AgRISTARS

SR-L9-00409
JSC-16088

80-10093
NASA CR-
160469

FEB 6 1980

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A Joint Program for
Agriculture and
Resources Inventory
Surveys Through
Aerospace
Remote Sensing

Supporting Research

November 1979

TECHNICAL REPORT

CROP PHENOLOGY LITERATURE REVIEW FOR CORN, SOYBEAN, WHEAT, BARLEY, SORGHUM, RICE, COTTON, AND SUNFLOWER

T. Hodges and P. C. Doraiswamy

(E80-10093) CROP PHENOLOGY LITERATURE REVIEW FOR CORN, SOYBEAN, WHEAT, BARLEY, SORGHUM, RICE, COTTON, AND SUNFLOWER (Lockheed Electronics Co.) 90 p HC A05/MF A01 CSCL 02C G3/43

N80-23720

Unclas 00093

NASA

LOCKHEED ELECTRONICS COMPANY, Inc.
1830 NASA Road 1, Houston, Texas 77058

SR-L9-00409
JSC-16088

TECHNICAL REPORT

CROP PHENOLOGY LITERATURE REVIEW FOR CORN, SOYBEAN, WHEAT, BARLEY, SORGHUM, RICE, COTTON, AND SUNFLOWER

Job Order 73-312

This report describes Vegetation/Soils/Field Research activities of the Supporting Research project of the AgRISTARS program.

PREPARED BY

T. Hodges and P. C. Doraiswamy

APPROVED BY

Dale E. Phinney
D. E. Phinney, Supervisor
Agriculture Technology Section

Dale E. Phinney
For J. E. Wainwright, Manager
Development and Evaluation Department

LOCKHEED ELECTRONICS COMPANY, INC.
Under Contract NAS 9-15800

For

Earth Observations Division
Space and Life Sciences Directorate
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

November 1979

LEC-13722

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1. INTRODUCTION

The Agricultural and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) is a 6-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources beginning in fiscal year (FY) 1980. The AgRISTARS program is a cooperative effort of the National Aeronautics and Space Administration (NASA), the U.S. Agency for International Development (AID), and the U.S. Departments of Agriculture, Commerce, and the Interior (USDA, USDC, and USDI).

The goal of the program is to determine the usefulness, cost, and extent to which aerospace remote sensing data can be integrated into existing or future USDA systems to improve the objectivity, reliability, timeliness, and adequacy of information required to carry out USDA missions. The overall approach is comprised of a balanced program of remote sensing research, development, and testing which addresses domestic resource management as well as commodity production information needs.

The technical program is structured into eight major projects as follows:

1. Early Warning/Crop Condition Assessment (EW/CCA)
2. Foreign Commodity Production Forecasting (FCPF)
3. Yield Model Development (YMD)
4. Supporting Research (SR)
5. Soil Moisture (SM)
6. Domestic Crops and Land Cover (DCLC)
7. Renewable Resources Inventory (RRI)
8. Conservation and Pollution (C/P)

The majority of these projects will make direct use of information on crop phenology. Specific areas of these projects to which phenological information is pertinent include classification, acreage and yield estimation, and detection of episodal events.

This report is a review of technical literature pertaining to the effects of environmental and cultural factors on the phenological development of corn, soybean, wheat, barley, sorghum, rice, cotton, and sunflower. These crops have been identified as ones of primary interest during the formative stages of the AgRISTARS program. A similar report by Doraiswamy and Hodges (ref. 1) deals with the effect of environmental and cultural factors on yield for these crops.

Prediction of crop growth stages (phenology) may be achieved through three independent methods: calculating historical averages for an area (normal crop calendar); agrometeorological modeling from knowledge of crop-weather interactions; and detecting changes in multitemporal spectral signatures throughout the growing season. This report will focus on the agrometeorological modeling problem. The use of remotely sensed data is examined in a report by Cate et al (ref. 2).

The intent of this report is to go beyond a simple citation of literature. A general framework is presented within which a critical evaluation of past work is carried out. Strengths and weakness of individual models are identified to gain insight into the areas which need additional developmental work.

The problem of modeling crop phenology is presented in a generalized way as a component of the plant/soil/atmosphere system in section 2. Details of major environmental, cultural and genetic factors are discussed in section 3. A description of each crop and the associated crop growth scales for each are given in the following section. Section 5 presents several generalized modeling approaches and a historical review of modeling attempts for each crop. The most promising models for each crop (if any) are summarized in section 6. The final section gives recommendations on desirable modifications and on needed evaluation tests.

2. MODELING CROP PHENOLOGY

Although many crop phenology models fail to fit neatly into any one type, most may generally be classified as one of the following types.

a. Statistical models — use the least squares technique to choose variables and significant interactions and to evaluate coefficients

b. Realistic physiological models — involve detailed simulation of many plant process [Plant physiological theories are used to choose variables and interactions, and experimental data are used to evaluate coefficients (ref. 3).]

c. General physiological models — involve simulation of a few plant processes from a few variables based on physiological principles and theories with experimental data used to evaluate coefficients

These three basic model types may be evaluated for the AgRISTARS program. Statistical models include models by Robertson, Haun, Coligado, (refs. 4-6). Although these models are easier to develop than are physiological models, their development requires many years or points of data, and they are dependable only within the range of conditions in the developmental data set. Because most meteorological variables are highly intercorrelated, statistical models include variables and interactions which do not directly affect the modeled response.

Of the three model types, realistic physiological models are the most laborious to develop and test (ref. 7). Their primary application is in evaluating plant physiological theories (ref. 3). Although sophisticated field input data requirements for verification and operation make this type of model unsuitable for estimating large area crop growth, some realistic models may be simplified into general physiological models. Realistic models have been developed by de Wit, Duncan, Stewart, Monteith, et al. (refs. 8-11).

General physiological models may be simplified from realistic physiological models or be based on experimental data for a few key physiological processes (ref. 3). This model type includes a wide range of models (refs. 12-16) and has greater potential for accuracy and stability over a wider range of environmental conditions than have statistical models.

Figure 2-1 shows an overview developed by the authors to discuss how crop phenology is controlled by meteorological variables, varieties, planting date, day length, and soil nutrient supply. The planting date begins the crop growth cycle. Day length causes a varietal photoperiod response. Temperature and precipitation (and solar radiation and soil factors, not shown) control the amount of soil moisture available to the crop. Soil nutrient supply and available soil moisture interact to supply the crop with minerals; and temperature, modified by soil moisture and variety, causes a thermal response.

For a statistical model, the above-mentioned variables as well as other correlated variables such as solar radiation, rain days, average rainfall or temperature in various months and number of days from planting to emergence are regressed against days between various growth stages. Products of two or more terms and even quadratic or cubic variables may be added to the model. If the range of conditions is not too extreme, the resulting equation will accurately predict stages both in the development data set and in other data sets in a similar environment.

For a realistic physiological model, one might grow the plant at the organ level (e.g., leaves, roots, stems, or flowers) or for some processes at the cellular level (e.g., floral initiation). The output of such a model may be used to evaluate the theories of plant physiology on which the model is based.

For a general physiological model, one might derive equations for the phenological response to photoperiod and temperature from growth chamber data for different maturity groups of a crop. These equations should describe the photoperiod-temperature response over a wide range of conditions. Other equations would describe the soil moisture effect on temperature and the soil nutrient effect on phenology.

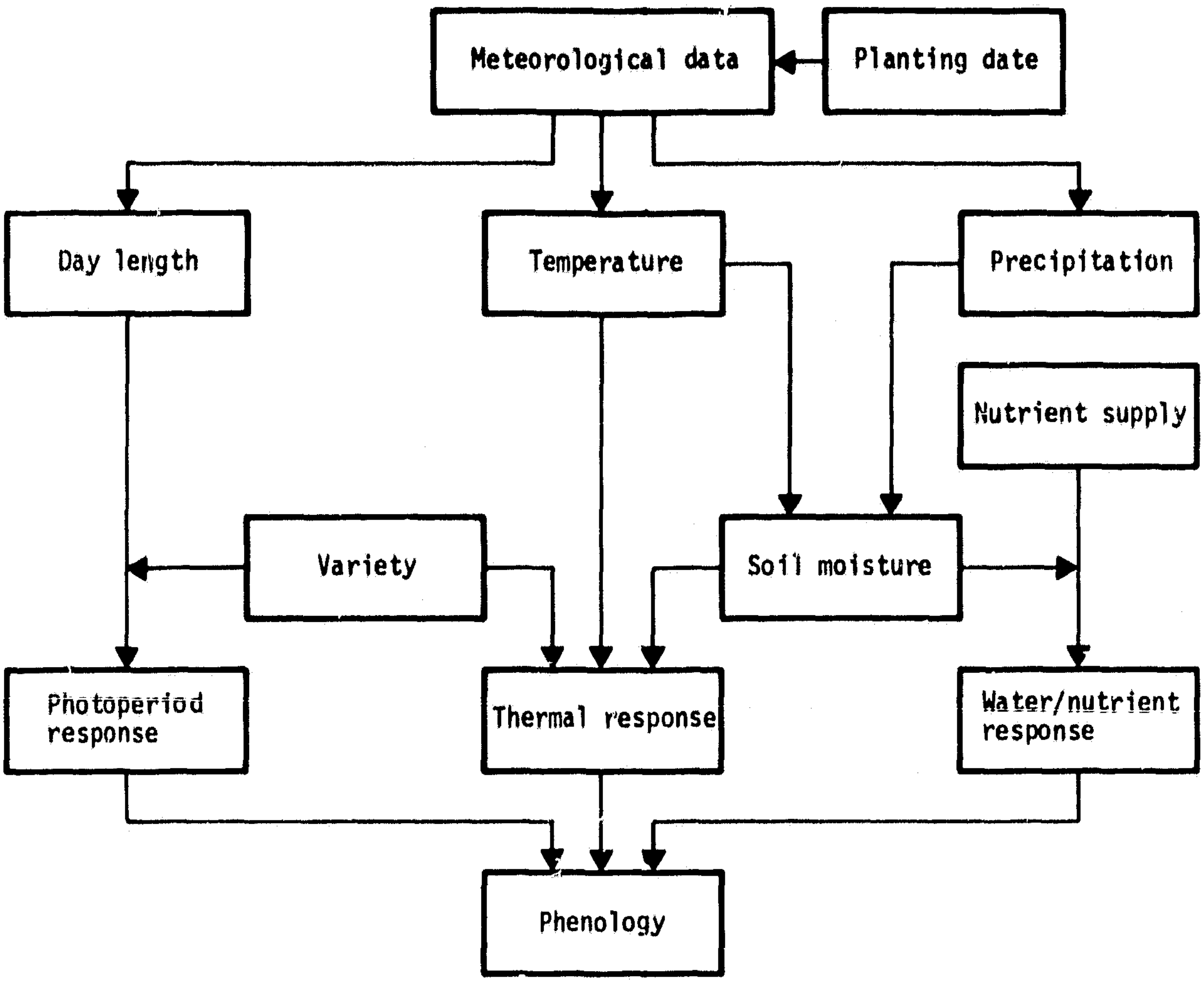


Figure 2-1.— Major factors influencing crop development.

3. CROP PHENOLOGY

The principal variables controlling crop phenology are planting date, day length, temperature, and plant genetic component. In some situations, moisture supply and nutrient availability may also strongly affect phenology.

3.1 PLANTING DATE

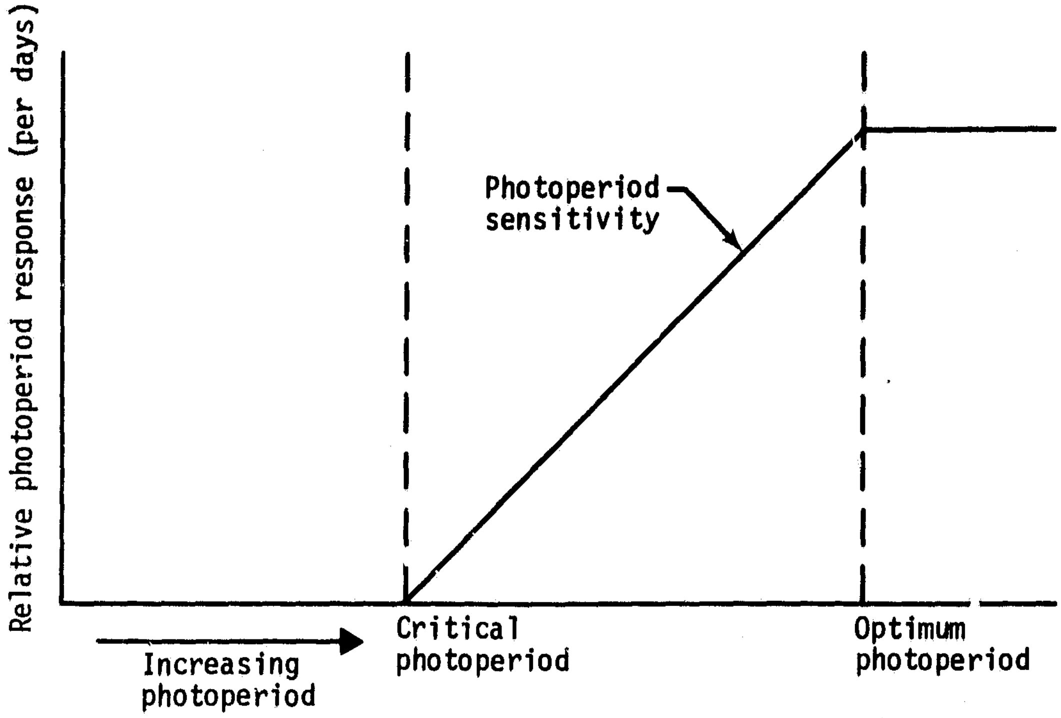
Planting date starts the biological clock by determining the meteorological influences to which the plant will actually be subjected. Planting date is influenced by meteorological, social, and economic factors, as well as by idiosyncrasies of individual farmers.

3.2 PHOTOPERIOD

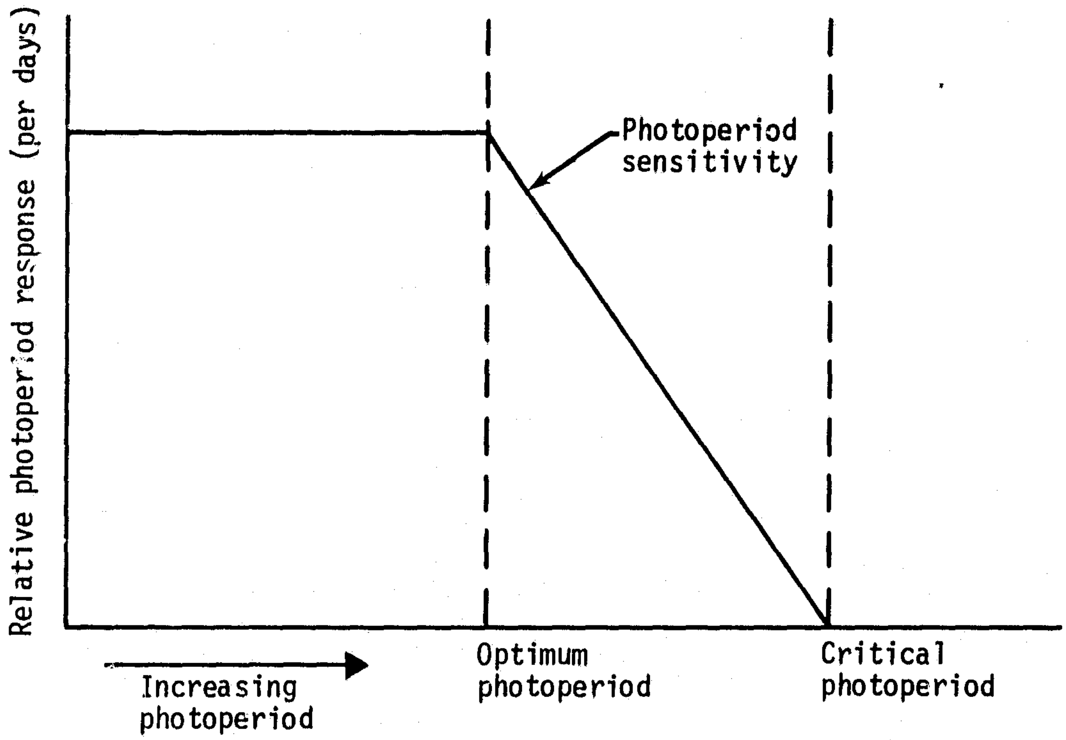
The response of plant phenology to day length is called photoperiodism. In 1920, Garner and Allard (ref. 17) became the first to study the photoperiod effect on flowering of plants. Subsequently, it was found that photoperiod influences not only the formation of flowers, fruit, and seeds but also the character and extent of branching, leaf abscission, pubescence, root development, dormancy, fruit ripening, senescence, and other morphological phenomena. The influence of photoperiodism on phenology is reviewed by Major and Johnson (ref. 18), Blondin et al. (ref. 19), and Vergara et al. (ref. 20).

