nodes. Extension rate limits are set to $1.5 \text{ cm day}^{-1} \text{ internode}^{-1}$ and to 3 cm day^{-1} on the plant as a whole. Because of the limitations inherent in the experiments from which the plant height functions were derived, several forced corrections need to be made in the model to account for the effects of temperature and water stress to simulate field-grown cotton (Baker et al., 1983). Recent studies have clearly shown that rates of stem elongation, leaf area expansion, and duration of expansion of leaves or internodes were greatly influenced by temperature under optimum water and nutrient conditions (Reddy et al., 1997a). Nitrogen and water deficiencies will also affect these growth rates (Reddy et al., 1997b). The objectives of this study were to (1) provide and incorporate the concepts involved in simulating plant height and leaf area development into a mechanistic cotton simulation model, GOSSYM, (2) validate the modified model with data sets under different weather and cultural practices, and (3) test the predictive capability of the new model with previous versions from the data sets obtained from several cotton growing areas.

MATERIALS AND METHODS

Cotton Simulation Model, GOSSYM

The development, characteristics, and applications of GOSSYM have been previously described (Baker et al., 1983; Boone et al., 1995). Briefly, GOSSYM, an acronym coming from the word *Gossypium*, the genus of cotton, is a material balance cotton simulation model that accounts for carbon, nitrogen, and water in the plant and soil root-zone. It simulates crop responses to environmental variables such as solar radiation, temperature, rain/irrigation, and wind as well as variation in soil and cultural practices. Growth and development are estimated, and a record of individual leaf and fruit ages is maintained. The model determines growth and developmental rates by calculating potential rates for daily temperatures assuming other conditions are not limiting, then it corrects the potential rates by intensity of environmental stresses (Baker et al., 1983; Reddy *et al.*, 1997b). The model provides daily values for most of the physiological parameters that can be readily measured such as weights and counts of the different plant organs, the growth stage of the crop, and the intensities of the stress factors. It also generates plant maps showing the main stem and branch nodes and the fruiting sites. The model also estimates leaf nitrogen concentration, nitrogen, water and root distribution in the soil, and lint yield as the crop matures. So, a grower can assume certain future weather (days and weeks) conditions to determine yield estimates depending on the maturity of the crop.

GOSSYM continues to evolve as new concepts or better ways of implementing existing concepts become available. Such recently made enhancements include (to name a few): new stem elongation and leaf expansion routines (Reddy et al., 1997a), using stress-specific reduction factors similar to the concepts proposed by Nobel (1984), and a fruit production efficiency function to simulate boll abscission due to high temperatures (Reddy et al., 1997c). These modifications increase the model's sensitivity to a wide range of environmental conditions such as changes projected in the future climate and cultural practices.

Model Modifications

Functional algorithms for plant height and leaf area development described by Reddy et al. (1997a,b) were incorporated into the cotton simulation model, GOSSYM. From these data, they derived several equations to estimate: a) the durations of stem

elongation and leaf expansion, b) the maximum relative internode elongation and leaf expansion rates and c) the rates of reductions for both internode elongation and leaf expansion. All of these equations are functions of temperature and [CO₂].

In order to make the simulation of plant height and leaf area development more mechanistic, modifications were made in accordance with these findings. The step-by-step model development and simulations are as follows:

1. The individual internode length and leaf area can be defined by:
 - a. The time required to initiate a node or leaf;
 - b. The rate of leaf expansion and internode elongation as well as the temperature effect on the duration of elongation and expansion;
 - c. The positional variation of mature internode lengths and leaf area on the mainstem; and
 - d. The influence of temperature on initial internode lengths and leaf areas.
2. The potential values are the summation of all the parts, i.e., plant height is a summation of all its internode parts, and total leaf area is a function of all the leaves and leaf sizes in the canopy.
3. The actual growth results from downward adjustments made to potential growth due to nutritional and water (drought) stresses and applications of plant growth regulators such as PIX.

