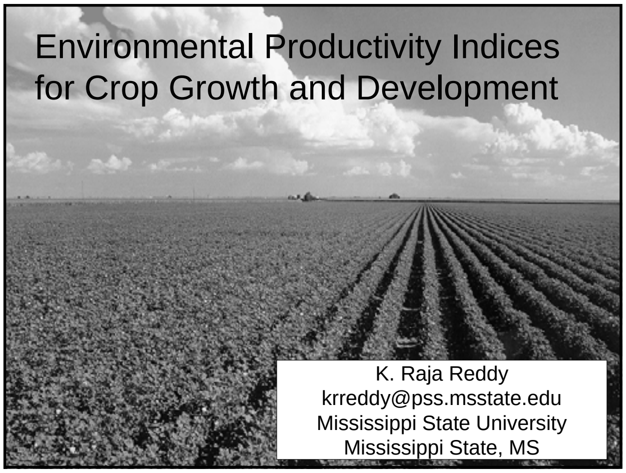


Environmental Productivity Indices for Crop Growth and Development

K. Raja Reddy
krreddy@pss.msstate.edu
Mississippi State University
Mississippi State, MS

Crop Growth and Development and Environment

Goals and Learning Objectives:

- To understand the effects of multiple environmental factors on crop growth and development.
  - Crop growth and development and environment and applying Environmental Productivity Index (EPI) concept using cotton as an example crop.
  - Crop growth and development and environment: Species variability, and applicability of EPI concept across species.

Crop growth and Development and Environment

You will learn:

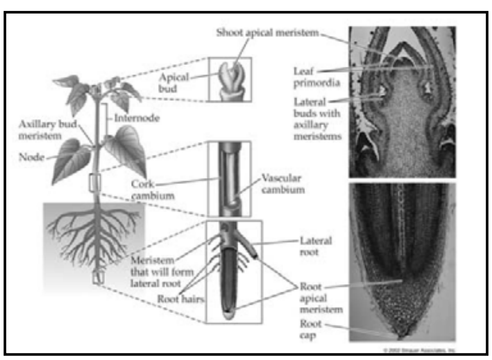
- ✓ Effects of environmental factors on crop growth-phenology and growth of various individual organs and plant as a whole.
- ✓ How to develop build whole plant or canopy from organ-based functional algorithms.
- ✓ How to calculate potential growth and developmental rates under optimum conditions.
- ✓ How to develop environmental productivity indices for various environmental factors to decrement the potential crop growth and developmental rates under multiple environmental conditions.

Plant Growth and Development

- Plant growth is *modular* in nature.
- Modular growth and development depends upon functional *meristems*.
- *Meristematic cells are totipotent.*
- Modules undergo primary and secondary growth.
- Modules respond to the environment in a *programmable manner.*
- Quantifying and understanding plant module responses to the environment is important to develop management tools.

Plant Growth and Development

Modular growth depends on functional meristems

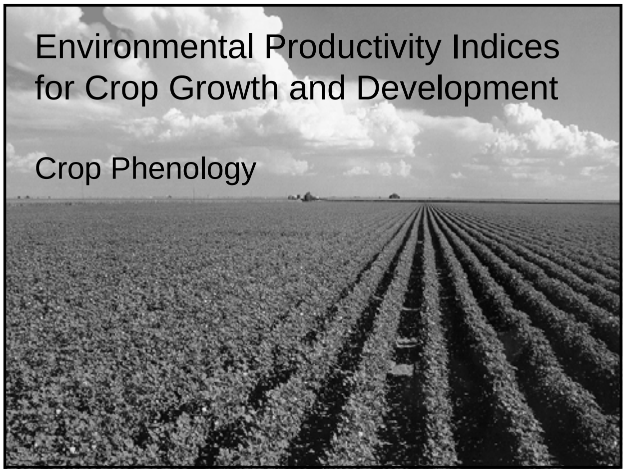


Plant Growth and Development

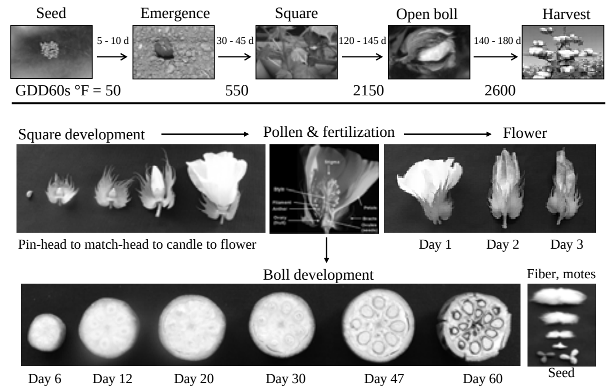
- Crop phenology
- Crop growth
  - Shoot (leaves, stems and fruiting structures)
  - Roots
- Crop growth and development – Species variability
- High temperature injury