Flowering is the major crop response to photoperiod. In terms of a normal 24-hour day-night cycle and ignoring complexities revealed by growth chamber studies which consider longer or shorter day-night cycles (ref. 21), it may be said that plants respond to photoperiods that are shorter or longer than some genetically determined photoperiod length; i.e., short-day plants and long-day plants. [See figure 3-1 (ref. 22) and the following discussion.]

For a qualitatively photoperiod sensitive plant if the photoperiod is longer (for a short-day plant) or shorter (for a long-day plant) than the critical photoperiod, no photoperiod response occurs and the plant does not flower (ref. 18), while for a quantitatively photoperiod sensitive plant flowering is delayed.



(a) Long-day plant.



(b) Short-day plant.

Figure 3-1.— Number of days required for the plant to reach some stage as a function of photoperiod for long-day (a) and short-day (b) plants. (From reference 22.)

If the photoperiod is shorter (for a short-day plant) or longer (for a long-day plant) than the optimum photoperiod, the plant flowers independently of photoperiod length (ref. 18), unless the photoperiod is so short that the photosynthate supply limits growth and delays development (ref. 23).

If the photoperiod is between the critical and the optimum lengths, flowering occurs more rapidly as the photoperiod length extends from the critical to the optimum length (ref. 18). The rate of increase in development rate as the photoperiod changes from the critical to the optimum photoperiod lengths defines the photoperiod sensitivity.

Short day and long day are poor terms for this phenomenon because some short-day varieties of corn may have a longer critical day length than some long-day varieties of winter wheat.

For domesticated crop plants, the photoperiod response may be more complex. Development in some varieties seems independent of day length (ref. 24), at least in areas where such varieties have been adapted. This is because the photoperiod is either longer (long-day plant) or shorter (short-day plant) than the optimum photoperiod or because the photoperiod sensitivity of the variety is low.

Several consecutive phenological events may have different photoperiod requirements. Thus, the minimum number of photoinductive cycles (days) to initiate floral development in some rice varieties is insufficient to cause stem elongation, so several additional cycles are needed to cause head emergence (ref. 20). Auxin may cause head emergence without additional photoinductive cycles (ref. 25).

Once the photoperiod induction requirement is satisfied by a specific day length for a given number of days, the phenological process is initiated and continues irrespective of change in day length.

The influence of day length on plant development is often modified and at times inhibited by other environmental factors, particularly temperature. Many plants do not respond to critical photoperiods unless their thermal requirements are met (ref. 26). Biennial plants such as winter cereals fail to flower until they pass through a period of low temperature (vernalization). Also, there are critical temperatures below which a plant will not flower even though the day length requirement is satisfied. Certain plants may be induced to flower by substituting a thermal response for the photoperiodic response (ref. 19).

3.2.1 FLOWERING RESPONSE TO PHOTOPERIOD

Plant growth may be divided into four stages in terms of photoperiod responses: (1) basic vegetative period (bvp) when floral induction and floral initiation (FI) cannot occur, (2) photoperiod sensitive period (psp) when floral induction occurs as soon as light, temperature, and water requirements are met, (3) the reproductive stage from FI to flowering, and (4) the grain filling or ripening stage.

Several possible reasons have been advanced for the existence of the bvp (ref. 27): (1) the first leaves are insensitive to photoperiod, (2) the first leaves are nearly insensitive, so the induction level is not reached until the much more sensitive later leaves are formed, (3) the first leaves senesce before they can induce flowering, (4) the necessary total leaf area is not reached until later leaves emerge, or (5) the growing plant is unable to respond to the floral stimulus, or the stimulus is unable to reach the growing point during early growth. If the bvp is due to one of the above reasons, then it could be shortened by warm temperatures hastening leaf emergence and expansion (reasons 1, 2, 4) or lengthened by warm temperatures hastening leaf senescence (reason 3). If bvp is due to reason 5, its duration could be affected by temperature, intercepted solar radiation, water stress, nutrient uptake (to produce protein or hormone molecules needed for FI), or possibly other factors.

The bvp exists in winter wheat (ref. 28), rice (ref. 20), sorghum (ref. 29), soybean (ref. 18), and possibly cotton (ref. 30). Confirmation of the bvp has not been found in barley, corn, and sunflower. It is apparently not present in some spring wheats (ref. 31). In winter wheat, vernalization ends the bvp. Thereafter, long days and high temperatures induce FI in winter wheat. Both qualitative and quantitative photoperiod sensitive plants may have the psp. In qualitative photoperiod sensitive plants it may last as long as 12 years if the proper photoperiod is not received (ref. 32). In quantitative photoperiod sensitive plants, psp may range from zero days up to 30 days.

Many plants are sensitive to extremely small differences in daylength. Thus in Malacca, where daylength varies by only 14 minutes, days from planting to flowering for Siam-29 varies by up to 168 days, depending on date of planting (ref. 33).

For sunflower (ref. 19) and cotton (ref. 34), an appropriate temperature treatment may be substituted for a photoperiod treatment to induce floral initiation and flowering.

3.3 AIR TEMPERATURE

Generally, air temperature affects the rate of plant development (ref. 21) as shown in figure 3-2 (refs. 18 and 35). Below some genetically determined temperature, development does not occur. Above that temperature, the development rate increases with temperature until a peak rate or plateau is reached (ref. 36). The dashed line in figure 3-2 is an example of the smooth, continuous curve indicated by the plant's phenological response to photoperiod. This response is often modeled as a quadratic or higher order function. The temperature response may also be a limiting factor or law-of-the minimum type of response (ref. 35) where temperatures above and below the optimum temperature range limit development in a linear fashion; whereas in the optimum temperature range, development proceeds at a maximum rate or is limited by some other

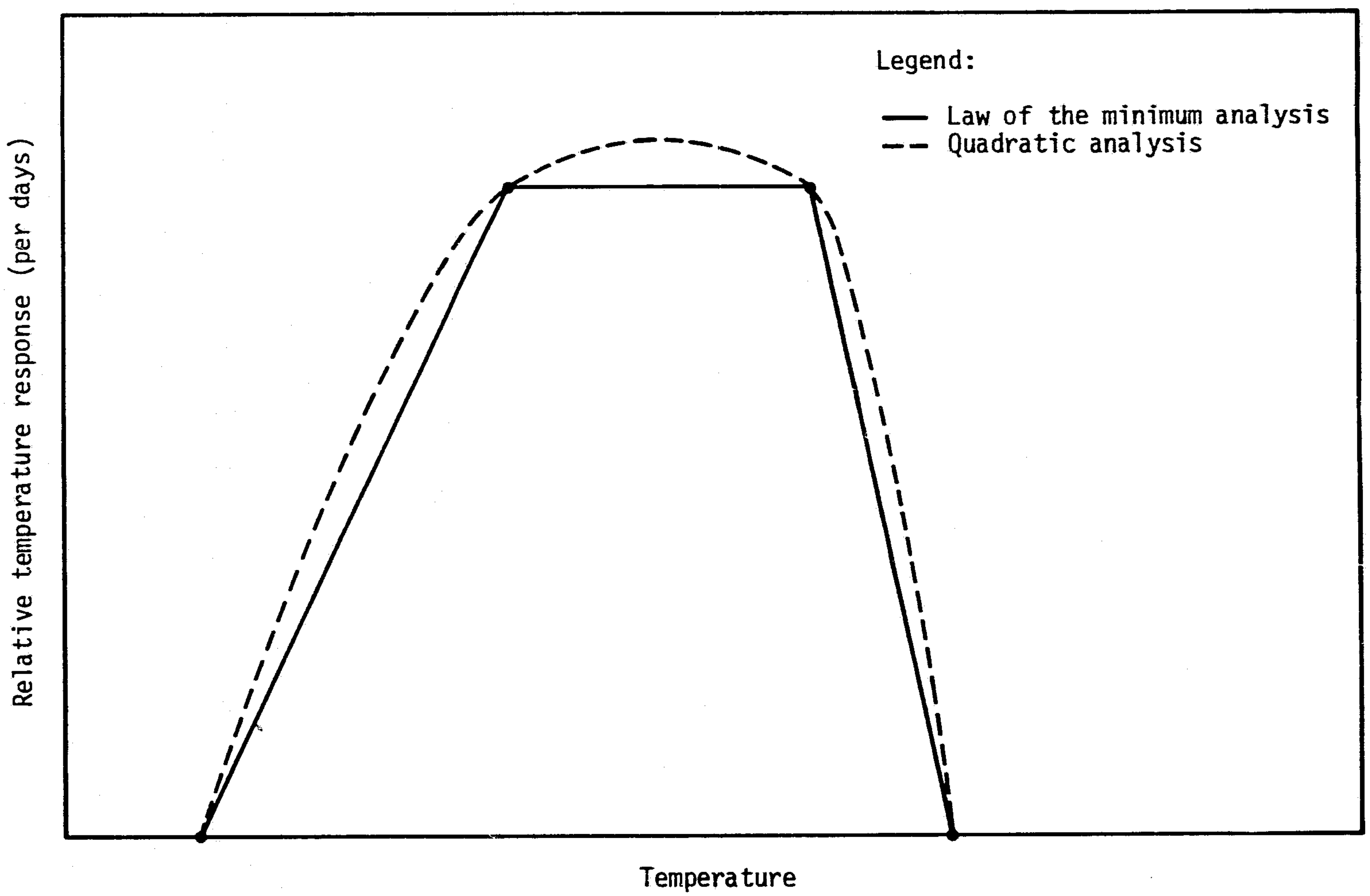


Figure 3-2.— Days for the plant to reach some stage as a function of temperature for a law-of-the minimum analysis and a quadratic analysis. (From references 18 and 35.)

factor. The continuous line in figure 3-2 is an example of this type of response.

In temperate zone plants, such as small grains, high temperature accelerates the development rate and results in a small mature plant. In plants of tropical origin, however, high temperature affects growth more than it affects development, resulting in a large mature plant at an earlier date.

3.4 THERMOPERIODICITY

One of the objections to the use of degree-day (DD) models is that they do not take into account the diurnal temperature regime known as the thermoperiod. Phytotron experiments have demonstrated that the development of certain plants depends on the diurnal temperature range (ref. 37) rather than on the mean daily temperature (ref. 26). For example, high night temperatures accelerate vegetative growth of tomatoes but inhibit flower size and fruit development. In many plants, translocation is found to increase with decreasing temperature to some minimum temperature (ref. 38). The quality of fruit and seed is often affected by thermoperiodicity. Such is the case in Hawaii, where the highest quality sugarcane juice is associated with low night and high day temperatures (ref. 39).

3.5 VERNALIZATION

Biennial plants require a period of cold before floral initiation can be induced by day length (ref. 19). Flowering of winter wheat and winter barley is delayed or prevented in a continuously warm climate (ref. 28). A few weeks of near-freezing weather in winter prepares the plant for floral induction by longer spring days. Spring-planted grains and wheat grown in semitropical or tropical regions have little or no vernalization requirement (ref. 31). A study of Australian wheat varieties found a wide range of responses to vernalization and photoperiod (ref. 40).

3.6 SOIL TEMPERATURE

From planting to emergence, the plant is affected by soil temperature rather than air temperature. After emergence, however, the plant is increasingly affected by air temperature, although air temperature remains a secondary influence until the plant's apical meristem is above ground. (Soybean is an exception to this pattern because at emergence the apical meristem is above ground and air temperature begins to have a primary effect on its growth.) After the apical meristem is above ground, the effect of soil temperature decreases sharply.

3.7 SOIL MOISTURE

Severe water stress delays development of crop plants capable of suspending growth, and kills plants incapable of becoming dormant. This dormancy effect has been reported for barley (refs. 41 and 42) and sorghum (ref. 43). For sorghum, a 10-day wilting period before floral initiation was reflected in a 10-day delay in flowering. Stress after floral initiation of 14, 21, and 28 days delayed flowering by 10, 24, and 30 days. Water stress of sorghum just before floral initiation reduced the number of leaves initiated, suggesting a time lag between floral induction and floral initiation during which additional leaves are initiated if no water stress occurs.

Water stress has also been reported to delay floral initiation of corn, but the degree of water stress was not well defined (refs. 41 and 44).

Moderate water stress reduces transpiration and so increases leaf temperature (ref. 45) which may speed up or slow down plant development (see section 3.3).

Excess water reduces soil temperature variability and also reduces soil oxygen supply and so may delay development or injure the plant.

3.8 NUTRIENT EFFECTS

Soil nutrients, the effects of which can be discovered only through carefully controlled experiments, may affect plant development and yield in a wide variety of ways. For example, excess nitrogen accelerates vegetative growth and inhibits flowering of many crops, while excess phosphorus accelerates development (ref. 46).

3.9 VARIETAL EFFECTS

Over thousands of years, the main crop plants have been bred into many varieties which now have a wide range of responses to factors mentioned in sections 3 through 3.8. Thus, in the Northern Hemisphere, corn is found from Canada (latitude 58° N.) to the Tropics, from sea level to an altitude of 4000 meters, and in growing seasons which range from 50 to 330 days (ref. 47). Wheat varieties grow from latitude 66° N., throughout the temperate regions, to the equatorial highlands of Kenya and Ecuador (ref. 47). Barley and soybeans are less widely adapted and are not found in extremely low or extremely high latitudes, respectively.

4. DESCRIPTION OF CROPS

4.1 CORN

Corn is a tropical C_4, warm season, short-day, cereal grass. Highest corn yields are in areas with irrigation, high solar radiation, hot days, and cool nights.

Some researchers have reported day-neutral varieties of corn (refs. 18 and 24). Such varieties may be qualitative short-day plants with an optimum day length which is longer than that of experimental conditions, or they may be quantitative, short-day plants with very low photoperiod sensitivity.

Although corn varieties are adaptable to a wide range of latitudes and altitudes, they grow best in a mean temperature of 21° C. Development is hastened and yield is reduced in areas where the mean temperature is above 27° C. While some varieties are injured by temperatures below 7° C, most can tolerate a light freeze during early vegetative growth (ref. 47).

The flower has separate male and female parts. The male flowers are in the tassel at the top of the plant, while the female flowers are in cobs or ears at nodes along the middle of the stem. Because corn is a short-day plant, adapted corn varieties flower as the days become shorter; i.e., after the summer solstice.

Under moderate water stress, leaf elongation stops. Under more severe water stress, stomata close, transpiration is reduced, and leaf temperature increases above air temperature, which may hasten or delay development.

Because corn has brief stages of floral initiation and anthesis, yield may be reduced by short periods of stress at these stages. However, before floral initiation and while the apical meristem remains below ground, the plant is tolerant of mild frosts.

In 1977, world production of corn was 344 million metric tons, of which 41 percent was produced in the United States. World trade in corn was 64.2 million metric tons, of which 71 percent was produced in the United States (ref. 48).

4.1.1 DEFINITION OF GROWTH STAGES

Hanway (ref. 49) has provided the most complete definition of corn growth stages (see table 4-1). The Hanway scale, however, skips the tassel-initiation stage, which is controlled by day length and temperature. Instead, the Hanway scale defines stages before tassel emergence by number of leaves, which is controlled by temperature, soil moisture, and soil nutrient supply. Also missing from this scale is the tassel-emergence stage, which is primarily controlled by day length, temperature, and water stress.