The stress index resulting from the multiplicative effects of the nutritional and drought stresses and plant growth regulators was based on the EPI concept. The equations that define the effects of these stresses on stem elongation and leaf expansion are found in Reddy et al. (1997b). The effect of PIX is described in Reddy et al (1995).

Model Validation

When enhancements to GOSSYM are made, the model is calibrated with standard data sets, representative of various cultivars, to modify variety-dependent model parameters to obtain an optimal simulation of the field data. These standard data sets were collected over years and were obtained from cooperating researchers from experiment stations from several states. The data include: plant height, node numbers, fruit counts, and in some cases LAI and dry weights measured at several intervals during the growing season. The detailed weather, soil, cultural practices and growth and yield data can be found at URL: wizard.arsusda.gov/cotton/ars2.html. Model performance was tested using the "Comparison of Observations and Predictions to Assess Model Performance" (COPAMP) method proposed by Mitchell and Sheehy (1997).

The leaf area development algorithm was calibrated against LAI. Since it is improper to use the calibration data for validation purposes, no validation work was performed on the leaf area simulation.

The performance of the models for plant height and mainstem nodes was tested on 25 cropping systems representing irrigated and rainfed conditions, three cultivars, with several soils and cultural practices such as plant growth regulator applications, row spacing and fertilizer applications. Both models were also tested for their lint yield predictions because any change in leaf area development and plant height simulation will directly affect canopy light interception and thus lint yield. The data sets include 43 cropping systems spanned across six years from five major cotton-growing areas, Alabama, Mississippi, Missouri, Texas and South Carolina. They represent 18 different soil types with three or more cultivars and with three or more row spacing. Also, 28% of the fields were irrigated, and 30% of the fields were managed with plant growth regulator applications.

RESULTS Because of insufficient data on leaf area, only the results for plant height, node numbers and yield will be presented. Figure 1 (a and b) shows the scatter plots for observed and predicted plant height of the two versions of GOSSYM, the 1994 version (V1994) and the new model (V2001). Regression lines for both versions show a high linear correlation between the observed and predicted values. The slope of the regression

equation for the new version of the model is closer to one compared to the 1994 version. Furthermore, if accuracy is based on the scatter plots of plant heights over time, it is clear that the performance of the new model is superior to the 1994 version (Fig. 1 c and d).

Figure 2 shows the scatter plots of deviations set to $\pm 15\%$ of the observed values for plant height, mainstem nodes and lint yields for both models. For plant height and mainstem nodes, more values are within $\pm 15\%$ of the observed values for the new version (V2001) than the 1994 version. Similar results were observed for lint yields.

DISCUSSION

Evaluating the accuracy of the new and improved model against the previous version with observed data is not always straightforward. Several different techniques have been proposed to judge the performance of the simulation models (Loague and Green, 1991, Reddy et al., 1995). Results from regression analysis of predicted versus observed values have inherent problems when used to evaluate model performance (Mitchell and Sheehy, 1995). They argued against the use of regression for assessing model accuracy. Their alternative method for determining model adequacy used the concept of an "Envelope of Acceptable Precision (EAP) and the proportion of points (deviations of the model from the observed values) that are within that envelope." Figure 2 illustrates the COPAMP technique for plant height, mainstem node numbers, and lint yield across several management units.

With predetermined allowable error of $\pm 15\%$ of the observed value, whether plant height, node numbers or yields, the envelopes of acceptable precision are defined by the straight lines originating from the plots of these positive and negative points. Figure 2 show that the 1994 version over-predicted node numbers and plant height more than the new model (V2001). Seventy percent of the new model plant height predictions were within the EAP compared to 24% for the 1994 version of the model (Fig. 2 a and b). Far more new model-predicted node numbers were within its EAP than the 1994 version by about a 3:1 margin (79% vs. 30%) (Fig. 2 c and d). With respect to lint yield, the difference between the two models was smaller than for plant height and node numbers. Forty nine percent of the simulated yields were within the EAP for the new model, whereas in the 1994 version, 40% of the estimated yields were within its EAP (Fig. 2 e and f). Thus, the new model is better able to predict node numbers, plant height and lint yields than the 1994 version of the cotton model.