Environmental Productivity Indices for Crop Growth and Development

Crop Phenology



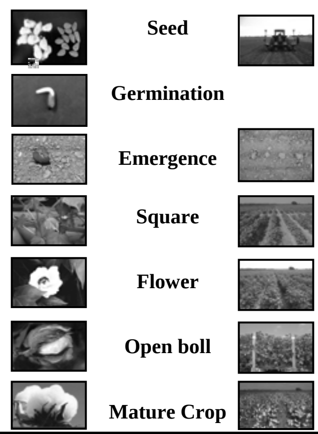
Cotton Developmental Aspects

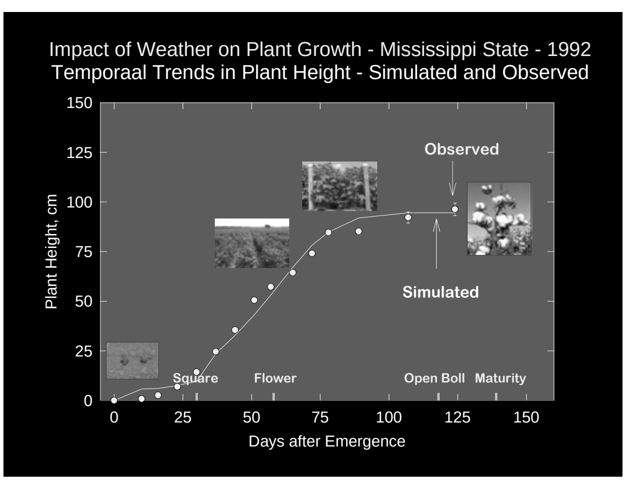


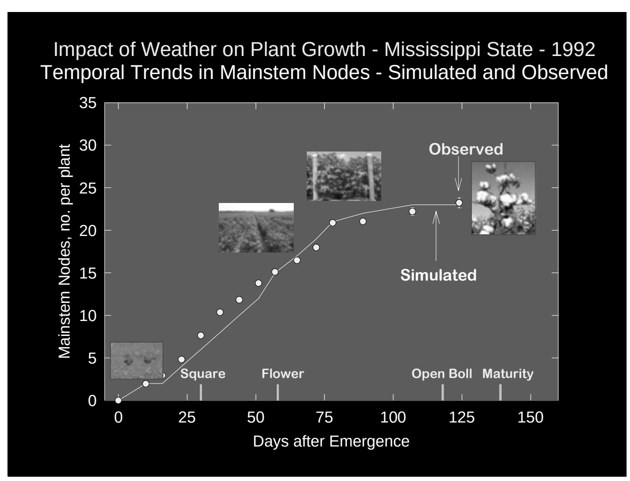
Environmental and Cultural Factors Influencing Crop Phenology

- Atmospheric Carbon Dioxide (indirect)
- Solar Radiation (indirect)
- Photoperiod (direct on flowering, no effect on day-neutral plants such as modern cotton cultivars)
- Temperature (direct)
- Water (indirect)
- Wind (indirect)
- Nutrients (N, P and K) (direct & indirect)
- Growth Regulators (PIX) (indirect)

Canopy Development Over the Growing Season







Terminology and Definitions

- Phenology:
  - Phenology is the study of periodic biological phenomena.
  - It refers to like events such as the time intervals between mainstem or branch leaves on a plant, time intervals between two successive flower buds or flowers on a branch, unlike events such as the time intervals between plant emergence and formation of flower bud, flower or mature fruit, and /or a duration of process such as the time interval between unfolding or appearance of leaf or internode, and until those organs reach maximum size or length.
  - Therefore, phenology refers to the initiation, differentiation, and development of organs. It involves qualitative changes in form, structure and general state of the complexity of the plant. Phenostages or the developmental processes are irreversible.

Terminology and Definitions

- Growth:
  - Growth, on the other hand, is an irreversible increase in length, area, or weight of plants as a whole or individual organs that is quantitative.
  - Distinction between phenology (development) and growth may be blur at some times.

Terminology and Definitions


- Phenology:

  Plastochrons and phyllochrons:

  The time interval between two successive leaf primordia formation at the tip of a growing meristamatic region of stem or branch is defined as the plastochron. For this study, we need at least a light microscope and take anatomical sections of stems or branches to estimate the time intervals.

  If the time interval refers to two successive leaf tip appearance or leaf unfolding, it is known as the phyllochron. If the leaf tip appearance or leaf unfolding is defined as a discrete size or event, then it can be examined visually without a microscope.

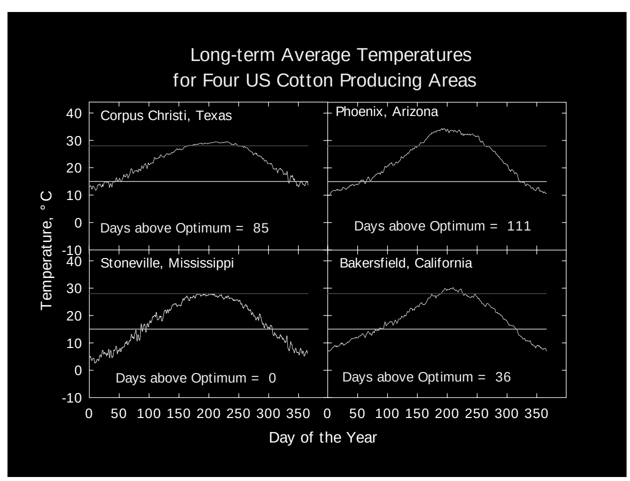
  Also, phyllochron or leaf appearance rates are easy to verify in the field.

Crop Phenology - Environment

- Crop phenology or development is driven by temperature and modulated by nutritional demand, particularly leaf development/supply.
- Temperature and photoperiod are the two main environmental factors that determine flowering in young and established plants.
- Winter annuals and biennials as well as the buds of some woody species (e.g. Peach) require a cold season in order to flower normally. In other words, they have a chilling requirement (temperatures below 3°C to 13°C, ideally 3 to 15°C for weeks). This process is called vernalization.
- If this process is too short or interrupted by warming above 15°C, then the effect will be cancelled or extended.

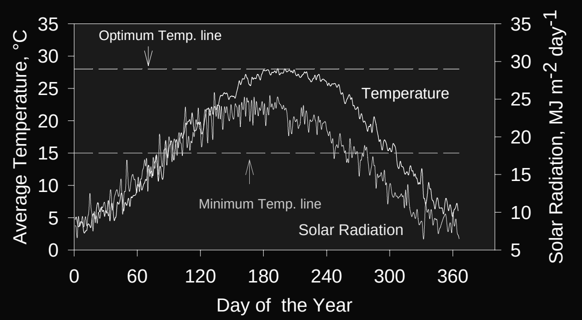
Crop Phenology – Climate Change

- If the climate in the future is more variable, then we can expect seasonal fuzziness and variation in extreme conditions. And this phenomenon may pose a serious problem for certain crops, particularly for those crops that require vernalization.
- All crops have minimal, optimal and maximum temperature limits for each phenological event.
- These limits vary depending upon the phenological or developmental event, even within a crop or species.
- Floral initiation in commercially-grown cotton varieties, for example, is mostly governed by temperature, and is relatively insensitive to photoperiod.
- The major reproductive events (sowing to emergence, emergence to square initiation, square to flower and flower to open boll) are all directly governed by temperature to which they were exposed.



Mississippi Long-term Climatic Data

Temperature and Solar Radiation



Quantifying the Effects of Environmental Factors on Crop Growth

One way to quantify the effects of environmental factors on phenology is to use environmental productivity index (EPI) concept like the way we used in calculating photosynthesis.