For yield modeling, important stages are planting, emergence, (Hanway 0), floral initiation, tasseling (Hanway 5), and maturity (Hanway 10). Floral initiation does not correspond to any Hanway stage (see table 4-1) because it is controlled primarily by day length, whereas Hanway stages 1 and 2 are primarily temperature dependent.

For ground observation, the following stages are recommended: Planting, Hanway 0, tassel initiation, Hanway 3, Hanway 4, tassel emergence, Hanway 5, Hanway 9, Hanway 10, and harvest. Stages that are visible from the edge of a field are planting, Hanway 0, tassel emergence, Hanway 5, and harvest. Observation of the other stages is difficult since several plants may need to be cut open for inspection.

4.2 SOYBEAN

The soybean is a temperate, C_3, warm season, short-day legume.

Because it is a legume crop, the soybean has roots which support nitrogen-fixing bacteria, making it a high-protein crop that requires little nitrogen fertilizer (ref. 47).

TABLE 4-1.— CORN GROWTH STAGES

Description of stage			Controlling factors	Yield factors influenced
Number	Hanway	Other[a]		
		Planting	Soil moisture, soil temperature, frost-free date, farmer choice	Plant density, stand quality — starts meteorological variables
0	Emergence		Soil temperature, soil moisture	Stand quality, plants/acre
1	4 leaf		Soil temperature, soil moisture	
		Floral initiation	Day length, soil temperature, soil moisture	Grains/ear, ears/tiller, tillers/plant — hereafter susceptible to frost damage
2	8 leaf		Air temperature, soil temperature, soil moisture	
3	12 leaf		Air temperature, soil moisture	
4	16 leaf		Air temperature, soil moisture	
		Tassel emergence	Day length, air temperature, soil moisture	Very susceptible to temperature stress and water stress
5	Silk emergence and pollen shedding		Day length, air temperature, soil moisture	Grains/ear — very susceptible to temperature stress and water stress
6	Blister		Air temperature, soil moisture	Grains/ear, grain weight — susceptible to water stress
7	Dough		Air temperature, soil moisture	Grain weight — susceptible to water stress
8	Beginning dent		Air temperature, soil moisture	Grain weight — susceptible to water stress
9	Full dent		Air temperature, soil moisture	Grain weight — susceptible to water stress
10	Maturity	Maturity	Air temperature, soil moisture	
		Harvest	Soil moisture, farmer choice	

[a]Stages other than those included in the Hanway scale.

Determinant varieties of the soybean cease vegetative growth at flowering and are usually later than indeterminant varieties which continue vegetative growth during flowering. The soybean is a branching plant with the potential for branches or flowers at each node.

The basic vegetative period (bvp) of the soybean is quite short, possibly less than 10 days from emergence. Flowering can be induced after the full expansion of the primary leaves (first true leaves) although the flower buds require another 20 days of development to become readily visible (ref. 50).

During the photoperiod-sensitive phase, which is usually of indefinite length in the soybean, floral initiation is delayed or prevented and flowering is prevented for most varieties by 16-hour day lengths. Varieties in the high latitude maturity groups (0-III) have long critical photoperiods and greater photoperiod sensitivity than varieties from the intermediate and low latitude groups.

Soil temperatures below 20° C delay germination, but germination does not change with temperatures from 21° C to 32° C. All growth process cease at about 10° C. Young and nearly mature plants can tolerate a light frost. Although temperature above 38° C may not affect development rate, high temperature causes a reduction in seed quality and quantity (ref. 51).

During 1977, world soybean production was 61 million metric tons, of which 57 percent was produced in the United States. World soybean trade was 19.6 million metric tons, of which 83 percent was produced in the United States (ref. 48).

4.2.1 DEFINITION OF GROWTH STAGES

The soybean growth-stage scale which was developed by Fehr and Caviness (ref. 52) is shown in table 4-2. This scale and the Thompson scale (ref. 53) are nearly identical. For yield modeling, important stages are planting, emergence (VE), floral initiation (about 2 weeks before R1), and the stages of flowering and bean filling (R1, R2, R3, R4, R5, R6, and R8). For ground

TABLE 4-2.— SOYBEAN GROWTH STAGES

Description of stage			Controlling factors	Yield factors influenced
Number	Fehr-Caviness	Other[a]		
		Planting	Soil moisture, soil temperature, frost-free date, farmer choice	Plant density, stand quality — starts meteorological variables
VE	Emergence		Soil temperature, soil moisture	Stand quality, plants/area — susceptible to flooding
VC	Cotyledon		Air temperature, soil moisture	Hereafter susceptible to frost damage
VO	Unifoliate leaves developed		Air temperature, soil moisture	
VN	N fully developed trifoliate leaves on nodes of main stem		Air temperature, soil moisture	Nodes/branch, branches/plant
R1	First open flower		Day length, air temperature, soil moisture	Pods/branch, flower and pod abortion — important hereafter
R2	Full bloom		Day length, air temperature, soil moisture	Seeds/pod, pods/branch
R3	Beginning pod development		Air temperature, soil moisture	Seed weight, seeds/pod, pods/branch
R4	Full pod		Air temperature, soil moisture	Seed weight, seeds/pod
R5	Beginning seed development		Air temperature, soil moisture	Seed weight, seeds/pod
R6	Full seed		Air temperature, soil moisture	Seed weight, seeds/pod
R7	Beginning maturity		Air temperature, soil moisture	Seed weight, seeds/pod
R8	Maturity		Air temperature, soil moisture	
		Harvest	Soil moisture	

[a]Stages other than those included in the Fehr-Caviness scale.

observation, recommendations include observation of all stages in the Fehr-Caviness scale, planting and harvest dates, and floral initiation date. Stages which are visible from the edge of a field are planting, VE, VC, VO, R2, and harvest. Observation of other stages may be important but may require close inspection of several individual plants, making such observation difficult.

4.3 WHEAT AND BARLEY

Wheat and barley are cool season, C_3, long-day, cereal grasses that are grown throughout the temperate regions of the world. Highest yields for both wheat and barley are found in northern Europe and the northwestern United States because of the mild winters, cool summers, and ample rainfall in these areas (ref. 47).

Heat tolerance in wheat and barley is much lower than that which is found in corn or soybeans. In India, even heat resistant varieties are planted so as to flower before the hottest part of the season (ref. 54). Both crops have winter and spring varieties. Winter varieties are planted in the fall and require a cold period of several weeks (vernalization) before longer spring days can trigger flowering. Wheat varieties are generally quantitatively long-day plants, that is with flowering delayed but not prevented by short days.

Barley varieties generally have slightly shorter growth periods than do wheat varieties, and in given areas are planted later and mature earlier than wheat. On the other hand, wheat has a wider environmental range than barley, and wheat varieties are adaptable to somewhat warmer climates. The flowers of both wheat and barley are in the heads at the top of the stem.

World wheat production in 1977 was 382 million metric tons, of which 14 percent was produced in the United States. World trade in wheat was 74 million metric tons, of which 41 percent was from the United States (ref. 48).

4.3.1 DEFINITION OF GROWTH STAGES

Feekes (ref. 55) provided the first detailed growth stage scale for small grains (see table 4-3). Several of Feekes' stages (such as 5, 9, 10.2 through

10.5, and 11.3) are described rather subjectively. Recently, however, Waldren and Flowerday (ref. 56) developed a scale for wheat (see table 4-3) in which stages are defined more objectively than the Feekes scale stages. For yield modeling, the most important stages are planting, beginning tillering, jointing, heading, dough, and harvest. Recommendations for ground observation of wheat and barley include observation of the Waldren and Flowerday stages and planting date because they are more precisely and objectively defined than the Feekes scale stages. Waldren-Flowerday stages 0 and 5 are visible from the edge of a field. However, observation of other stages may require close inspection or handling of several plants.

4.4 SORGHUM

Sorghum is a tropical, C_4, warm season, short day, perennial grass. It ranges from 2 to 15 feet in height. Flowers and later seeds are found in a loose-to-dense panicle or head at the top of the stalk. Additional heads may occur on tillers growing from nodes near the base of the plant. Sorghum is generally planted about 2 weeks after corn in temperate regions, after the soil becomes warm (20°-27° C). The optimum temperature is about 27° C. The plant can tolerate quite high temperatures, but sustained heat during grain filling reduces yield (ref. 47). Temperatures below 15° C injure sorghum; so, in temperate regions, the plant dies in the fall. In continuously warm areas, several grain harvests may be obtained from one planting.

Although summer rains or irrigation are needed for good yields in hot regions, sorghum is quite tolerant of drought stress. The plant becomes dormant under severe water shortage and resumes growth upon rewetting (ref. 41). This characteristic may cause yield reduction due to frost damage if extended drought delays maturity too far into the fall in temperate regions. Short-season sorghum varieties can be grown in the Negev region of Israel on 20 centimeters of stored soil moisture (ref. 57). Sorghum tolerance of water stress is partly due to a waxy cuticle deposited over leaf and stem surfaces that reduces water loss when the stomata are closed.

TABLE 4-3.— WHEAT GROWTH STAGES

Description of stage					Controlling factors	Yield factors influenced
Number	Feekes	Number	Waldren-Flowerday	Other[a]		
				Planting	Soil moisture, soil temperature, frost-free date, farmer choice	Plant density, stand quality — starts meteorological variables
1	One shoot	0	Emergence		Soil temperature, soil moisture	Stand quality, plants/acre
2	Beginning tillering	1	Beginning tillering		Solar radiation, nutrient supply, soil temperature, soil moisture, air temperature	Tillers/plant
3	Tillers formed	1.5	One or more leaf collars visible		Soil temperature, soil moisture	Ears/tiller, tillers/plant
4	Beginning pseudostem erection	2	Pseudostem formed		Soil temperature, soil moisture	Ears/tiller
5	Pseudostem strongly erected				Soil temperature, soil moisture	Ears/tiller
6	First node visible	3	First node visible		Day length, soil temperature, soil moisture	Flowers/ear, ears/tiller — hereafter susceptible to frost damage
7	Second node visible	3.5	Second node visible		Air temperature, soil moisture	Flowers/ear
8	Flag leaf visible	4	Flag leaf visible		Air temperature, soil moisture	Flowers/ear
9	Flag leaf ligule barely visible				Air temperature, soil moisture	Flowers/ear
10	Flag leaf fully grown	4.5	Booting		Air temperature, soil moisture	Flowers/ear
10.1	First head visible	5	First head visible		Air temperature, soil moisture	Flowers/ear
10.2	One-fourth of head visible				Air temperature, soil moisture	
10.3	One-half of head visible				Air temperature, soil moisture	
10.4	Three-fourths of head visible				Air temperature, soil moisture	
10.5	All of head visible				Air temperature, soil moisture	
10.5.1	Beginning flowering	6	Anthesis		Air temperature, soil moisture	Seeds/ear
10.5.2	Whole head flowering				Air temperature, soil moisture	Seeds/ear
10.5.3	Flowering over at base of ear	7	Flowering complete		Air temperature, soil moisture	Seeds/ear
10.5.4	Flowering over, kernel watery ripe				Air temperature, soil moisture	Kernel weight
11.1	Milky ripe				Air temperature, soil moisture	Kernel weight
11.2	Mealy ripe	8	Stiff dough		Air temperature, soil moisture	Kernel weight
11.3	Kernel hard, difficult to crack	9	Kernel hard, will not crack		Air temperature, soil moisture	Kernel weight
11.4	Ripe for cutting	10	Ripe	Harvest		

[a]Stages other than those included in the Feekes or Waldred-Flowerday scale.

Sorghum is one of the best crops for producing a good yield in warm or hot, dry, nonirrigated conditions. It also grows well in hot humid conditions. Its chief disadvantage is that it depletes the soil nutrient supply, and the succeeding crop must be fairly heavily fertilized.

Sorghum is not used for green pasturage since young shoots contain about 0.01 percent hydrogen cyanide which can be fatal to livestock. Sorghum stubble is high in sugar (15-50 percent compared to 1-5 percent for corn) and may find use as an energy source.

Most sorghum varieties seem to be quantitative short-day plants; e.g., flowering is delayed rather than prevented by short days. Flowering of tropical sorghum varieties is delayed by days longer than 11.1 hours to 12.6 hours (ref. 58). In one study, 3 U.S. sorghum varieties were delayed by 14-hour days (ref. 59) and, in another study, by 17-hour days (ref. 60). Some U.S. sorghum varieties were found to have an approximately 15-day bvp (ref. 60). The bvp might be shortened by rapid growth due to high temperatures and high photosynthesis associated with long days during the bvp (ref. 60). High temperatures clearly cause rapid leaf initiation and expansion in sorghum (ref. 14).

4.4.1 DEFINITION OF GROWTH STAGES

Vanderlip and Reeves (ref. 61) have defined growth stages of sorghum (see table 4-4). For yield modeling, the most important stages are planting, emergence, floral initiation, half bloom or anthesis, and maturity. For ground observation, we recommend the stages listed in table 4-1, i.e., the stages defined by Vanderlip and Reeves (ref. 61) and planting and harvest dates. Planting, emergence, half bloom, maturity, and harvest can be observed from the edge of the field. The other stages require close inspection or cutting open of several plants.

TABLE 4-4.— SORGHUM GROWTH STAGES (REF. 61)

Number	Description	Controlling factors	Yield factors influenced
	Planting	Soil moisture, soil temperature, frost-free date, farmer choice	Plant density, stand quality, starts meteorological variables
0	Emergence	Soil temperature, soil moisture	Stand quality, plants/acre
1	Collar of 3rd leaf visible	Soil moisture, soil temperature,	Tillers/plant
2	Collar of 5th leaf visible	Soil moisture, soil temperature	
3	Growing point differentiation or floral initiation	Day length soil moisture, soil temperature	Leaves/tiller, ears/tiller, grains/ear. Hereafter very susceptible to frost damage
4	Final leaf visible in whorl	Day length, air temperature, soil moisture	
5	Boot stage	Day length, air temperature, soil moisture	
6	Half bloom	Day length, air temperature, soil moisture	Grain/ear. Hereafter most susceptible to water and temperature stress
7	Soft dough	Air temperature, soil moisture	Grain weight
8	Hard dough	Air temperature, soil moisture	Grain weight
9	Maturity	Air temperature, soil moisture	Grain weight
	Harvest		

4.5 RICE

Rice is an annual, short day, C_3, tropical grass. Flowers and later seeds are found in a loose-to-dense panicle or head at the top of the stalk. Additional heads may occur on tillers growing from nodes near the base of the plant. Highest yields are in areas with irrigation and high solar radiation.

Flowering is prevented and most rice varieties are injured by temperatures below 15 C (ref. 62). Temperatures above 35° C or below 15° C before or during anthesis cause sterility in many rice varieties (refs. 63-66). Sterility occurs in most rice varieties at temperatures above 41° C (refs. 64-66).

Rice is unique among major field crops in thriving in standing water during most of its growth cycle (ref. 47). Up to 20 pounds per acre of nitrogen may be fixed by bluegreen algae living in the paddies where rice is growing, which slightly reduces the requirement for nitrogen fertilizer to obtain high yields.

Rice is grown from the equator to about latitude 40°. In the tropic areas, two or more rice crops may be harvested if sufficient water and sunlight are available.

Although some researchers have reported long-day rice varieties, rice is clearly a short-day plant (ref. 67). Twelve reportedly long-day varieties of rice were tested at the International Rice Research Institute (IRRI) at Los Banos, Philippines, (ref. 67) and all were qualitative or quantitative short-day plants.

The basic vegetative phase (bvp) of rice has been reported to last from 14 days to 63 days (papers cited by Vergara et al., ref. 20). The photoperiod-sensitive phase has been found to range from 0-to-30 days for quantitative short-day rice varieties (ref. 20) and up to 12 years for a qualitative short-day rice variety (ref. 32). For qualitative photoperiod sensitive varieties, the critical photoperiod ranges from 13 to 16 hours. The optimum photoperiod for qualitative and quantitative photoperiod-sensitive varieties ranges from 10 to 13 hours (ref. 67). At 8-hour photoperiods, flowering of most varieties is slightly delayed, probably due to insufficient photosynthesis (ref. 23).