In summary, the new model with mechanistic leaf and stem growth algorithms, improved predictive performance by 52% for plant height, 55% for number of nodes and 13% for lint yields over the previous version of the model in terms of absolute over/under prediction. The new model may be used in diverse production environments as a management tool to optimize resources such as water, nitrogen, or plant growth regulator.

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Figures

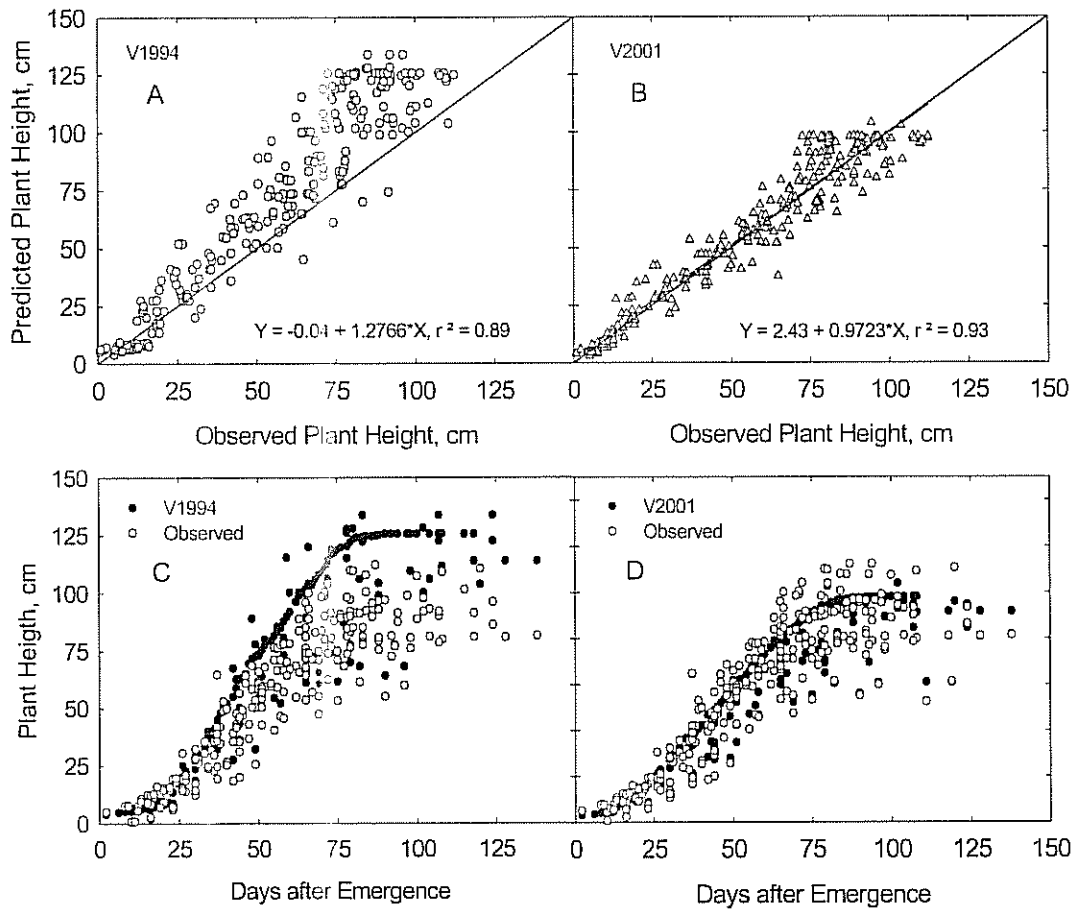


Fig. 1. Scatter plots of predicted versus measured cotton plant height of the two versions of the GOSSYM model, V1994 and V2001 (A and B) including the one to one line and the linear regression equation. Also, scatter plots of predicted and observed plant height over time are shown for both versions (C and D). The V2001 includes the new stem elongation and leaf area development subroutines.

