



Cotton Phenology and Growth Processes: Model Development

K.R. Reddy¹ and V.R. Reddy²

¹Dept of Plant and Soil Sci., Box 9555, Mississippi State University, Mississippi State, MS 39762, USA

²USDA-ARS Remote Sensing and Modelling Lab., Bldg 007, BARC-West, Beltsville, Maryland 20705, USA,

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

The following equation estimates leaf area at leaf unfolding (Y , cm²) as a function of temperature:

$$Y = 18.599 + 2.186 * X - 0.0381 * X^2; R_2 = 0.62,$$

where X is average temperature.

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 (cm² cm⁻²) on day one. The maximum RLER and slopes of the RLER with age for each leaf (cm² cm⁻² 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 (cm² cm⁻²):

$$Y = -0.03390 + 0.02041 * X; R_2 = 0.95$$

and reduction in slope of RLER (cm² cm⁻² 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 , cm²) 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 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 , cm²) 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.

Acknowledgements

Part of the research was funded by the USD_oE National Institute for Global Environment Change through the South Central Regional Centre at Tulane University (DoE co-operative agreement no. DE-FCO3-90ER 61010).

References

- Hesketh, J.D., D.N. Baker, and W.G. Duncan.(1972): Simulation of growth and yield in cotton. II. Environmental control of morphogenesis. *Crop Sci.* 12: 436-439.
- Hodges, H.F., F.D. Whisler, S.M. Bridges, K.R. Reddy, and J. M. McKinion. (1998): Simulation in crop management - GOSSYM/COMAX. In: *Agricultural Systems Modelling and Simulation*. R. M. Peart and R. B. Curry (Eds.), Marcel Dekker, Inc., New York, New York. Pp.235-282.
- Mauney, J.R. (1984): Anatomy and morphology of cultivated cottons. In: *Cotton*. R.J. Kohe and C.F. Lewis. (Ed.). *Agron. Monograph no. 24*, ASA-CSSA-SSSA, Madison, WI. Pp. 59-80.
- Marani, A., D.N. Baker, V.R. Reddy, and J.M. McKinion. (1985): Effect of water stress on canopy senescence and carbon exchange rates in cotton. *Crop Sci.*, 25:798-802.
- Mutsaers, H.J.W. (1983a): Leaf growth in cotton (*Gossypium hirsutum* L.) 1. Growth in area of main-stem and fruiting branch leaves. *Ann. Bot.* 51:503-520.
- Mutsaers, H.J.W. (1983b): Leaf growth in cotton (*Gossypium hirsutum* L.) 2. The influence of temperature, light, water stress and root restriction on the growth and initiation of leaves. *Ann. Bot.* 51:521-529.
- Reddy, K.R., H.F. Hodges, and J.M. McKinion. (1993a): A temperature model for cotton phenology. *Biotronics* 22:47-59.
- Reddy, K.R., H.F. Hodges, and J.M. McKinion. (1993b): Temperature effects on Pima cotton leaf growth and development. *Agron. J.* 85:681-686.
- Reddy, K.R., H.F. Hodges, and J.M. McKinion. (1997a): Modelling temperature effects on cotton internode and leaf growth. *Crop Sci.* 37:503-509.
- Reddy, K.R., H.F. Hodges, and J.M. McKinion. (1997b): Modelling and applications: A cotton example. *Adv. Agron.* 59:225-290.
- Sassenroth-Cole, G.F., L. Guiyu, H.F. Hodges, and J. M. McKinion. (1996): Photon flux density versus leaf senescence in determining photosynthetic efficiency and capacity of *Gossypium hirsutum* L. leaves. *Environ. Expt. Bot.* 36:439-446.

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
Branche 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