In 1977, world production of rice was 363 million metric tons, of which about 1.5 percent was produced in the United States. World trade in rice was 8.4 million metric tons, of which 26.5 percent came from the United States (ref. 48).

4.5.1 DEFINITION OF GROWTH STAGES

Feekes (ref. 55) provided the first detailed growth stage description for wheat and other small grains (see table 4-3). Several of the Feekes' stages, such as 5, 9, 10.2-10.5, and 11.3, are described rather subjectively. Recently, however, Waldren and Flowerday (ref. 56) developed a scale for wheat (see table 4-3) in which stages are defined more objectively than the Feekes scale stages. For yield modeling, the most important stages are planting, beginning tillering, jointing, heading, dough, and harvest.

Because of morphological similarities between wheat and rice (both are determinent, annual, tillering grasses), the Waldren and Flowerday scale may also be applied to rice. For ground observation for rice, we recommended observation of the Waldren and Flowerday stages and planting and harvest dates.

4.6 COTTON

Cotton is an indeterminant, C_3, tropical annual or perennial dicot. It is grown primarily for the fiber found in fruit around the seeds and secondarily for the cotton seed and cotton-seed oils. In 1977, cotton production was 63.7 million bales worldwide, of which 23 percent was grown in the United States. International trade in cotton was 19.5 million bales, with 28.7 percent from the United States (ref. 48).

The cotton plant produces a branching stem with flowering or vegetative branches possible at each node. As the lower node begins to produce flowering nodes, the growing points at the tips of the upper branches continue to produce new leaves and vegetative branches (ref. 68).

Cotton grows best in areas with mild, moist springs and warm, moist summers with mostly sunny days during the growing season. Except in irrigated areas, cotton requires about 50 to 150 centimeters of rain per year (ref. 47).

Because cotton continues producing new leaves, branches, and flowers indefinitely, it is usually harvested only after being killed by drought, defoliants, or frost.

The cotton seedling is especially sensitive to low temperature injury during the first few hours of germination and then 24 to 30 hours later (ref. 69). The plant grows in the 15° to 50° C range, with the optimum temperature at 34° C, and the mean summer temperature greater than 25° C. Two species of cotton (<u>Gossypium arboreum</u> L. and <u>G. herbaceum</u> L.) are believed to have been domesticated in south Asia and Africa, and two species (<u>G. hirsutum</u> L. and <u>G. barbadense</u> L.) are believed to be from Central or South America (ref. 70).

Cotton grows from latitude 37° N to 32° S except in the Ukraine where it is found up to 47° N latitude (ref. 47). It generally needs a frost-free growing season of 180 to 300 days.

Although cotton is a short-day plant, many varieties are quantitative short-day plants and show very little response to photoperiod in terms of first-flowering date (ref. 47). Floral initiation begins no earlier than 14 to 16 days after emergence (ref. 71) at the same time as the expansion of the 1st through 3rd true leaf. Long days or high (7°-8° C) temperatures may delay first floral initiation. Beginning flowering is earlier, with increasing temperatures up to 25° C.

4.6.1 DEFINITION OF GROWTH STAGES

A complete set of cotton growth stages from planting to harvest has not been located in the technical literature. Based on the work of several researchers (refs. 72, 68, 69), the stages in table 4-5 are proposed to cover the critical events in the cotton cycle. First square or first flower bud visible follows floral initiation by about 10 days (ref. 73).

TABLE 4-5.— COTTON GROWTH STAGES (REF. 67, 68, 71)

Number	Recommended	Controlling factors	Yield factors influenced
1	Planting	Soil moisture, soil temperature, frost-free dates, farmer's choice	Plants/acre, stand quality, starts meteorological variables
2	1st square	Air temperature, day length, soil moisture	Flowers/plant
3	1st flower	Air temperature, day length, soil moisture	Flowers/plant
4	1st boll	Air temperature, day length, soil moisture	Fiber length
5	1st open ball	Air temperature, day length, soil moisture	Fiber quality and length
6	Mature for harvest	Air temperature, soil moisture, defoliant application	Fiber quality
7	Harvest		

4.7 SUNFLOWER

The sunflower is a determinant, annual, C_3, temperate, short-day dicot. The sunflower is grown mostly for oil from its seeds but also for silage and for feeds and confectionary from the seeds (ref. 47).

The sunflower is more tolerant to high and low temperatures than are many other summer crops. Until the 6-leaf stage, the young plants can stand temperatures down to -5° C, and during the seed-ripening period, the plants are not harmed at -2° C (ref. 74). The sunflower requires many days of full sunlight. Maximum assimilation rate occurs at 28° C, but temperature has little affect on assimilation from 18° C to 32° C (ref. 75).

Although the sunflower plant is not very resistant to plant water deficits, (ref. 74) it grows relatively well in semiarid conditions because a very deep (2.7m) and very wide (3.0m) root system allows the plant to extract water from a large soil volume (ref. 74).

The sunflower ranges in height from 5 to 20 feet. Seeds are borne in large flowers at the top of the main stem and of any secondary stems. Until anthesis, the head and leaves of sunflowers are phototropic, always moving to face the sun (ref. 76).

As a quantitative short-day plant, sunflower phenology is relatively insensitive to photoperiod (ref. 74). Some research in predicting sunflower stages has used growing degree days and latitude (ref. 77) to predict beginning of flowering.

World production of sunflower seed was 10.5 million metric tons in 1977, with 5 percent of that in the United States. The U.S.S.R. is by far the largest producer of sunflower seed (ref. 48).

4.7.1 DEFINITION OF GROWTH STAGES

Robinson (ref. 74) described the sunflower growth stages which are shown in table 4-6. Head visible follows floral initiation by about 10 to 20 days.

TABLE 4-6.— GROWTH STAGES OF SUNFLOWER (REF. 74)

Number	Description	Controlling factors	Yield factors influenced
1	Planting	Soil moisture, soil temperature, frost-free dates, farmer's choice	Plant/acre, stand quality
2	Emergence	Soil moisture, soil temperature	Plant/acre, stand quality
2.5	Floral initiation	Air temperature, day length, soil moisture	Flowers/head
3	Head visible	Air temperature, day length, soil moisture	Flowers/head
4	First anther	Air temperature, day length, soil moisture	Seeds/head
5	Last anther	Air temperature, day length, soil moisture	Seeds/head, seed weight
6	Maturity	Air temperature, day length, soil moisture	Seed weight
7	Harvest		

For yield modeling, all the defined stages are important and should be noted in ground observations.

5.0 PHENOLOGICAL MODELS

The following two sections will review phenological models by modeling approach (section 5.1) and by specific crop (section 5.2). In most cases the generic equations of a modeling approach will be presented in the first section with crop specific coefficients in the following section. The most promising models will be summarized in section 6.

5.1 GENERAL MODELING APPROACHES

Phenology or plant development may be defined as the sequence of ontogenetic events involving both growth and differentiation, leading to changes in functions and morphology. It is an enormously complex process which involves controls at molecular level; the activation and repression of genes; and differentiation leading to organ formation, maturity, and senescence. Although this subject has been studied in depth, our present knowledge of control systems is still inadequate because of the complexity of the process. Thus, there has been no attempt to model plant phenology from the available basic information. The most comprehensive models have attempted to predict plant development as influenced by weather by incorporating two basic plant responses; namely, thermal and photoperiodic. This discussion of significant models available will be organized from the simple thermal response models to a more complex treatment of photothermal interactive models.

5.1.1 THERMAL MODELS

Temperature affects plant development through its influence on the rate of plant metabolic processes. Low temperatures may retard development, and increasing temperature (up to a limit) accelerates progress toward maturity. An arbitrary scaling measure used to describe temperature influence on plant phenology is heat units (HU's) or growing degree-days (GDD's). The concept of HU's and GDD's dates back more than a century. It postulates that plant growth and development are dependent upon the total amount of heat the plant receives. There are some subtle differences between the two models as used in the literature. In estimating HU's, one is defining the average response of plants to maximum and minimum temperatures. The parameters required to calculate HU's are maximum and minimum temperatures and a threshold temperature (TH), below which development is inhibited. The DD (degree day) is a measure of the departure of mean daily air temperature above the minimum TH.

HU is a more frequently used term; and, in agronomic literature, it is usually applied to corn development. Aspiazu and Shaw (ref. 78) reviewed six different methods of HU calculations for corn development (refs. 79-82) and suggested that the model used by Brown (ref. 83) is the method with the least variability. Brown (ref. 83) estimated the contribution of maximum (T_{MAX}) and minimum (T_{MIN}) temperatures (degrees Fahrenheit) to GDD's as follows:

$$\left.\begin{aligned} &\text{Maximum temperature effect } Y_{MAX} = 1.85(T_{MAX} - 50) - 0.026(T_{MAX} - 50)^2 \\ &\text{Minimum temperature effect } Y_{MIN} = T_{MIN} - 40 \\ &HU = \frac{(Y_{MAX} + Y_{MIN})}{2} \end{aligned}\right\} \quad (1)$$

The DD method was also used in predicting harvesting dates (ref. 84) and planting dates (ref. 85). Lindsey and Newman (ref. 86) developed the most precise method, taking into account the changes in diurnal air temperature. The three conditions for computation of DD are as follows:

a. If $MIN \leq TH \leq MAX$, $DD = \frac{(MAX - TH)^2}{2(MAX - MIN)}$.

b. If $TH \geq MAX$, $DD = 0$.

c. If $TH < MIN$, $DD = (\text{Average} - TH)$

In spite of its lack of theoretical soundness, the HU/DD method is easy to apply and has been widely used to guide agricultural operations and the planning of land usage. The success of this method depends on a close relationship between radiation and temperature, photoperiod and temperature, and to varieties adapted to local photoperiods.

The sorghum phenological model described by Vanderlip and Arkin (ref. 87) may be considered as a heat unit model with heat unit base temperatures specified for emergence, floral initiation, half bloom, rate of leaf appearance of the first 5 leaves, rate of leaf appearance of later leaves, and rate of leaf expansion. This model is described in section 5.2.4.

5.1.2 PHOTOTHERMAL MODELS

The HU/DD concept assumes that photoperiodic effects do not influence the development rate of plants. As discussed earlier, photoperiodic effects are very pronounced during certain stages of development, and the photothermal interaction is quite complicated. Thus, the DD method has to be adjusted with changes in location. The three following sections review work by three researchers to develop photothermal models. The work of Nuttonson, Robertson, and Coligado and Brown represents increasingly sophisticated photothermal models.

5.1.2.1 Nuttonson Model

Nuttonson (ref. 88) conducted a study on the range of DD requirements for development of marquis wheat. The data covered a range of photoperiod and thermal regimes. Figure 5-1 shows the integration of photothermal responses of marquis wheat development.

Nuttonson's photothermal concept could be written in mathematical form for development between stages S1 and S2 as follows:

$$1 = \int_{S1}^{S2} F_1(P) \times F_2(T)dt \qquad (2)$$

where S1 and S2 are arbitrary numbers and F_1 and F_2 are functions relating development (t) to temperature (T) and photoperiod (P).

For a given stage of development in a mathematical form that assumes a linear photothermal response and equal influence of night and day temperatures

$$1 = k_2 \Sigma P(\overline{T} - b_0) \qquad (3)$$

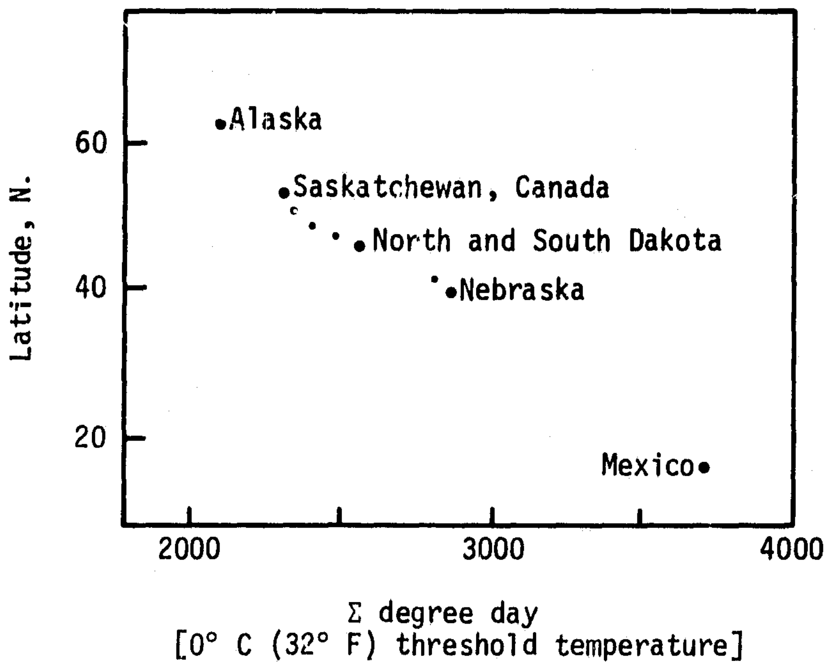


Figure 5-1.— Changes of cumulative DD's as they occur with changes in latitude (ref. 88).

where k_2 is the development rate per hour of photoperiod per degrees Celsius, $\bar{T}$ is the mean diurnal temperature (degrees Celsius), and b_0 is a temperature coefficient.

5.1.2.2 Robertson Model

Robertson (ref. 4) expanded on Nuttonson's photothermal concept for spring wheat development in the following manner.

a. The response of temperature is nonlinear, allowing for upper and lower critical limits as well as an optimal value.

b. The response to photoperiod is also a nonlinear function, allowing for thr cardinal points.

c. Night and day temperature responses are considered separately.

d. The above three factors are considered over a fairly short phenological period when phenological processes are uniform.

The final equation of Robertson's (ref. 4) triquadratic model is as follows:

$$1 = \text{Maturity} = \sum_{S1}^{S2} \left[\left\{ a_1(P - a_0) + a_2(P - a_0)^2 \right\} \times \left\{ b_1(T_{MAX} - b_0) + b_2(T_{MAX} - b_0)^2 + d_1(T_{MIN} - b_0) + d_2(T_{MIN} - b_0)^2 \right\} \right] \quad (4)$$

Coefficients a_0, a_1, a_2, b_0, b_1, b_2, d_1, and d_2 are determined by an iterative regression technique which provides the best relationship between the three environmental factors and their interactions for the set of data used. The values of the coefficients are given in table 5-1.

The stages considered to have fairly uniform phenological processes are planting, emergence, jointing, heading, soft dough, and hard dough/ripe. Although the Robertson model is theoretically more acceptable than the methods discussed earlier, there are drawbacks to its use. For instance, it was difficult to obtain coefficients that covered the complete range for each factor. Additionally, the model was limited to conditions represented by the data set used.

TABLE 5-1.— FINAL REGRESSION COEFFICIENTS IN THE ROBERTSON (REF. 4) MODEL AS DETERMINED FROM 1953 THROUGH 1957 DATA

Coefficient	Period[a]				
	PE	EJ	JH	HS	SR
a_0		8.413	10.93	10.93	24.38
a_1		1.005	.9256	1.389	-1.140
a_2		0	-.06025	-.08191	0
b_0	44.37	23.64	42.65	42.18	37.67
b_1	.01086	-.003512	.0002958	.0002458	.00006733
b_2	-.000223	.00005026	0	0	0
b_3	.009732	.0003666	.0003943	.00003109	.0003442
b_4	-.0002267	-.000004282	0	0	0

[a]PE = planting to emergence.
EJ = emergence to jointing.
JH = jointing to heading.
HS = heading to soft dough.
SR = soft dough to ripe.