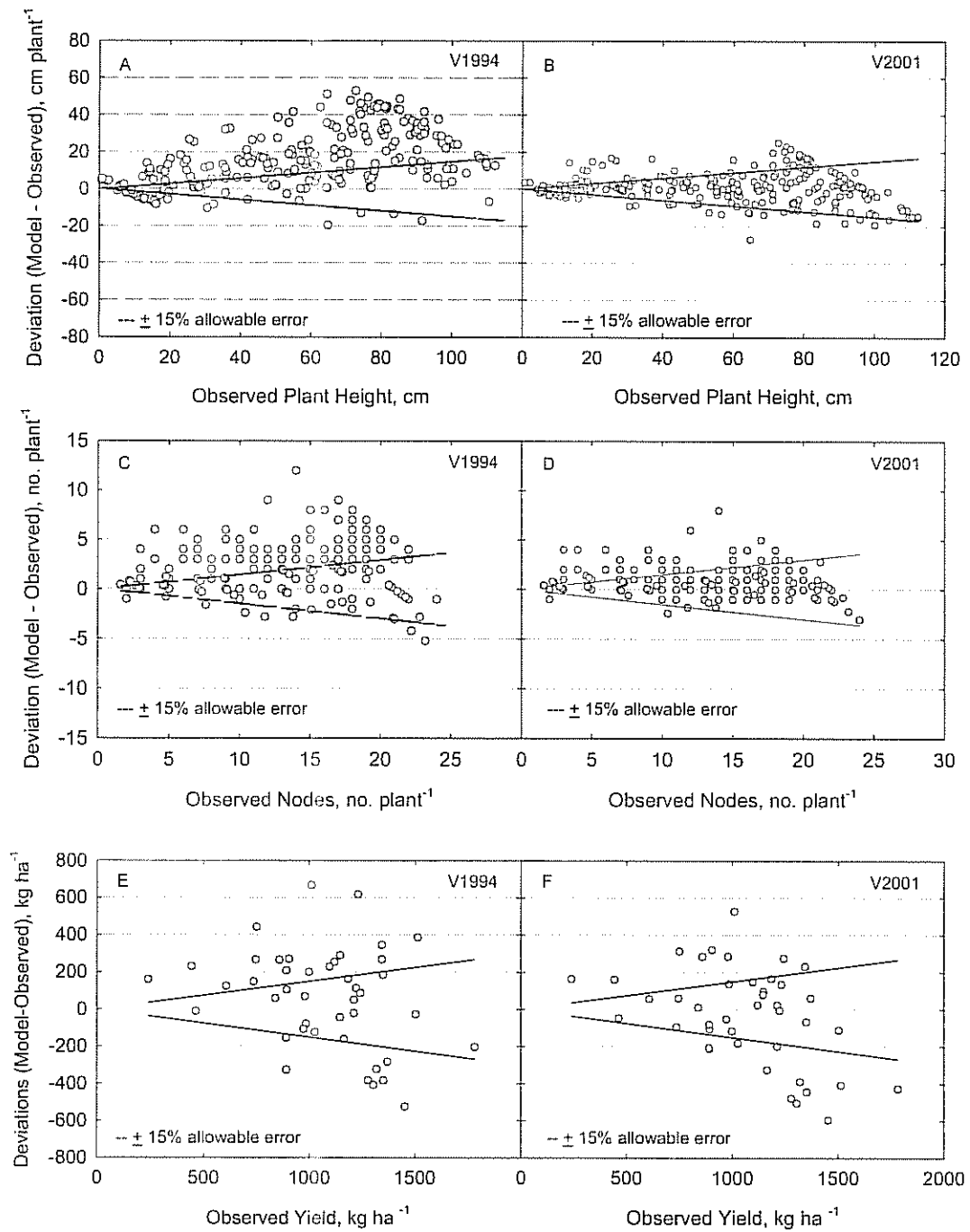


Fig. 2. Plots of deviations versus observed values of GOSSYM for plant height (A=V1994 and B=V2001), mainstem nodes (C=V1994 and D=V2001) and lint yield (E=V1994 and F=V2001).