EPI-phenology = Temperature (potential) * Nutrient Index (C, N, P, K) * Water index * PPF Index * PGR Index etc.,

First, we have to define the potential phenology for given species or cultivar. Potential phenology is defined as the rate of development that takes place at a range of temperatures under optimum environmental conditions (optimum water and nutrient conditions).

Quantifying the Effects of Environmental Factors Crop Growth and Development

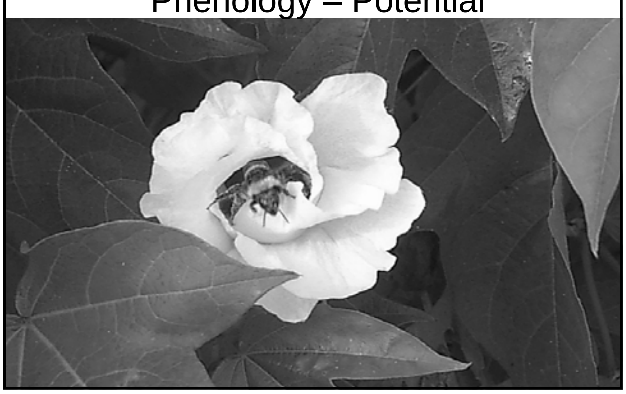
- Then, we have to account for all the environmental factors limiting to obtain that potential.
- Individual environmental factors affect the potential phenology multiplicatively, not additively, as in photosynthesis. For instance, if prolonged water stress causes plants to grow slower, the rate of addition of leaves on the mainstem or branches will reflect that condition even if the temperature and other factors are optimum.
- All the indices, range from 0 when it is totally limiting phenology and 1 when it does not limit phenology, represent the fractional limitation due to that particular factor. Therefore, phenological rates will be slower as the effect of that particular stress becomes more severe.

Quantifying the Effects of Environmental Factors Crop Phenology

This way allows one to quantify the effect of environmental factors limiting crop development or phenology in a multi-stress environment or in field conditions.

Cotton - Phenology

Phenology – Potential



Quantifying the Effects of Environmental Factors Crop Phenology – Some Considerations

It is difficult to build process-level or application-oriented crop models from data collected from the field because many factors often simultaneously affect rates of crop development and growth processes, and because many environmental and biological factors are covariants.

This makes it literally impossible to reasonably assess the causes and effects with accuracy. Instead, it is most appropriate to develop relationships or models with data from controlled-environments and validate such relationships or models with data from the field.

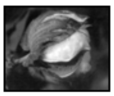
Again, the environmental variables in the controlled-environmental facilities, including radiation should be close to the radiation received in the field conditions, and must be not-limiting or well-defined and controlled for the given variable under consideration.

Phenology - Discrete Events and Definitions

Time from seed to germination defined as radicle of half the length of the seed and time from germination to emergence of the seedling above the ground are defined as a discrete events.

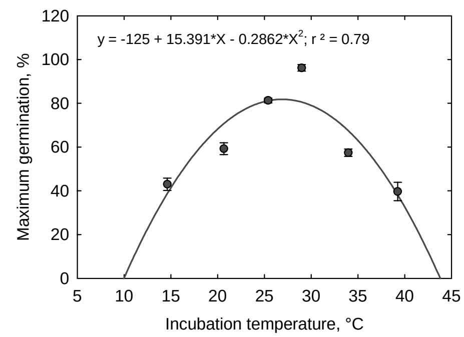
Time from emergence to square of 3-mm size is defined as a discrete event known as squaring in cotton.

The day of flower is a discrete event again. Cotton flowers are yellow or creamy – white on the first day, and then turn pink the next day.

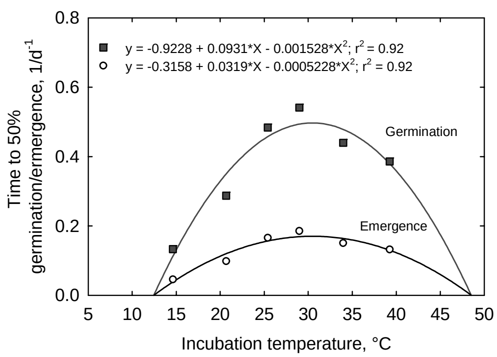


The day of boll-opening again is a discrete event. The day when one can see the lint through the sutures of carpel wall or burr in cotton is defined as open boll