As expected, the model showed no photoperiod response during the planting-to-emergence stage. However, the thermal response was quite supportive of those reported in the literature. The greatest response to photoperiod occurred during the emergence-to-jointing stage. The model did incorporate both linear and curvilinear responses wherever the data permitted. Maximum and minimum temperature and photoperiodic responses for each stage of development were used in generating the development rates. This made the model sensitive to small changes in environmental conditions and more applicable over different environments. The Robertson triquadratic model performed extremely well in comparison to the HU and photothermal models for the test data of spring wheat development (ref. 4).

Major et al. (ref. 89) modified the Robertson spring wheat model to determine the rate of development of soybeans by using a mean daily temperature instead of maximum and minimum temperatures. The modified form is as follows:

$$1 = \sum_{S1}^{S2} \left[a_1(P - a_0) + a_2(P - a_0)^2\right]\left[b_1(\bar{T} - b_0) + b_2(\bar{T} - b_0)^2\right] \tag{5}$$

Major et al. (ref. 89) determined the regression coefficients from field experiments and analytical procedures for 10 soybean varieties (see table 5-2).

Phinney and Trenchard (ref. 90) adapted the Robertson (ref. 4) spring wheat model for winter wheat. A new set of coefficients was derived for each stage of development in winter wheat. To account for the effect of dormancy on winter wheat phenology, the development rate equation was multiplied by a correction factor (MF) suggested by Feyerherm (ref. 91). The vernalization correction factor was used as an adjustable crop calendar from emergence to the heading stage.

$$MF = 0.5684 + 0.025081(\bar{T}_J) - 0.006139(\overline{PP}) \tag{6}$$

TABLE 5-2.— REGRESSION COEFFICIENTS FOR MAJOR AND JOHNSON (REF. 89) SOYBEAN PHENOLOGY MODEL

Period[a]	Cultivar	Regression coefficients for —					
		Day length			Temperature		
		a_0	a_1	a_2	b_0	b_1	b_2
PE	All cultivars	0	0	0	10.90	0.02150	-0.0008560
EF	Chippewa 64	8.09	0.02284	-0.002209	4.15	0.03713	0
	Hark	8.02	.02370	-.002309	5.17	.03850	0
	Amsoy 71	9.31	.02571	-.003386	2.50	.04027	0
	Beeson	8.72	.02435	-.002804	3.50	.03877	0
	Calland	9.63	.02701	-.003886	2.24	.04163	0
	Williams	8.85	.02689	-.003403	4.98	.04228	0
	Clark 63	9.44	.02606	-.003785	1.03	.04010	0
	Cutler 71	8.34	.02590	-.003158	4.41	.04095	0
	Hill	18.30	-.01336	0	8.97	.02405	0
	Dare	17.37	-.01365	0	4.88	.02457	0
FPF	Chippewa 64	17.43	-0.01633	0	0	0	0
	Hark	16.95	-.01785	0	0	0	0
	Amsoy 71	17.43	-.01471	0	0	0	0
	Beeson	18.00	-.01249	0	0	0	0
	Calland	21.00	-.00619	0	0	0	0
	Williams	18.53	-.00960	0	0	0	0
	Clark 63	17.53	-.01238	0	0	0	0
	Cutler 71	17.84	-.01139	0	0	0	0
	Hill	16.68	-.01257	0	0	0	0
	Dare	16.10	-.01655	0	0	0	0
FTF	Chippewa 64	18.46	-0.03322	0.000165	13.01	0.06151	-0.003619
	Hark	17.97	-.03493	.001503	14.64	.06248	-.004150
	Amsoy 71	16.94	-.04352	0	14.81	.08140	-.005508
	Beeson	16.86	-.04256	0	13.89	.07940	-.005032
	Calland	15.43	-.05743	-.011789	7.96	.12793	-.005991
	Williams	15.31	-.06078	-.013805	4.91	.13743	-.005709
	Clark 63	15.38	-.06184	-.012611	10.11	.13802	-.007228
	Cutler 71	15.35	-.06082	-.012775	9.19	.13621	-.006726
	Hill	18.25	-.01255	0	46.66	-.02259	0
	Dare	17.48	-.01337	0	47.28	-.02407	0
FPM	Chippewa 64	18.64	-0.02638	0	16.88	0.04921	-0.003096
	Hark	18.72	-.02095	0	11.89	.03874	-.001852
	Amsoy 71	18.23	-.01956	0	11.88	.03604	-.001475
	Beeson	17.91	-.01908	0	11.03	.03508	-.001307
	Calland	18.09	-.02301	0	13.10	.04277	-.002444
	Williams	17.26	-.02479	0	12.58	.04599	-.002458
	Clark 63	17.42	-.02474	0	12.96	.04595	-.002575
	Cutler 71	17.97	-.02341	0	12.85	.04351	-.002478
	Hill	15.08	-.02021	0	11.16	.03638	0
	Dare	15.65	-.01508	0	7.01	.02714	0

[a]PE = planting to emergence.
EF = emergence to flowering.
FPF = flowering to beginning pod fill.
FTF = flowering to termination of flowering.
FPM = flowering to physiological maturity.

where $\overline{T}_J$ is the normal average daily temperature for January and $\overline{PP}$ is the normal average annual precipitation. The vernalization factor showed significant improvement only for the emergence-to-jointing stage of development and the soft-dough-to-ripe stage (refer to table 5-3).

Phinney and Trenchard (ref. 90) suggested the need to incorporate a moisture interaction term for phenological assessment. A mean rain day frequency term ($\overline{RD}$) was substituted in place of day length. The new variable was computed on a daily basis by means of a low-pass filter function

$$\overline{RD}_i = \overline{RD}_{i-1} + k(RD_i - \overline{RD}_{i-1}) \tag{7}$$

where $\overline{RD}_i$ is the mean value of RD for the *ith* day. The rain day variable was useful in improving predictions after emergence.

5.1.2.3 Coligado and Brown Model

Coligado and Brown (ref. 6) reviewed all the major HU/DD models and developed a bio-photothermal model incorporating the photothermal principle suggested by Nuttonson (ref. 88). It differs from the Robertson (ref. 4) model in that temperature and day length responses are considered separately as well as interactively. The model accounts for a genetic factor (G), mean daily temperature ($\overline{T}$), photoperiod (P), temperature range (R), and development potential (DP).

The model was formulated to predict tassel initiation time in corn. The model determines the length of delay (number of days) in tassel initiation which is caused by suboptimal predictor variables calculated on a daily basis. The shortest time to tassel initiation was under optimum conditions of $\overline{T}$ = 25° C, P = 10 hours, and R = 0° C. The duration of the period from emergence to tassel initiation is t:

$$t = (G,\overline{T},P,R) \tag{8}$$

TABLE 5-3.— WINTER WHEAT REGRESSION COEFFICIENTS FOR THE ROBERTSON MODEL (EQUATION 7) AS DEVELOPED BY PHINNEY AND TRENCHARD (REF. 90)

Coefficient	Period[a]				
	PE (b)	EJ	JH (b)	HS (b)	SR
a_0	V1 = 1.0	0.8413×10^{1}	0.1093×10^{2}	0.1094×10^{2}	0.1262×10^{2}
a_1	V1 = 1.0	$.1005\times10^{1}$	.9256	$.1389\times10^{1}$	$.1224\times10^{4}$
a_2	V1 = 1.0	$-.8311\times10^{-1}$	$-.6025\times10^{-1}$	$-.8191\times10^{-1}$	0
b_0	0.4437×10^{2}	$.1971\times10^{2}$	$.4265\times10^{2}$	$.4218\times10^{2}$	$.4779\times10^{2}$
b_1	$.1086\times10^{-1}$	$.2202\times10^{-3}$	$.2958\times10^{-3}$	$.2458\times10^{-3}$	$.6146\times10^{-6}$
b_2	$-.2230\times10^{-3}$	$-.3376\times10^{-5}$	0	0	$.3178\times10^{-9}$
c_1	$.9732\times10^{-2}$	$.2707\times10^{-4}$	$.5943\times10^{-3}$	$.3109\times10^{-4}$	$.1511\times10^{-5}$
c_2	$-.2267\times10^{-3}$	$.1215\times10^{-6}$	0	0	$-.5998\times10^{-7}$

[a]PE = planting to emergence.
EJ = emergence to jointing.
JH = jointing to heading.
HS = heading to soft dough.
SR = soft dough to ripe.

[b]Unchanged from operation crop calendar.

The genetic factor G is interpreted as a constant defined by the length of each period under optimal conditions (hybrid determined). More precisely,

$$t = G + \sum_{i=1}^{T_I} \left[(t_{T_i} - t_{T_0}) + b_P(P_i - P_0) + b_R(R_i - R_0) \right] \tag{9}$$

where $\overline{T}_0$ = 25° C, P_0 = 10 hours, R_0 = 0° C, b_P is the rate of development caused by photoperiod, and b_R is the rate of development caused by temperature change.

Tassel initiation can be calculated using the following formula:

$$t_T = k_T\left(T^{-m_T}\right) \quad ; \quad 0° < T \leq 25°\ C \tag{10}$$

where k_T and m_T are the coefficient and exponent for a hybrid. The response to daily mean temperature can be calculated as follows:

$$(\Delta t)_{T_i} = t_{T_i} - t_{T_0} = k_T\left(T_i^{-m_T} - T_0^{-m_T}\right) \tag{11}$$

For the optimum photoperiod, k_T and m_T are determined by using linear regression analysis with logarithmic transformation of the data.

A linear response function relating time to tassel initiation is as follows:

$$t_P = a_P + b_p \tag{12}$$

where 10 hours < P, a_P is a constant, b_P is time to tassel initiation (photoperiod, day and hour). The rate b_P was determined by using t_P and P for three mean temperatures. Additionally, b_P is calculated as follows:

$$b_P = k_P\left(T^{-m_P}\right) \tag{13}$$

where k_p and m_p are the coefficient and exponent determined by using regression analysis with logarithmic transformation of the data. The change in time caused by photoperiod is

$$(\Delta t)_{P_i} = b_P(P_i - P_0) = k_P T_i^{-m_P}(P_i - P_0) \quad (14)$$

The response to temperature can be calculated using the following equation:

$$t_R = a_R + b_r \times R \quad ; \quad 0° \text{ C} \leq R \quad (15)$$

where a_R is a constant and b_R is the time of tassel initiation (range).

$$b_R = k_R\left(T_R^{-m_R}\right) \quad (16)$$

The change in time caused by range of temperature is:

$$(\Delta t)_{R_i} = b_R(R_i - R_0) = k_R T^{-m_R}(R_i - R_0) \quad (17)$$

A development potential factor DP, which is considered to be dependent on the number of days from planting to emergence under optimum conditions, is given as:

$$DP = 1 - \left[(t_e - 5)b_{DP}\right] \quad (18)$$

where b_{DP} is a rate of decrease in development potential and is selected based on the least average deviation of the predictions from the observed time to tassel time (ref. 55). The total coefficients needed to run the model are k_T, m_T, k_p, m_p, k_R, m_R, and b_{DP}, as listed in table 5-4.

Coligado and Brown (ref. 6) compared the bio-photothermal model with the HU and GDD models to predict tassel initiation time. The HU model was found to have the least average deviation, followed by the GDD model. The better results obtained by using the HU method may have been due to the curvilinear response used for maximum temperature ranging from 10° C threshold to 30° C

TABLE 5-4.— VALUES OF THE COEFFICIENTS AND EXPONENTS USED BY COLIGADO AND BROWN (REF. 6) IN THE BIO-PHOTOTHERMAL MODEL TO PREDICT TASSEL INITIATION TIME IN CORN

Variety	k_T	m_T	k_P	m_P	k_R	m_R
Hybrid United-108	56.0	-0.5666	548.1	-2.4757	11,497.6	-3.7567
Hybrid Guelph G×122	226.0	-1.0039	117.1	-2.0593	3,084.3	-3.1997

optimum. These ranges were comparable to the temperature relationship in the bio-photothermal model. An introduction of a photothermal factor to the GGD and HU models improved predictions more for the GDD model than for the HU model. However, the bio-photothermal model combines all three independent variables in a form that provides the best predictions of tassel initiation time.

5.2 REVIEW OF CROP SPECIFIC MODELS

The following sections review crop specific phenological models for corn, soybean, wheat, barley, sorghum and cotton. No published model was reviewed for rice or sunflower.

5.2.1 CORN

Most of the early work in predicting corn phenology has been in terms of HU's. The two HU models described under model I were derived for the purpose of predicting maturity in corn. These models are usually restricted to a regional use (refs. 79-82) and a given group of varieties, and they are useful in recommending planting schedules and rough predictions of maturity dates. It is also a common practice to select varieties that are labeled by the HU's they require from planting to black layer development.

HU's are useful markers for predicting corn development in a given region where climatic changes from year to year are not drastic. Corn is adapted to do well under high day temperatures of 27° to 29° C and night temperatures of 10° to 24° C. Extremely high temperatures may be injurious, especially during the tasseling stage. The moisture requirements are fairly low with respect to other crops (except sorghum). Corn is most sensitive to soil moisture deficit during the period of tasseling and silking which occurs immediately before and during pollination. When moisture is limited, cool air temperatures help the plant to tolerate certain levels of moisture stress.

Baron et al. (ref. 93) studied the relationship of climatic parameters to corn maturity. As measured by kernel moisture, corn maturity was correlated with solar radiation, latitude, HU, GDD (above 10° C), and planting date. The highest correlation for maturity was between GDD and latitude in three different maturity classifications. The effect of day length was quite evident and was consistent with the observations of Ragland et al. (ref. 94) and Hunter et al. (ref. 95), who found that increasing day length significantly increases time from plant emergence to tassel emergence and silking.

The influence of photoperiod response on corn phenology is modeled by Coligado and Brown (ref. 6). Unlike other photothermal models (ref. 4), this model considers only the period during which the plant is photosensitive. Other important points of the Coligado model are as follows:

a. The photoperiod response is limited to the day length photoperiod requirement of $P \geq 10$ hours.

b. The upper critical limit of the photoperiod response is not mentioned, probably because the data were collected in areas where this was unnecessary.

c. The model also considers the influence of temperature on photoperiod response but does not account for the temperature effects on development when $P < 10$ hours. Perhaps this effect is reflected in the direct thermal effects on development. [See equation (14); coefficients are in table 5-4].

Figure 5-2 describes a hypothetical interaction of day length and varietal effect on development. Varieties I and II are short day, and III is a day neutral variety. The absolute magnitude of the photoperiod response is not to scale. Variety I will develop at a constant rate with an increasing day length of up to an optimum of 10 hours, and between 10 to 14 hours development rate will gradually decline. Similarly, variety II will have an optimum development rate of 16 hours, and the rate will then decline to a minimum of 20 hours. Variety III will develop at a constant rate irrespective of day length. The primary controls on flowering for variety III may be temperature

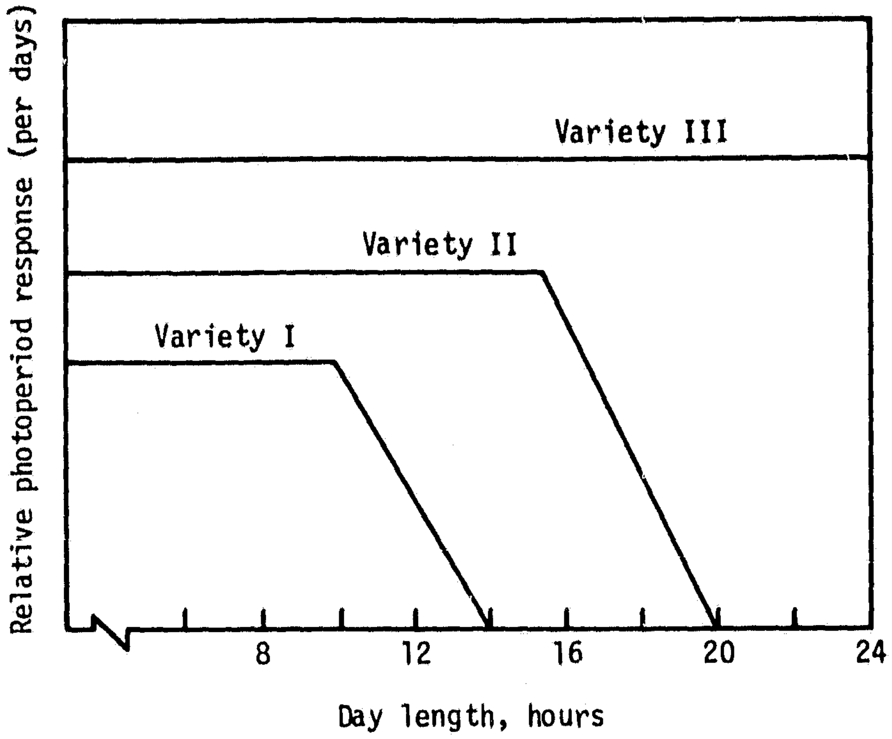


Figure 5-2.– The relative photoperiod response of corn varieties that are short day (I and II) and day neutral (III). (From reference 22.) The Y-axis is a relative scale with no specific reference to the magnitude of the response of varieties I, II, and III.

range and duration. It is quite possible that phenological predictions based on HU's are highly applicable to day neutral varieties. This may be possible for varieties I and II as long as predictions are made up to the optimum photoperiod. Also, it follows that if variety II is planted in a latitude where day length does not exceed 16 hours, then flowering is independent of day length, and one may conclude that the variety is day neutral (see table 5-5).

Duncan at Kentucky State University has been developing a corn growth and yield model, but the model has not yet been published (ref. 96).

5.2.2 SOYBEAN

Soybean adapts best to regions with temperatures ranging from cold temperate to tropical. Most varieties do well at high temperatures (ref. 97), with optimum temperature for development around 28° C. Being short-day plants, soybeans flower rapidly during day lengths which are less than the optimum photoperiod. Major (ref. 22) discusses photothermal influences on soybean development by classifying development into a juvenile phase (germination to flower initiation), reproductive phase (flower initiation to flowering), and ripening phase (flowering to full seed development).

During the first part of the juvenile phase called the basic vegetative phase (bvp), the plant is too immature to respond to photoperiod stimulus. However, once this vegetative stage is over, flower initiation will occur immediately after a sufficient number of photoinductive cycles. While there is no information available on how temperature affects these responses, it is known that as temperature increases, the development rate increases until an optimum of 28° C (ref. 98), after which flowering is delayed.

Although photoperiod may influence the reproductive and ripening phases, it does not exert as strong an influence as it did during earlier phases. Once the flower is initiated, development appears to be mainly a function of temperature. In indeterminate varieties, development is more complicated because photoperiod also affects the duration of flowering and even maturity.

TABLE 5-5.— APPROXIMATE LENGTH OF DAY ON VARIOUS DATES AT DIFFERENT LATITUDES NORTH OF THE EQUATOR

Latitude, N	December 21 (winter solstice)		March 21 (spring equinox)		April 21		May 21		June 21 (summer solstice)		July 21		August 21		September 21 (autumn equinox)	
	Hr	Min	Hr	Min	Hr	Min	Hr	Min	Hr	Min	Hr	Min	Hr	Min	Hr	Min
0°	12	7	12	7	12	7	12	7	12	7	12	7	12	7	12	7
10°	11	33	12	7	12	24	12	37	12	43	12	38	12	24	12	8
20°	10	56	12	9	12	42	13	9	13	19	13	11	12	43	12	10
25°	10	35	12	10	12	53	13	28	13	42	13	29	12	54	12	10
30°	10	11	12	10	13	4	13	47	14	4	13	48	13	6	12	12
35°	9	48	12	12	13	17	14	9	14	32	14	12	13	18	12	12
40°	9	20	12	12	13	31	14	35	15	2	14	36	13	32	12	13
45°	8	46	12	14	13	48	15	4	15	38	15	6	13	49	12	15
50°	8	4	12	15	14	9	15	41	16	24	15	44	14	9	12	17
55°	7	10	12	17	14	34	16	29	17	24	16	33	14	35	12	19
60°	5	52	12	18	15	8	17	38	18	54	17	41	15	9	12	21

Statistics from Allard and Zaumeyer, in U.S. Department of Agriculture Tech. Bull. 867, 1944.

Decreasing day lengths in the fall may bring maturity more quickly to such varieties even though temperatures are decreasing.

Modeling of soybean phenology has been attempted with the basic HU concept. Lawn et al. (ref. 99) and Brown (ref. 83) were among the few who applied the HU models to soybeans. Major et al. (ref. 100) evaluated 11 thermal unit methods for predicting soybean development. They concluded that development of early cultivars (long day length requirement) was predicted more accurately by all thermal unit methods than was development of late cultivars. Late cultivars had a higher coefficient of variability, especially from emergence to the flowering period. This suggests that there are other environmental factors (day length) that influence the development of late cultivars. The HU method was found to fail seriously in accurately predicting postflowering development.

The need for a more complete prediction model that would include the photothermal concept was evident from the comparative study by Major et al. (ref. 100). They used the Robertson model to predict development in soybeans. The model varied from the Robertson model only in the use of a daily mean temperature rather than daily maximum and minimum temperatures used by Robertson. The results obtained by using model III suggested that this model was more accurate than were the HU models in predicting development of soybeans. The effects of cool spring temperatures on flowering predominated in the early part of the season, whereas the effects of day length predominated in flowering of plantings after June 1 (delayed). The hastening effects of short days on maturity were greater than the delaying effects of cool autumn temperatures. [See equation (5); coefficients are in table 5-2.]

There are other environmental factors such as soil moisture that retard or hasten development. The period between seed development stages R5 and R6 marks the peak of many physiological processes. In this period, as in the tasseling stage in corn, the vegetative growth ceases, and the potential number of reproductive sink are set. The environmental conditions that arise after beginning seed development (R5) and until maturity control how much of that potential can be expressed in yield. Moisture availability has a greater effect on yield than on the rate of development. Moisture stress may shorten the length of the vegetative growth period, causing a corresponding decrease in the length of the seed-filling period and in early maturity.

Curry (ref. 101) at Ohio State University has been developing a soybean growth and yield model, but the model has not yet been published in full.

5.2.3 WHEAT AND BARLEY

Wheat and barley are cool season, cereal grasses grown throughout the temperate regions of the world. Winter wheat is widely grown and requires a period of exposure to cool temperatures in order to initiate the reproductive portion of its life cycle. Usually planted in autumn, it undergoes a chilling process in winter, renews the active growth cycle in the spring, and is ready for harvest in early to mid summer. Spring wheat is usually planted in early spring and harvested in summer or early autumn.

There is some evidence of the development of models for predicting wheat phenology prior to Robertson (ref. 4). He provides a detailed summary of this early scientific work. Nuttonson (ref. 88) evaluated the GDD model to predict growth during major stages of winter wheat development. He obtained a high coefficient of variation at sites other than those where this model was developed, and he concluded that universal applicability was not possible. The introduction of a photothermal unit in the development of a phenology model was an improvement over the GDD model (ref. 89).

The Biometeorological Time Scale was developed by using the photothermal concept for spring wheat by Robertson (ref. 4). Reasonably good results were obtained when the model was applied to independent data from Brazil. [See equation (4); coefficients are in table 5-1.] The coefficients were variety dependent and had to be rederived, especially for winter wheat predictions. Feyerherm (ref. 91) developed a model for winter wheat by modifying the Robertson model. The modification was made as a result of considering the over-wintering factors which affect the rate of development in winter wheat.

Phinney and Trenchard (ref. 90) successfully adapted this model for a range of data sets to predict winter wheat phenology. [See equation (7); coefficients are in table 5-3.] Williams (ref. 102) used the Robertson model for a single variety of barley grown in Canada, with data from between 42 and 56 site-years. He concluded that the model-derived values were probably applicable within the area in which the model was developed, but he had little confidence in the applicability of the model in other areas.

Several environmental factors that influence the phenology of winter wheat need to be incorporated into the Williams model. Vernalization treatment in an appropriate temperature range effectively hastened flowering. Chujo (ref. 103) observed a relative maximum vernalization effect of about 4° to 8° C with a minimum near 1° C and another minimum above 11° C. Plants treated at less than optimum chill conditions and then exposed to warm temperatures were found to be adversely affected in reproductive development. An improvement in Feyerherm's vernalization factor may be necessary to account for the complex temperature effects during vernalization. Additionally, soil moisture effects should be considered.

5.2.4 SORGHUM

Arkin and Vanderlip and their associates have developed a sorghum phenology model (refs. 87, 104) based on heat units and normal leaf number and leaf size distribution of sorghum hybrids.

In its early form, the model predicts emergence (EM), leaf appearance for the first five leaves (L5), and leaf emergence for later leaves (L) as functions of daily mean temperature and temperature cutoff levels:

$$\begin{aligned} EM &= 1/(-1.05T + 26.6) \quad \text{for } T \leq 21.4°C \\ &= 1/4.13 \qquad\qquad\quad\ \ \text{for } T > 21.4°C \end{aligned}$$

where T is mean daily temperature in degrees C, and the seedling emerges when EM = 1:

$$
\begin{aligned}
L5 &= 1/(2.8 + 0.0292(T-22)^2 && \text{for } T \leq 22^\circ\ C \\
&= 1/2.8 && \text{for } T > 22^\circ\ C
\end{aligned}
$$

$$
\begin{aligned}
L &= 1/(2.9 + 0.0567(T-22 && \text{for } T \leq 21^\circ\ C \\
&= 1/(2.9 - 0.0562(T-21)) && \text{for } 21^\circ\ C < T \leq 30^\circ\ C \\
&= 1/2.45 && \text{for } T > 30^\circ\ C
\end{aligned}
$$

where L5 and L are in units of leaves/day.

Leaf expansion (LX) is estimated in cm^2/day as:

$$
\begin{aligned}
LX &= 5.1(T-12) && \text{for } T > 12^\circ\ C \\
&= 0 && \text{for } T \leq 12^\circ\ C
\end{aligned}
$$

Floral initiation is estimated as the day halfway between the date that the fifth leaf is fully expanded and the date that the last leaf appears. Half bloom is estimated as the date that the last leaf is fully expanded plus .86 times the days from floral initiation to that date. Maturity is estimated as the date of half bloom plus .6 times the days from emergence to half bloom.

In a later form of the model (ref. 104) for a medium late genotype, seed germination occurs when 18 heat units are accumulated over a base temperature of 6.3° C, emergence occurs when 66 additional heat units are accumulated over a base temperature of 11.4° C, floral initiation occurs when 497 additional heat units are accumulated over a base temperature of 7° C. The formula for calculating half bloom remains unchanged, and for maturity, .4 is substituted for .6 times days from emergence to half bloom. Although the phenology model works fairly well for sorghum hybrids planted in their normal latitude ranges (refs. 16, 105, 87), it has nothing in it to account for photoperiod effects when hybrids are planted outside their normal ranges.

5.2.5 COTTON PHENOLOGY MODELS

Hesketh et al. (ref. 106) have published several papers in the process of developing a cotton phenology model (Simcot II). The model, which has not been published to date, estimates physiological events of cotton from daily temperature but may not consider photoperiod.

Whisler, Landivar, and Baker (ref. 107) are also developing an as yet unpublished cotton growth model (Gossym). No details about the phenology submodel are currently available.

Cotton phenology has points in common with that of corn and soybean. Like soybean, cotton is an indeterminant plant with vegetative growth continuing after flowering. However, like corn, most commercial cotton varieties are somewhat insensitive to photoperiod.

6. SUMMARY OF SELECTED PHENOLOGICAL MODELS FOR SPECIFIC CROPS

The following sections describe the most promising phenological models for corn, soybean, wheat, barley, and sorghum. No model was found acceptable for further testing for cotton, rice, or sunflower.

6.1 CORN

Two models are suitable for predicting phenology, and the choice of either would be determined by the data available to run the models (tables 6-1 and 6-2). The GDD model (ref. 78) requires knowledge of the HU's necessary for development from one stage to the next. The HU required to reach a particular stage of development is variety specific and restricts the model application to a certain regional limit. The photothermal model (ref. 6) is theoretically more sound than the GDD model and has rigid information requirements regarding the thermal and photoperiod responses to development. This model was formulated to predict tassel initiation and has been used only by Coligado and Brown (ref. 6). Several versions of the GDD models have been in use for over a decade. Aspiazu and Shaw (ref. 78) evaluated six GDD models and suggested a new version that has the least error of prediction.

6.2 SOYBEAN

The biometeorological time scale (BMTS) model (ref. 4) adapted by Major et al. (ref. 89) is the best model for predicting development of soybeans. The only change made by Major et al. in the adapted version was in the use of a mean daily temperature rather than daily maximum and minimum temperatures. Major (ref. 100) tested this model, along with a GDD model, for experimental data collected at Elora, Ontario; Ames, Iowa; and Columbia, Missouri. The BMTS model made consistently better predictions than the GDD model, and the applicability of the model over a range of climatic conditions was quite evident. The model coefficients were rederived for different varieties rather than for different locations. The data requirements for running the model are listed in table 6-3.

TABLE 6-1.— GDD MODEL FOR CORN

[HU model of Aspiazu and Shaw (ref. 78), evaluated to be the most suitable GDD model]

Description	Data requirements	Application range
Easy to apply because no response of coefficients is required	Daily maximum temperature Daily minimum temperature	Application may be restricted to a given climate and location
Linear response for development is major assumption; does not account for photoperiodic response	Threshold temperature (constant) Varietal HU's for each stage	May be suitable for varieties grown in latitudes where photoperiod influence is not evident
May over or under predict during extreme temperature conditions		
For each variety of interest, requires HU's for emergence, silking, and maturity		

TABLE 6-2.— BIO-PHOTOTHERMAL MODEL FOR CORN

[Developed by Coligado and Brown (ref. 6)]

Description	Data requirements	Application range
Nonlinear thermal and photoperiodic responses are accounted for, both independently and interactively	Daily mean temperature	Could be used for a wide range of latitudes if varieties are climatically adapted
	Temperature range	
Used only for predicting tassel initiation; applicability beyond this stage unknown	Photoperiod	Requirement of coefficients from the responses of development to temperature and photoperiod may be generalized
	Development response to temperature	
Requires detailed varietal responses of development to temperature and photoperiod	Development response to photoperiod	
Requires information for two constants (i.e., genetic factor and development potential), which are not clearly defined		
Predicts more accurately than HU model (model I)		

TABLE 6-3.— PHOTOTHERMAL MODEL FOR SOYBEANS

[Developed by Major et al. (ref. 89)]

Description	Data requirements	Application range
Incorporates the nonlinear responses of development to temperature and photoperiod	Daily mean temperature	Has been tested for a wide range of temperature climates
	Photoperiod	Coefficients were variety specific, were rederived for each variety, and were used at all locations
Predicts development over fairly short phenological periods	Initial set of coefficients	
Surpassed the GDD prediction estimates, especially in the postflowering stages	Phenological data set for derivation of coefficients for varieties of interest	
Coefficients were variety specific; need to be rederived for maturity groups		

6.3 WHEAT

The Robertson (ref. 4) BMTS model is the model best suited for predicting development of spring and winter wheat. Because this model was originally formulated for spring wheat, Robertson was not completely convinced that it would be as applicable in predicting development in other types of wheat. The variety-specific coefficients were the greatest drawback. Phinney and Trenchard (ref. 90) adapted the BMTS model for winter wheat with a vernalization coefficient. In general, the model predictions were good, showing no particular dependence on variety and climatic factors for the same set of coefficients. However, the limitation of the model became evident after a certain degree of moisture stress was reached. A moisture stress factor suggested by Trenchard seems to account for some of the prediction error. However, this aspect of the model needs further evaluation. The data required to run this model are listed in table 6-4.

6.4 BARLEY

The adapted version of the BMTS model suggested by Williams (ref. 102) is the only suitable model currently available (see table 6-5). Since the development of barley is similar to that of wheat, using the BMTS model for predicting development of barley is quite acceptable. Williams introduced a threshold coefficient as one of the temperature coefficients derived in the model to improve the model theoretically. However, there is no evidence that this addition improved the predictions. Since the model has not been extensively tested, little comment can be made on its range of applicability.