Temperature - Maximum Seed Germination

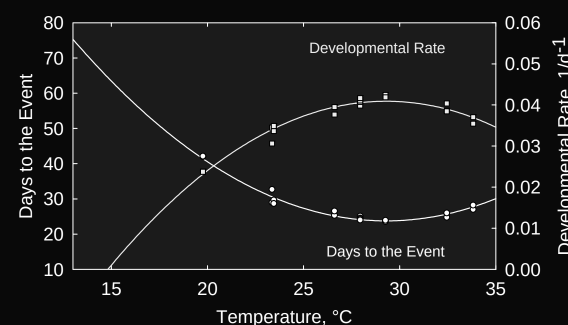


Temperature – Rate of Seed Germination and Emergence



Temperature - Phenology

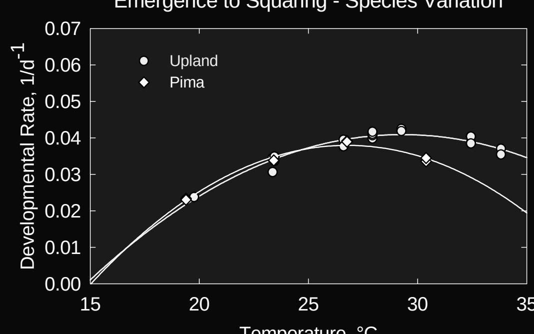
Emergence to Square

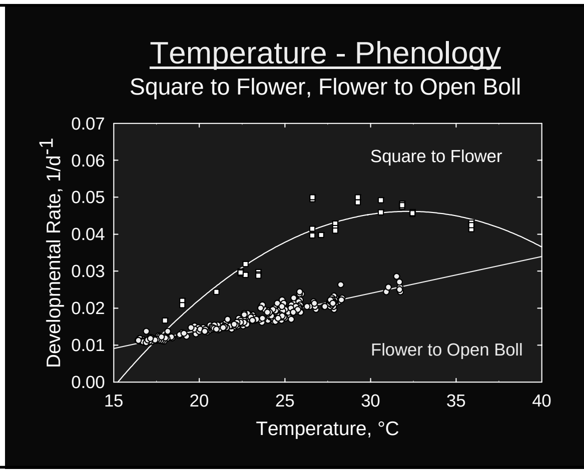


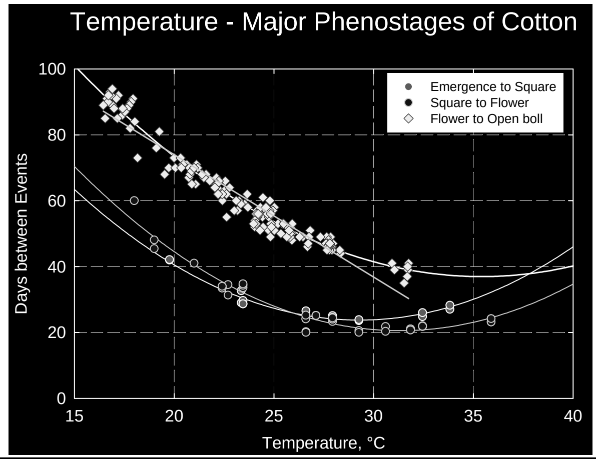
Schematic Representation of Cotton Plant Development

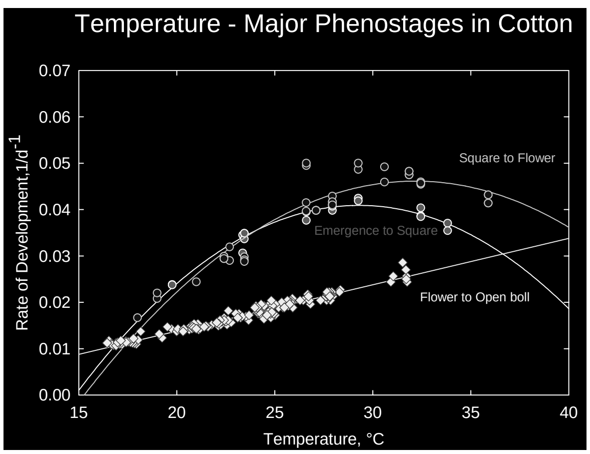
Temperature - Phenology

Emergence to Squaring - Species Variation









Parameters for quadratic equations regressing daily developmental rates of major cotton phenological events (y) as functions of average temperature (x), and correlation coefficients (r^2).

$$(y = a + bx \text{ or } y = a + bx + cx^2)$$

Event	Regression parameters a	b	c	r^2
Seed to germination	-0.9228	0.0931	-0.001528	0.92
Seed to emergence	-0.3158	0.0319	-0.0005228	0.92
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	0.000995	--	0.92

An example of how to calculate time to 1st square formation in cotton from a changing average temperature is shown. The daily development (Y) for cotton plants to reach 1st square from emergence can be calculated as a function of temperature (X) as follows: Daily developmental rate.

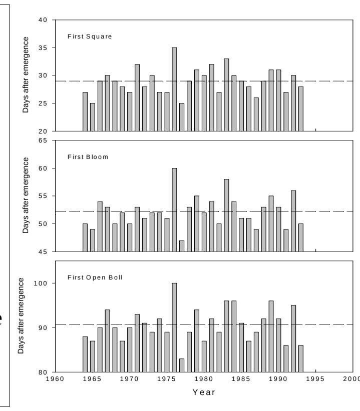
$$Y = - 0.1265 + 0.01142 * X - 0.0001949 * X^2, r^2 = 0.95.$$

Days Since emergence	Average Temperature, °C	Days to 1st square at that temp.	Daily developmental rate	Cumulative value
1	22	32.89	0.030408	0.030408
2	18	62.85	0.015912	0.046320
3	14	Below the threshold temperature	No development	0.046320
4	20	41.77	0.02394	0.070260
n				1.0 or >1.0

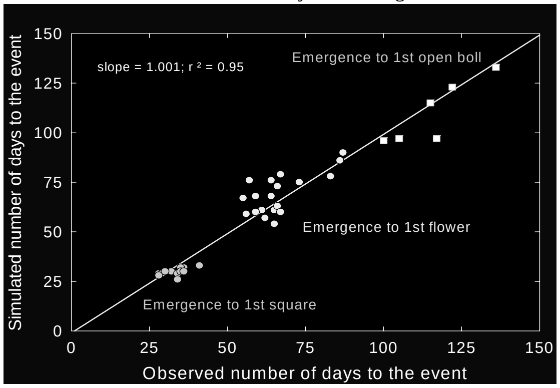
EPI – Phenology – Variability - Different Years

EPI – Phenology:

- Using the functions described earlier, the simulated dates of major phenological events for cotton for 30 years.
- Notice year-to-year variability in days for major phenological events caused by variation in temperature conditions during those stages of crop development.



Applying Environmental Productivity Index to Crop Phenology
Observed vs. Simulated – Major Phenological Events



Temperature – Phenology – Growing Degree-day Concept

- Heat units, expressed in growing degree-days (GDD), are frequently used to describe the timing of biological processes.
- The basic equation used is:

$$GDD = [(T_{max} + T_{min})/2 - T_{base}]$$

Where T_{max} and T_{min} are daily maximum and minimum air temperatures, respectively, and T_{base} is the base temperature for a given developmental event or process of a crop where the development is zero.

Temperature – Phenology – Growing Degree-day Concept

- Two methods or interpretations have been reported in the literature.

Method 1:

GDD = [(maxT + minT)/2 – Tbase]

If [(maxT + minT)/2] <Tbase, then [(maxT + minT)/2] = Tbase

This approach seems to the most widespread method used for calculating GDD in small grain crops such as wheat, barley and several other crops.

Notice that the comparison to Tbase occurs after calculating avgT.

Temperature – Phenology – Growing Degree-day Concept

Method 2:

GDD = [(maxT + minT)/2 – Tbase]

where if maxT <Tbase, then maxT = Tbase,

and if minT <Tbase, then minT= Tbase.