6.5 SORGHUM

The phenology model of Vanderlip and Arkin (ref. 87) has been tested in the southern and central U.S. Great Plains with favorable results where detailed information is available about hybrid and leaf number leaf size. If values for leaf number and leaf size of maturity groups are developed, the phenology model could be tested for use in large area production estimates. The model is described in table 6-6 and in section 5.8.

TABLE 6-4.— ROBERTSON TRIQUADRATIC MODEL FOR WHEAT

[Developed by Robertson (ref. 4); determined to be the best suited model for predicting winter wheat phenology]

Description	Data requirements	Application range
Incorporates nonlinear responses of development to temperature and photoperiod	Maximum temperature (spring and winter wheat)	Successfully predicted spring and winter wheat development over a large range of climate variations
Predicts development over fairly short phenological periods	Minimum temperature (spring and winter wheat)	Less variety dependent for wheat than soybeans
Surpassed the GDD model and Nuttonson's (ref. 88) photothermal model in predicting phenology	Photoperiod (spring and winter wheat)	Insensitive to extreme water stress effects, resulting in erroneous predictions
Coefficients determined by iterative technique; can be easily adjusted to data requirements	Initial set of coefficients (spring and winter wheat)	
Adapted by Phinney and Trenchard (ref. 89) for winter wheat phenology; vernalization coefficient added	Phenological data set for derivation of final set of coefficients (spring and winter wheat)	
Predictions accurate for winter wheat; coefficients changed only for emergence-to-jointing and soft-dough-to-ripe stages	30-year mean January temperature (winter wheat)	
	Mean annual precipitation (winter wheat)	

TABLE 6-5.— ROBERTSON TRIQUADRATIC MODEL FOR BARLEY

[Developed by Robertson (ref. 4); modified by Williams (ref. 102) for predicting spring barley development]

Description	Data requirements	Application range
Incorporates the nonlinear responses of development to temperature and photoperiod	Maximum temperature Minimum temperature	Data tested for small range of locations in Canada
Makes predictions of development over fairly short phenological stages	Photoperiod Temperature threshold	Further testing necessary before applicability in other environmental conditions can be determined, according to Williams
Temperature threshold coefficient introduced by Williams adds derivable coefficient to the iterative process, resulting in an improvement that is more theoretical than applicable.	Phenological data set for derivation of coefficients	

TABLE 6-6.— HEAT UNIT MODEL FOR SORGHUM

[Heat unit model of Vanderlip and Arkin (ref. 87) evaluated as best available sorghum phenology model]

Description	Data requirements	Application range
Linear response to temperature at each developmental stage is major assumption	Daily maximum temperature Daily minimum temperature	Application may be difficult without detailed hybrid information
May over or under predict development during extreme temperature conditions or water stress conditions	Threshold temperatures for stages Varietal heat units required for each stage	May be suitable for varieties grown in latitudes where photoperiod influence is not evident
For each variety of interest, requires heat units for each stage of interest		

7. CONCLUSIONS AND RECOMMENDATIONS

Recommendations for further research of agromet phenological models are as follows:

a. A bio-photothermal model that will predict all stages of corn development needs to be formulated. Coligado's model (ref. 6), which predicts development only up to tassel initiation, is the only theoretically sound model currently available.

b. The Major et al. (ref. 89) soybean model requires testing for a wide range of locations and maturity classes. The influence of variety and climatic factors on the individual coefficients of the model needs further investigation.

c. The BMTS (ref. 4) wheat model could be further improved by incorporating into it a water stress factor that reflects the physiological response of the wheat crop. A soil moisture budget submodel run simultaneously with the BMTS model would be appropriate.

d. The vernalization coefficient of Feyerherm (ref. 91) could be made more sensitive to the temperature range and length of cool temperatures during the vernalization process. An improved function suggested by Nix (personal communication, 1978) would accomplish this requirement.

e. The modified BMTS model for barley (ref. 102) has not been sufficiently tested, nor have the coefficients been evaluated for a range of climatic conditions. Such testing and evaluating must be done before this model can be suggested for predicting phenology of barley.

f. The phenology model developed by Vanderlip and Arkin (ref. 87) may be applicable to large area production estimation if leaf number and leaf size values can be determined for maturity groups rather than individual varieties. If this is done, then the model should receive further testing.

g. For cotton, corn, and soybean (refs. 106, 96, 101), researchers at several centers are developing growth and yield models. When available, the phenology sections of these models should be tested against available phenology data.

8. REFERENCES[1]

1. Doraiswamy, P. C.; and Hodges, T: Crop Yield Literature Review for Corn, Soybeans, Wheat, Barley, Sorghum, Rice, Cotton and Sunflowers. Lockheed Electronics Company, Inc. Tech. Memo. LEC-13791.

2. Cate, R. B.; Artley, J. A.; and Phinney, D. E.: Survey of Literature on Quantitative Estimation of Plant Characteristics Using Spectral Measurements. Lockheed Electronics Company, Inc. Tech. Memo. LEC- (to be published).

3. Loomis, R. S.: Summary, Section I. Dynamics of Development of Photosynthetic Systems. Prediction and Measurement of Photosynthetic Productivity. Proc. IBP/PP Technical Meeting (Trebon), Sept. 14-21, 1969.

4. Robertson, G. W.: A Biometeorological Time Scale for a Cereal Crop Involving Day and Night Temperatures and Photoperiod. Int. J. Biometeorol., vol. 12, 1968, pp. 191-223.

5. Haun, J. R.: Prediction of Spring Wheat Yields From Temperature and Precipitation Data. Agron. J., vol. 66, 1974, pp. 405-409.

6. Coligado, M. C.; and Brown, D. M.: Response of Corn (Zea mays L.) in the Pre-Tassel Initiation Period to Temperature and Photoperiod. Agricultural Meteorology, vol. 14, 1975, pp. 357-367.

7. Passioura, J. B.: Sense and Nonsense in Crop Simulation. J. Australian Inst. Agricultural Sci., Sept. 1973, pp. 181-183.

8. de Wit, C. T.; Brouwer, R.; and Penning de Vries, F. W. T.: A Dynamic Model of Plant and Crop Growth. Potential Crop Production, A Case Study, P. P. Wareing and J. R. Cooper, eds., Heineman Educational Books, Ltd. (London), 1971, pp. 117-142.

9. Duncan, W. G.; Loomis, R. S.; Williams, W. A.; and Hanau, R.: A Model for Simulating Photosynthesis in Plant Communities. Hilgardia, vol. 38, no. 4, 1967, pp. 181-205.

10. Stewart, D. W.: Modeling Plant Atmosphere Systems. Impacts of Climatic Change on the Biosphere. CIAP Monograph 5. Part 2 — Climatic Effects. Dept. of Transportation, Climatic Impact Assessment Program, Office of the Secretary of Transportation (Washington, D.C.), 1975, ch. 3, pp. 3-3-3-17.

---

[1]A bibliography of these references is given in the appendix.

11. Monteith, J. L.: Light Distribution and Photosynthesis in Field Crops. Annals of Botany (N.S.), vol. 29, 1965, pp. 17-37.

12. Connor, D. J.: Growth, Water Relations, and Yield of Wheat. Australian J. Plant Physiology, vol. 2, 1975, pp. 353-366.

13. Rasmussen, V. P.; and Hanks, R. J.: Spring Wheat Yield Model for Limited Moisture Conditions. Agron. J., vol. 70, no. 6, 1978, pp. 940-944.

14. Arkin, G. F.; Vanderlip, R. L.; and Ritchie, J. T.: A Dynamic Grain Sorghum Growth Model. Trans. ASAE, 1976, pp. 622-626, 630.

15. Hodges, T.; and Kanemasu, E. T.: Modeling Dry Matter Production of Winter Wheat. Agron. J., vol. 69, 1977, pp. 974-978.

16. Hodges, T.; Kanemasu, E. T.; and Teare, I. D.: Modeling Dry Matter Accumulation and Yield of Grain Sorghum. Canadian J. Plant Sci., vol. 59, 1979, pp. 803-818.

17. Garner, W. W.; and Allard, H. A.: Effect of the Relative Length of Day and Night and Other Factors of the Environment on Growth and Reproduction in Plants. J. Agricultural Res., vol. 18, 1920, pp. 553-606.

18. Major, D. J.; and Johnson, D. R.: A Review of the Effect of Daylength and Temperature on Development of Soybeans (Glycine max (L.) Merrill). Agriculture Canada Research Station, LRS Mimeo Report 2 (Lethbridge, Alberta, Canada), Feb. 1977.

19. Blondin, F.; Jacques, M.; Jacques, R.; and Mousseau, M.: IV. 2. The Combined Action of Light and Temperature on Development: Some Examples Analyzed in a Phytotron. Environmental Effects on Crop Physiology: Fifth Long Ashton Symp. Academic Press (London), 1975.

20. Vergara, B. S.; Chang, T. T.; and Lilis, R.: The Flowering Response of the Rice Plant to Photoperiod — A Review of the Literature. Int. Rice Res. Inst. Tech. Bull. 8, 1969.

21. Hillman, W. S.: Photoperiodism and Vernalization.: Physiology of Plant Growth and Development. M. B. Wilkins, ed. McGraw-Hill (London), 1969.

22. Major, D. J.: Soybean Development. Proc. of the 1978 LACIE Corn-Soybean Seminar. NASA/JSC (Houston, Tex.), Oct. 1978.

23. Ikeda, K.: Photoperiodic Control of Floral Initiation in Rice Plants I. Light Requirement During the Photoperiod. Proc. Crop Sci. Soc. Japan, vol. 43, 1974, pp. 375-381.

24. Spector, W. S.: Handbook of Biological Data. Philadelphia: Saunders, 1956.

25. Janardhan, K. V.; and Murty, K. S.: Effect of Photoperiod on Panicle Emergence in Rice. Current Sci., vol. 36, 1967, pp. 382-383.

26. Coleman, O. H.; and Belcher, B. A.: Some Responses of Sorgo to Short Photoperiods and Variations in Temperature. Agron. J., vol. 44, 1952, pp. 35-39.

27. Best, R.: Some Aspects of Photoperiodism in Rice (Oryza sativa L.). Elsevier, Amsterdam, 1961.

28. Ahrens, J. F.; and Loomis, W. E.: Floral Induction and Development in Winter Wheat. Crop Sci., vol. 3, 1963, pp. 463-466.

29. Lane, H. C.: Effect of Light Quality on Maturity in the Milo Group of Sorghum. Crop Sci., vol. 3, 1963, pp. 496-499.

30. Mauney, J. R.; and Phillips, L. L.: Influence of Daylength and Night Temperature on Flowering of Gossypium. Botanical Gazette, vol. 124, 1963, pp. 278-283.

31. Gott, M. B.: Flowering of Australian Wheats and Its Relation to Frost Injury. Australian J. Agricultural Res., vol. 12, 1961, pp. 547-565.

32. Kondo, M.; Terasaka, A.; and Umino, M.: Experimental Studies on Photoperiodism in Rice. III. (Translation). Nogaku Kenkyu, vol. 33, 1942, pp. 1-24.

33. Dore, J.: Response of Rice to Small Differences in Length of Day. Nature, vol. 183, 1959, pp. 413-414.

34. Low, A.; Hesketh, J.; and Muramota, H.: Some Environmental Effects on the Varietal Node Number of the First Fruiting Branch. Cotton Growing Rev., vol. 46, 1969, pp. 181-188.

35. Cate, R. B.; and Hsu, Y. T.: An Algorithm for Defining Linear Programming Activities Using the Law of the Minimum. North Carolina Agricultural Experiment Station Tech. Bull. 253, 1978.

36. Salisbury, F. B.; and Ross, C.: Photoperiodism and the Physiology of Flowering. Plant Physiology. Wadsworth Publishing Co., Inc. (Belmont, Calif.), 1974.

37. Went, F. W.: The Response of Plant to Climate. Science, vol. 112, 1950, pp. 489-494.

38. Went, F. W.: The Physiology of Photosynthesis in Higher Plants. Preslia, vol. 30, 1958, pp. 225-249.

39. Das, U. K.: The Problem of Juice Quality. Hawaiian Planters' Record, vol. 35, 1931, pp. 163-200.

40. Halse, N. J.; and Weir, R. N.: Effects of Vernalization, Photoperiod, and Temperature on Phenology Development and Spikelet Number of Australian Winter Wheat. Australian J. Agricultural Res., vol. 21, 1970, pp. 383-393.

41. Slatyer, R. O.: Physiological Significance of Internal Water Relations to Crop Yield. Physiological Aspects of Crop Yield, J. D. Eastin et al., eds. American Society of Agronomy, Madison, Wisc., 1969.

42. Landsberg, J. J.: Effects of Weather on Plant Development. Environmental Effects on Crop Physiology. 5th Long Ashton Symposium. Academic Press (London), 1975.

43. Whiteman, P. C.; and Wilson, G. L.: The Effects of Water Stress on the Reproductive Development of Sorghum vulgare Pers. Queensland Univ. Papers (Dept. of Botany), vol. 4, 1965, pp. 233-239.

44. Volodarski, N. I.; and Zinevich, L. V.: Drought Resistance of Corn During Ontogeny. Fiziol. Rast., vol. 7, 1960, pp. 176-179.

45. Sumayo, C.; Kanemasu, E. T.; and Hodges, T.: Soil Moisture Effects on Transpiration and Net Carbon Dioxide Exchange of Sorghum. Agricultural Meteorology, vol. 18, 1977, pp. 401-408.

46. Tisdale, S. L.; and Nelson, W. L.: Soil Fertility and Fertilizers. Second ed. The MacMillan Company (New York), 1966.

47. Martin, J. H.; and Leonard, W. H.: Principles of Field Crop Production. Second ed. The MacMillan Company (New York), 1967.

48. FAO Production Yearbook, 1977. Food and Agriculture Organization of the United Nations. Rome, FAO, vol. 31, 1977.

49. Hanway, J. J.: Growth Stages of Corn (Zea mays L.). Agron. J., vol. 55, 1963, pp. 487-492.

50. Borthwick, H. A.; and Parker, M. W.: Effectiveness of Photoperiodic Treatments of Plants of Different Age. Botanical Gazette, vol. 100, 1938, pp. 245-249.

51. da Mota, F. S.: Soybean and Weather. World Meteorological Organization, Tech. Note 160. Secretariat of the WMO, Geneva, 1978.

52. Fehr, W. R.; and Caviness, C. E.: Stages of Soybean Development. Cooperative Extension Service. Iowa State Univ. and Home Econ. Exp. Station, Special Report 80 (Ames), 1977.

53. Thompson, H. E.: How a Soybean Plant Develops. Iowa State Univ., Cooperative Extension Service (Ames), 1971.

54. Asana, R. D.; and Williams, R. F.: The Effect of Temperature Stress on Grain Development in Wheat. Australian J. Agricultural Res., vol. 16, 1965, pp. 1-13.

55. Large, E. C.: Growth Stages in Cereals: Illustrations of Feekes' Scale. Plant Pathology, vol. 3, 1954, pp. 128-129. [Primary source — Feekes, W.: DeFarwe in Haar Millieu. Vers. XVII Tech. Farwe Comm. (Groningen, Germany), 1941, pp. 560-561.]

56. Waldren, R. P.; and Flowerday, A. D.: Growth Stages and Distribution of Dry Matter, N, P, and K in Winter Wheat. Agron. J., vol. 71, 1979, pp. 391-397.

57. Blum, A.; and Naveh, M.: Improved Water-Use Efficiency in Dryland Grain Sorghum by Promoted Plant Competition. Agron. J., vol. 68, 1976, pp. 111-116.

58. Miller, F. R.; Barnes, D. K.; and Cruzado, H. I.: Effect of Tropical Photoperiods on the Growth of Sorghum When Grown in 12 Monthly Plantings. Crop Sci., vol. 8, 1968, pp. 499-502.

59. Caddel, J. L.; and Weibel, D. E.: Effect of Photoperiod and Temperature on the Development of Sorghum. Agron. J., vol. 63, 1971, pp. 799-803.