Some times a variation of method 2 is also used:

GDD = [(maxT + minT)/2 – Tbase], where if minT <Tbase, then minT = Tbase.

Notice that the comparison to Tbase is made before calculating avgT by comparing maxT and minT or minT to Tbase individually.

This approach has also been used to calculate GDD in crops such as corn as well as in other crops.

Temperature – Phenology – Growing Degree-day Concept

- Not recognizing the discrepancy between methods can result in confusion and add error in quantifying relationships between heat unit accumulation and timing of biological events in crop development.
- Therefore, when describing and presenting the data on GDD's, description of method used and the base temperature are very important so that others can correctly interpret and apply reported results in their situation.

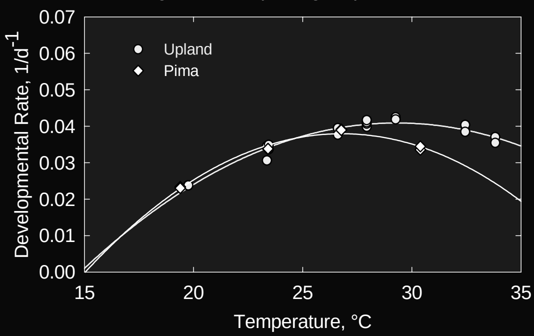
Reference: McMaster, G. S. and W. W. Wilhelm. 1997. Growing degree-days: one equation, two interpretations. Agricultural and Forest Meteorology 87: 291-300.

Temperature – Phenology

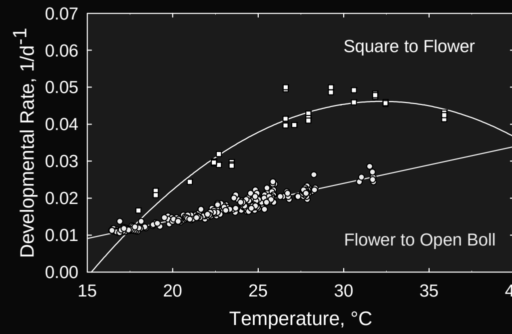
Can We Apply Growing Degree Days (GDD) Concept to Upland Cotton at a Range of Temperatures?

Event	GDD from a 12 ^{o}C
Emergence to square	380
Square to Flower	392
Flower to open boll	730
Open boll to crop maturity	392
Emergence to crop Maturity	1894

Temperature - Phenology
Emergence to Squaring - Species Variation



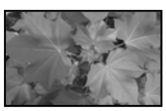
Temperature - Phenology
Square to Flower, Flower to Open Boll



Crop Phenology
Phyllochron intervals – Mainstem and branches

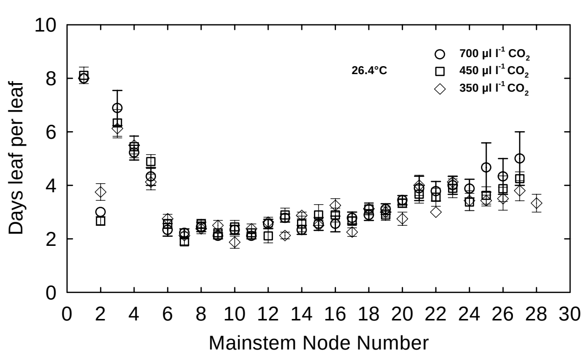
Developing mainstem and fruiting branch nodes and leaves are important aspects of overall crop development because these developmental aspects determine the number of leaves produced, and thus canopy development and light interception, particularly prior to canopy closure.

In cotton, phyllochron is defined as the day when 3 main veins appear clearly on an unfolding leaf. Defined in this way, leaf appearance or phyllochron can be used as discrete event.

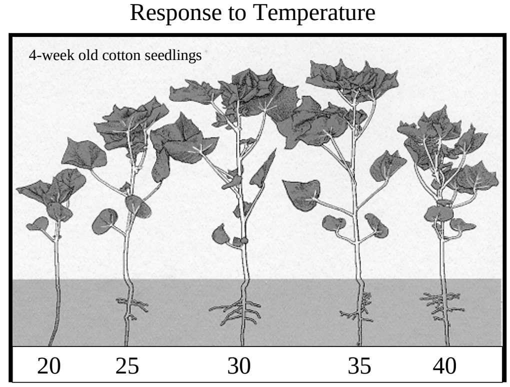



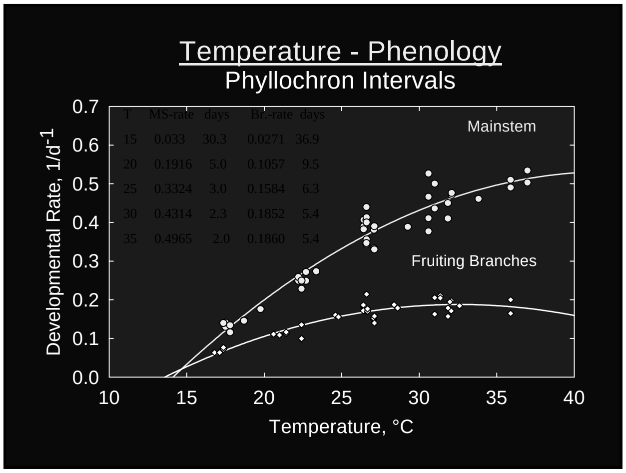

Cotton Developmental Aspects

Crop Phenology – Pre-squaring, Flowering and Post-Flowering Leaf Developmental Rates: Cotton



Crop Growth and Development - Environment
Response to Temperature





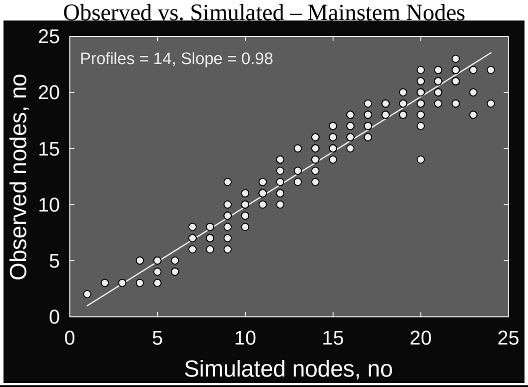
Parameters for quadratic equations regressing daily leaf developmental rates of mainstem or branches (y) for cotton as functions of average temperature (x), and correlation coefficients (r^2).

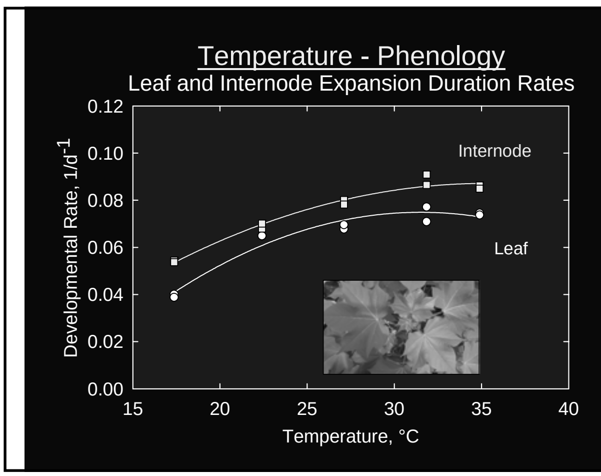
$(y = a + bx + cx^2)$

Event	Regression parameters a	b	c	r^2
Mainstem leaves	-0.6698	0.05700	-0.0006765	0.94
Branch leaves	-0.3645	0.03389	-0.00051890	0.84

Applying Environmental Productivity Index to Crop Phenology

Observed vs. Simulated – Mainstem Nodes





Parameters for quadratic equations regressing daily leaf area expansion or internode elongation duration rates (y) for cotton as function of average temperature (x), and correlation coefficients (r^2).

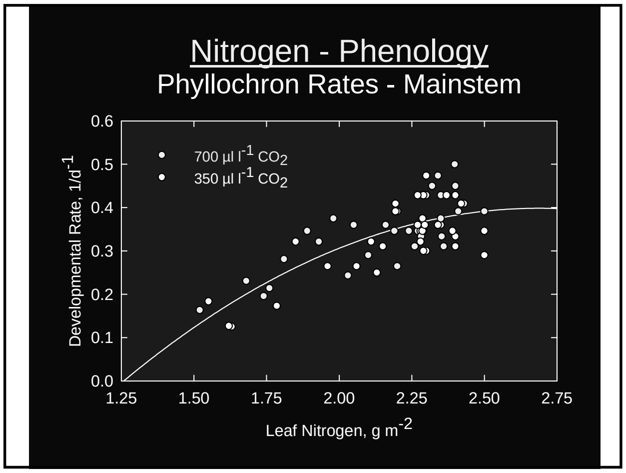
$(y = a + bx + cx^2)$

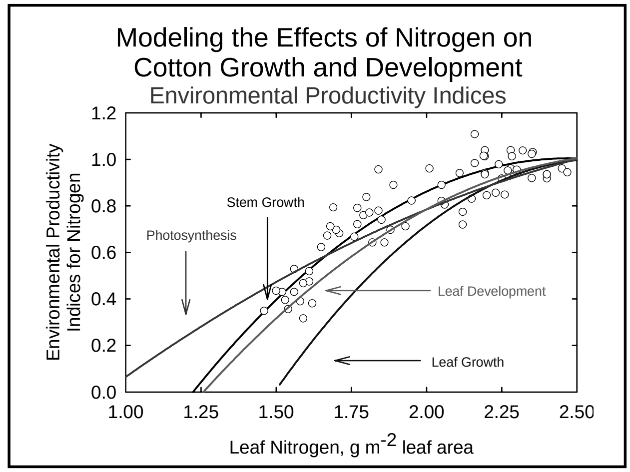
Event	Regression parameters a	b	c	r^2
Leaves	-0.09365	0.01070	-0.0001697	0.95
Internodes	-0.04312	0.007383	-0.0001046	0.96

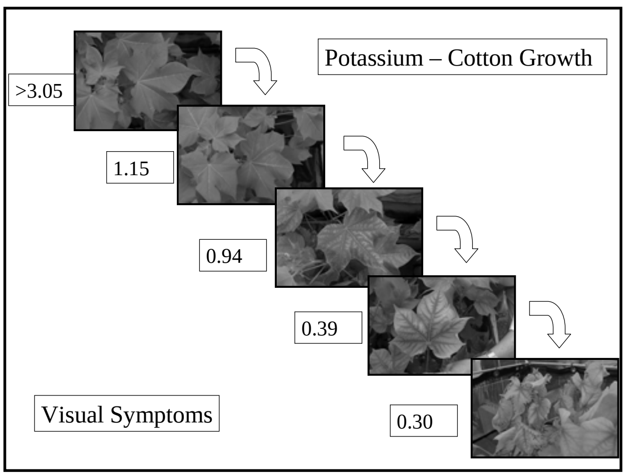
Cotton Phenology – Potential Rates

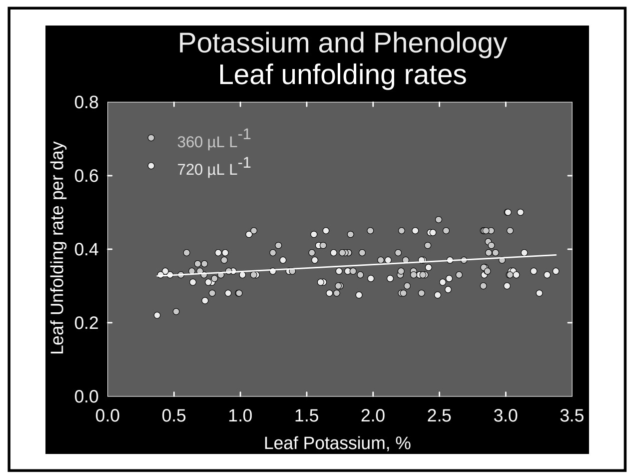
$Y = a + bx$ or $a+bx+cx^2$

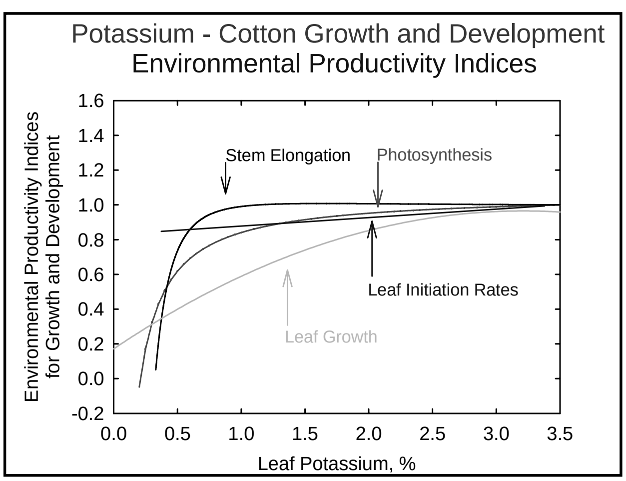
Seed to emergence:	a	b	c	r^2
Max. seed GR	-125	15.391	- 0.2862	0.79
Seed to germination	-0.9228	0.0931	-0.001528	0.92
Seed to emergence	-0.3158	0.0319	-0.0005228	0.92
Major life cycle events:				
Emergence to square	-0.1265	0.01142	-0.0001949	0.98
Square to flower	-0.1148	0.00967	-0.0001432	0.94
Flower to open boll	-0.00583	0.000995	--	0.92
Leaf addition rates:				
Mainstem Leaves	-0.6698	0.05700	-0.0006765	0.94
Branch leaves	-0.3645	0.03389	-0.00051890	0.84
Leaf and internode expansion duration rates:				
Leaves	-0.09365	0.01070	-0.0001697	0.95
Internodes	-0.04312	0.007383	-0.0001046	0.96

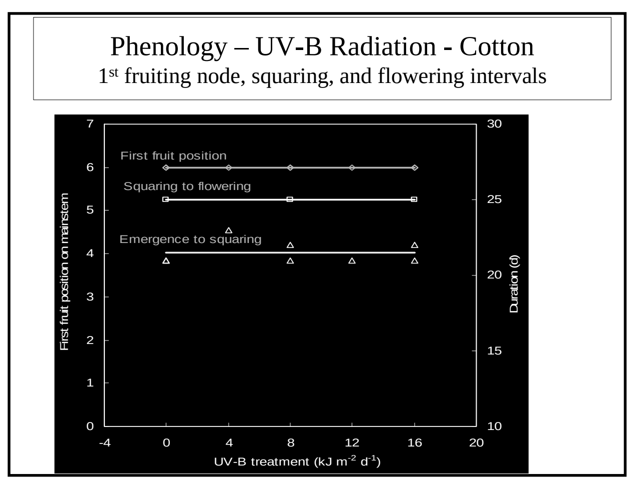

Nitrogen - Phenology
Phyllochron Rates - Mainstem
700 µl l-1 CO2
350 µl l-1 CO2
Developmental Rate, 1/d-1
Leaf Nitrogen, g m-2


Modeling the Effects of Nitrogen on Cotton Growth and Development
Environmental Productivity Indices
Environmental Productivity Indices for Nitrogen
Stem Growth
Photosynthesis
Leaf Development
Leaf Growth
Leaf Nitrogen, g m-2 leaf area

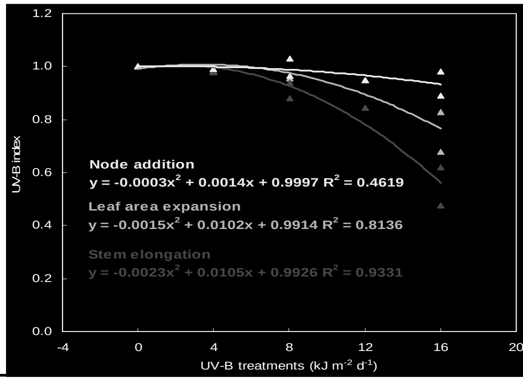

Potassium – Cotton Growth
>3.05
1.15
0.94
0.39
0.30
Visual Symptoms


Potassium and Phenology
Leaf unfolding rates
360 µL L-1
720 µL L-1
Leaf Unfolding rate per day
Leaf Potassium, %

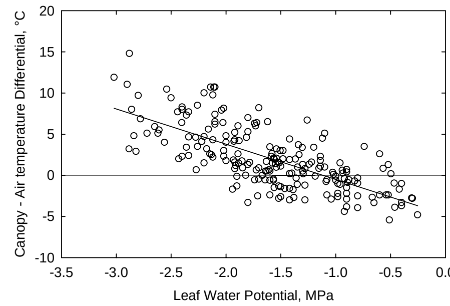

Potassium - Cotton Growth and Development
Environmental Productivity Indices
Environmental Productivity Indices for Growth and Development
Stem Elongation
Photosynthesis
Leaf Initiation Rates
Leaf Growth
Leaf Potassium, %


Phenology – UV-B Radiation - Cotton
1st fruiting node, squaring, and flowering intervals
First fruit position
Squaring to flowering
Emergence to squaring
First fruit position on mainstem
Duration (d)
UV-B treatment (kJ m-2 d-1)

UV-B Radiation – Phenology
EPI Factors for various Developmental Processes



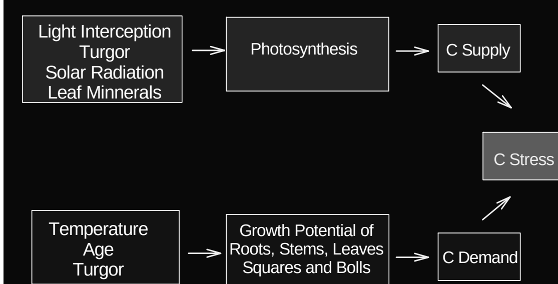
Water Stress – Phenology
Canopy and air temperature differential



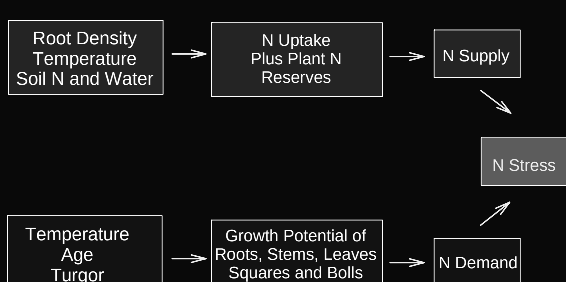
Environmental and Cultural Factors Influencing Crop Growth

- ◆ Atmospheric Carbon Dioxide (indirect)
- ◆ Solar Radiation (indirect)
- ◆ Photoperiod (direct effect on photoperiod-sensitive plants - flowering)
- ◆ Temperature (direct)
- ◆ Water (indirect)
- ◆ Wind (indirect)
- ◆ Nutrients (N, P and K) (direct & indirect)
- ◆ Growth Regulators (PIX) (indirect)

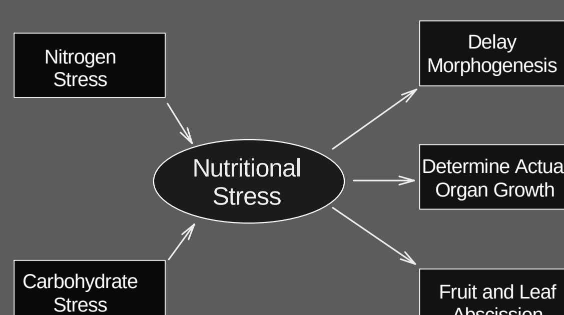
Carbohydrate Stress



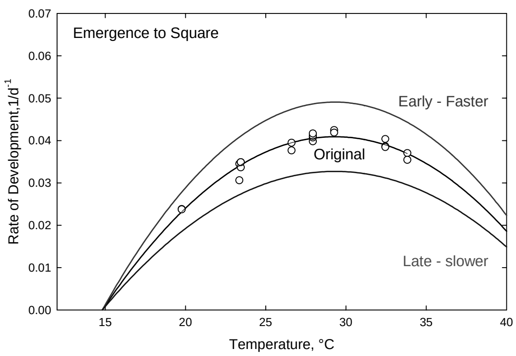
Nitrogen Stress



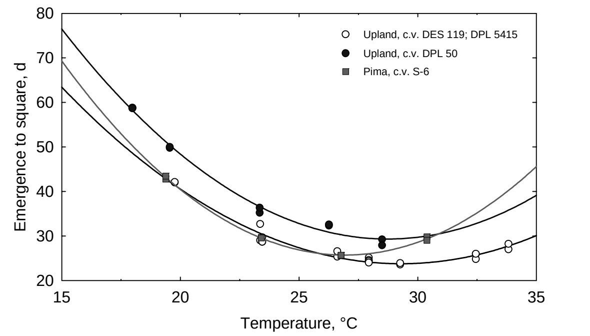
Nutritional Stress



Phenology and Developmental Rates
Dealing with cultivar variability



Temperature and Phenology
Emergence to Square - Species and Varietal Variability



Crop Phenology – Summary

- ✓ Phenology refers to the development, differentiation, and initiation of organs. It involves both like (adding leaves on mainstem and branches) and unlike events such as seed to germination, germination to emergence, emergence to square, square to flower, flower to open boll, and open boll to crop maturity) events.
- ✓ Phenological events respond to the environment in a programmable manner, and therefore the events are predictable – can be modeled.
- ✓ Phenology involves qualitative changes in form, structure, and general state of complexity of the plant.
- ✓ Major phenological events such as emergence to square, square to flower and flower to open boll are all temperature dependent and are not typically affected by other environmental factors in photoperiod insensitive crop such as modern cultivated cotton cultivars grown in the US.

Crop Phenology – Summary

- ✓ Therefore, we can estimate these events more accurately by temperature alone. However, any factor that that affects canopy temperature such as water stress can modify these events or response functions.
- ✓ Seed germination and emergence will not only dependent on temperature, but also on other factors such as soil moisture, seed placement (depth) etc.
- ✓ Also, photoperiod in day-length sensitive plants such as soybean can affect flowering, but not the other events.
- ✓ Phyllochron or leaf addition rates on the mainstem and branches are primarily governed by temperature, but modulated by other factors such as UV-B, water stress, nutrient stresses through their effects on photosynthesis (Supply) and growth conditions such as weight and sizes of various organs (that determine demand).

Crop Phenology – Summary

- ✓ Therefore, we can estimate the potential as a function temperature under optimum growing conditions, and then modify that potential based on EPI factors or demad/suppy concept.
- ✓ Again, leaf addition rates go hand-in-hand with internode addition rates on mainstem and branches.
- ✓ Leaf and square addition rates on fruiting branches go hand-in-hand so that we can use one function to predict those events.
- ✓ Once the leaves and internodes are initiated, then their duration of expansion are more or less dictated temperature independent of position the plant
- ✓ Similarly, once the squares are formed, then their duration of growth are dependent on temperature conditions.

Crop Phenology – Summary

- ✓ Accurate prediction of crop developmental events will assist farm managers in adjusting sowings of the crop so that the most critical stages of crop growth occur during periods of favorable weather.
- ✓ Also, accurate prediction crop growth stages is also needed for several other management decisions such as scheduling water, nutrient, pesticide, growth regulator, crop termination chemical applications, etc.
- ✓ Crop simulation models need accurate functional algorithms so that the models can be used for several different area:
  - ✓ Crop growth stage forecasts
  - ✓ Management and policy decisions
  - ✓ Natural resource management decisions
  - ✓ Climate change forecasts, etc.

Crop Phenology – Suggested Reading

- ✓ Reddy, K. R., H.F. Hodges and J. M. McKinion. 1997. Crop modeling and applications: A cotton example. Advances in Agronomy, 59: 225-289.
- ✓ Oosterhuis, D.M. J. Jernstedt. 1999. Morphology and anatomy of cotton plant. In: Cotton: Origin, History, Technology, and Production, W.C. Smith (Ed.) John Wiley & Sons, Inc. pp. 175-206.
- ✓ Plant growth Modeling for Resource Management, Vol 1. Current Models and Methods, 1987, K. Wisol and J. D. Hesketh (Eds.), CRS Press, pp. 170.
- ✓ Plant Growth Modeling for Resource Management, Vol II. Quantifying Plant Processes. 1987. K. Wisol and J. D. Hesketh (Eds.), CRC press, pp. 178.
- ✓ Predicting Crop Phenology. 1991. T. Hodges (Ed.), CRC Press. Pp. 233.