60. Caddel, J. L.; and Weibel, D. E.: Photoperiodism in Sorghum. Agron. J., vol. 64, 1972, pp. 473-476.

61. Vanderlip, R. L.; and Reeves, H. E.: Growth Stages of Sorghum (Sorghum bicolor (L.) Moench.). Agron. J., vol. 64, 1972, pp. 13-16.

62. Owen, P. C.: The Effects of Temperature on the Growth and Development of Rice. Field Crop Abstracts, vol. 24, 1971, pp. 1-8.

63. Board, J. E.; Peterson, M. L.; and Rutger, J. N.: Response of California Rice Varieties to Cool Temperatures. California Agriculture, vol. 33, no. 2, 1979, pp. 10-11.

64. Satake, T.; and Yoshida, S.: A Mechanism of Sterility Caused by High Temperature at Flowering Time in Indica Rice. Japanese Agricultural Res. Quart., vol. 11, 1977, pp. 127-128.

65. Satake, T.; and Yoshida, S.: Critical Temperature and Duration for High Temperature-Induced Sterility in Indica Rice. Japanese Agricultural Res. Quart., vol. 11, 1977, pp. 190-191.

66. Satake, T.; and Yoshida, S.: High Temperature-Induced Sterility in Indica Rices at Flowering. Japanese J. Crop Sci., vol. 47, 1978, pp. 6-17.

67. Vergara, B. S.; and Lilis, R.: Response to Photoperiod of Reported Long-day and Intermediate Varieties of Rice. Nature, vol. 216, 1967, p. 168.

68. Mauney, J. R.: Morphology of the Cotton Plant. Advances in Production and Utilization of Quality Cotton: Principles and Practices, E. C. Elliot et al., eds. Iowa State Univ. Press. (Ames), 1968.

69. Carnes, H. R.; and Mauney, J. R.: Physiology of the Cotton Plant. Advances in Production and Utilization of Quality Cotton. Principles and Practices, E. C. Elliot et al., eds. Iowa State Univ. Press (Ames), 1968.

70. Lewis, C. F.; and Richmond, T. R.: Cotton As a Crop. Advances in Production and Utilization of Quality Cotton. Principles and Practices, E. C. Elliot et al., eds. Iowa State University Press (Ames), 1968.

71. Mauney, J. R.: Floral Initiation of Upland Cotton Gossypium hirsutum L. in Response to Temperatures. J. Experimental Botany, vol. 17, 1966, pp. 452-459.

72. Tharp, W. H.: The Cotton Plant: How It Grows and Why Its Growth Varies. USDA/ARS Agriculture Handbook No. 178, 1965.

73. Stanhill, G.: Cotton. Vegetation and the Atmosphere, Vol. II. Case Studies, J. L. Monteith, ed. Academic Press (New York), 1976, pp. 121-150.

74. Robinson, R. G.: Production and Culture. Ch. 4. Sunflower Science and Technology, J. F. Carter, ed. American Society of Agronomy (Madison, Wisc.), 1978, pp. 89-144.

75. Warren Wilson, J.: Effect of Temperature on Net Assimilation Rate. Annals of Botany, vol. 30, 1967, pp. 753-761.

76. Knowles, P. F.: Morphology and Anatomy. Ch. 3. Sunflower Science and Technology, J. F. Carter, ed., American Soc. Agronomy (Madison, Wisc.), 1978, pp. 55-88.

77. Robinson, R. G.: Sunflower Phenology-Year, Variety, and Date of Planting Effects on Day and Growing Degree-Day Summations. Crop Sci., vol. 11, 1971, pp. 635-638.

78. Aspiazu, C.; and Shaw, R. H.: Comparison of Several Methods of Growing Degree-Unit Calculations for Corn (Zea mays L.). Iowa State J. Sci., vol. 46, 1972, pp. 435-442.

79. Neild, R. E.; and Seeley, M. W.: Growing Degree Days Predictions for Corn and Sorghum Development and Some Applications to Crop Production in Nebraska. The Univ. of Nebraska Agricultural Experiment Station, Res. Bull. 280. Institute of Agriculture and Natural Resources (Lincoln), 1977.

80. Brown, D. M.: Heat Units for Corn in Southern Ontario. Ontario Ministry of Agriculture and Food, Soil and Crop Branch, 1976.

81. Prine, G. M.; Guilarte, T. C.; and Duncan, W. G.: Corn Maturity Dates for Different Florida Locations and Planting Dates Based on Growing Degree Days. Proc. Soil and Crop Sci. Society of Florida, vol. 34, 1975, pp. 134-137.

82. Shaw, R. H.: Growing Degree Units for Corn in the North Central Region. Iowa State Univ. Agri. and Home Ec. Exp. Station, Res. Bull. 581 (Ames), 1975.

83. Brown, D. M.: Soybean Ecology. I. Development-Temperature Relationships From Controlled Environment Studies. Agron. J., vol. 52, 1960, pp. 493-496.

84. Brooks, R. M.: Apricot Harvest Predictable. California Agriculture, vol. 5, 1951, pp. 3-14.

85. Wiggens, S. C.: The Effect of Seasonal Temperatures on Maturity of Oats Planted at Different Dates. Agron. J., vol. 48, 1936, pp. 21-25.

86. Lindsey, A. A.; and Newman, J. E.: Use of Official Weather Data in Springtime-Temperature Analysis of an Indian Phenological Record. Ecology, vol. 37, 1956, pp. 812-823.

87. Vanderlip, R. L.; and Arkin, G. F.: Simulating Accumulation and Distribution of Dry Matter in Grain Sorghum. Agron. J., vol. 69, 1977, pp. 917-923.

88. Nuttonson, M. Y.: Some Preliminary Observations of Phenological Data As a Tool in the Study of Photoperiodic and Thermal Requirements of Various Plant Material. Vernalization and Photoperiodism Symp. Chronica Botanica (Waltham, Mass.), 1948, pp. 129-143.

89. Major, D. J.; Johnson, D. R.; Tanner, J. W.; and Anderson, I. C.: Effects of Daylength and Temperature on Soybean Development. Crop Sci., vol. 15, 1975, pp. 174-179.

90. Phinney, D. E.; and Trenchard, M. H.: Rederivation of the Winter Wheat Adjustable Crop Calendar Based on Crop Reporting District Data. Lockheed Electronics Company, Inc., Tech. Memo. LEC-10692, 1977.

91. Feyerherm, A. M.: Adjusting Robertson's Biometeorological Time Scale to Winter Wheat Environments and Varietal Maturities. Kansas State Univ. (Manhattan). Unpublished Report, Feb. 23, 1976.

92. Kish, A. J.; Ogle, W. L.; and Loadholt, C. B.: A Prediction Technique for Snap Bean Maturity Incorporating Soil Moisture With the Heat Unit System. Agricultural Meteorology, vol. 10, 1972, pp. 201-210.

93. Baron, V.; Shaykewich, C. F.; and Hamilton, R. I.: Relation of Corn Maturity to Climatic Parameters. Canadian J. Soil Sci., vol. 55, no. 3, 1975, pp. 343-348.

94. Ragland, J. L.; Hatfield, A. L.; and Benoit, G. R.: Photoperiod Effects on the Ear Components of Corn (Zea mays. L.). Agron. J., vol. 58, 1966, pp. 455-456.

95. Hunter, R. B.; Hunt, L. A.; and Kannenburg, L. W.: Photoperiod and Temperature Effects on Corn. Canadian J. Plant Sci., vol. 54, 1974, pp. 71-78.

96. Fritton, D. D.; Knieval, D. P.; Martsolf, J. D.; McKee, G. W.; Norman, J. M.; Tukey, L. D.: Project NE-48: The Dynamics and Energetics of the Soil-Plant-Atmosphere Continum (SPAC). Annual Progress Report, the Pennsylvania Agricultural Experiment Station, 1976.

97. Howell, R. W.: Agron. J., vol. 50, 1958, pp. 664-667.

98. Steinberg, R. A.; and Garner, W. W.: Response of Certain Plants to Length of Day and Temperature Under Controlled Conditions. J. Agricultural Res., vol. 52, 1936, pp. 943-960.

99. Lawn, R. J.; and Byth, D. E.: Response of Soybeans to Planting Date in South Eastern Queensland. I. Influence of Photoperiod and Temperature on Phasic Development Patterns. Australian J. Agricultural Res., vol. 24, 1973, pp. 67-80.

100. Major, D. J.; Johnson, D. R.; and Luedders, V. D.: Evaluation of Eleven Thermal Unit Methods for Predicting Soybean Development. Crop Sci., vol. 15, 1975, pp. 172-174.

101. Curry, R. B.: Dynamic Simulation of Plant Growth – Part 1. Development of a Model. Trans. ASAE, 1971, pp. 946-949, and 959.

102. Williams, C. D. W.: Deriving a Biophotothermal Time Scale for Barley. Int. J. Biometeorology, vol. 18, no. 1, 1974, pp. 57-69.

103. Chujo, H.: Studies in Short-day Vernalization of Barley. 3. Difference in Short-day Vernalization Effect as Affect by Temperature. Proc. Crop Sci. Soc. Japan, vol. 31, 1962, pp. 150-154.

104. Maas, S. J.; Arkin, G. F.; Bremer, J. E.; and McFarland, M. J.: Sorghum Advisory Pilot Project: Application of Operational Weather Forecasts to Predicting Management-Oriented Crop Status. Preprint Volume, 14th Conference on Agriculture and Forest Meteorology and 4th Conference on Biometeorology, April 2-6, 1979 (Minneapolis, Minn.). American Meteorological Society.

105. Hodges, T.: Photosynthesis, Growth, and Yield of Sorghum and Winter Wheat as Functions of Light, Temperature, Water, and Leaf Area. Ph. D. Dissertation. Kansas State University (Manhattan, Kansas), University microfilm no. 78-21869, 1978.

106. Hesketh, J. D.; Baker, D. N.; and Duncan, W. G.: Simulation of Growth and Yield in Cotton: Vol. II. Environmental Control of Morphogenesis. Crop Sci., vol. 12, 1972, pp. 436-439.

107. Whisler, F. D.; Landivar, J. A.; and Baker, D. N.: A Sensitivity Test of Weather Variables in the GOSSYM Cotton Simulation Model. Program and Abstracts: Workshop on Crop Simulation. Purdue University (West Lafayette, Indiana), May 15-17, 1979.

APPENDIX A

BIBLIOGRAPHY

BIBLIOGRAPHY

Ahrens, J. F.; and Loomis, W. E.: Floral Induction and Development in Winter Wheat. Crop Sci., vol. 3, 1963, pp. 463-466.

Arkin, G. F.; Vanderlip, R. L.; and Ritchie, J. T.: A Dynamic Grain Sorghum Growth Model. Trans. ASAE, 1976, pp. 622-626, 630.

Asana, R. D.; and Williams, R. F.: The Effect of Temperature Stress on Grain Development in Wheat. Australian J. Agricultural Res., vol. 16, 1965, pp. 1-13.

Aspiazu, C.; and Shaw, R. H.: Comparison of Several Methods of Growing Degree-Unit Calculations for Corn (Zea mays L.). Iowa State J. Sci., vol. 46, 1972, pp. 435-442.

Baron, V.; Shaykewich, C. F.; and Hamilton, R. I.: Relation of Corn Maturity to Climatic Parameters. Canadian J. Soil Sci., vol. 55, no. 3, 1975, pp. 343-348.

Best, R.: Some Aspects of Photoperiodism in Rice (Oryza sativa L.). Elsevier, Amsterdam, 1961.

Blondin, F.; Jacques, M.; Jacques, R.; and Mousseau, M.: IV. 2. The Combined Action of Light and Temperature on Development: Some Examples Analyzed in a Phytotron. Environmental Effects on Crop Physiology: Fifth Long Ashton Symp. Academic Press (London), 1975.

Blum, A.; and Naveh, M.: Improved Water-Use Efficiency in Dryland Grain Sorghum by Promoted Plant Competition. Agron. J., vol. 68, 1976, pp. 111-116.

Board, J. E.; Peterson, M. L.; and Rutger, J. N.: Response of California Rice Varieties to Cool Temperatures. California Agriculture, vol. 33, no. 2, 1979, pp. 10-11.

Borthwick, H. A.; and Parker, M. W.: Effectiveness of Photoperiodic Treatments of Plants of Different Age. Botanical Gazette, vol. 100, 1938, pp. 245-249.

Brooks, R. M.: Apricot Harvest Predictable. California Agriculture, vol. 5, 1951, pp. 3-14.

Brown, D. M: Heat Units for Corn in Southern Ontario. Ontario Ministry of Agriculture and Food, Soil and Crop Branch, 1976.

Brown, D. M.: Soybean Ecology. I. Development-Temperature Relationships From Controlled Environment Studies. Agron. J., vol. 52, 1960, pp. 493-496.

Caddel, J. L.; and Weibel, D. D.: Effect of Photoperiod and Temperature on the Development of Sorghum. Agron. J., vol. 63, 1971, pp. 799-803.

Caddel, J. L.; and Weibel, D. E.: Photoperiodism in Sorghum. Agron. J., vol. 64, 1972, pp. 473-476.

Carnes, H. R.; and Mauney, J. R.: Physiology of the Cotton Plant. Advances in Production and Utilization of Quality Cotton. Principles and Practices, E. C. Elliot et al., eds. Iowa State Univ. Press (Ames), 1968.

Cate, R. B.; Artley, J. A.; and Phinney, D. E.: Survey of Literature on Quantitative Estimation of Plant Characteristics Using Spectral Measurements. Lockheed Electronics Company, Inc. Tech. Memo. LEC- (to be published).

Cate, R. B.; and Hsu, Y. T.: An Algorithm for Defining Linear Programming Activities Using the Law of the Minimum. North Carolina Agricultural Experiment Station Tech. Bull. 253, 1978.

Chujo, H.: Studies in Short-day Vernalization of Barley. 3. Difference in Short-day Vernalization Effect as Affect by Temperature. Proc. Crop Sci. Soc. Japan, vol. 31, 1962, pp. 150-154.

Coleman, O. H.; and Belcher, B. A.: Some Responses of Sorgo to Short Photoperiods and Variations in Temperature. Agron. J., vol. 44, 1952, pp. 35-39.

Coligado, M. C.; and Brown, D. M.: Response of Corn (Zea mays L.) in the Pre-Tassel Initiation Period to Temperature and Photoperiod. Agricultural Meteorology, vol. 14, 1975, pp. 357-367.

Connor, D. J.: Growth, Water Relations, and Yield of Wheat. Australian J. Plant Physiology, vol. 2, 1975, pp. 353-366.

Curry, R. B.: Dynamic Simulation of Plant Growth — Part 1. Development of a Model. Trans. ASAE, 1971, pp. 946-949, and 959.

Das, U. K.: The Problem of Juice Quality. Hawaiian Planters' Record, vol. 35, 1931, pp. 163-200.

Doraiswamy, P. C.; and Hodges, T.: Crop Yield literature Review for Corn, Soybeans, Wheat, Barley, Sorghum, Rice, Cotton and Sunflowers. Lockheed Electronics Company, Inc. Tech. Memo. LEC-13791.

Dore, J.: Response of Rice to Small Differences in Length of Day. Nature, vol. 183, 1959, pp. 413-414.

Duncan, W. G.; Loomis, R. S.; Williams, W. A.; and Hanau, R.: A Model for Simulating Photosynthesis in Plant Communities. Hilgardia, vol. 38, no. 4, 1967, pp. 181-205.

FAO Production Yearbook. 1977. Food and Agriculture Organization of the Unites Nations. Rome, FAO, vol. 31, 1977.

Fehr, W. R.; and Caviness, C. E.: Stages of Soybean Development. Cooperative Extension Service. Iowa State Univ. and Home Econ. Exp. Station, Special Report 80 (Ames), 1977.

Feyerherm, A. M.: Adjusting Robertson's Biometeorological Time Scale to Winter Wheat Environments and Varietal Maturities. Kansas State Univ. (Manhattan). Unpublished Report, Feb. 23, 1976.

Fritton, D. D.; Knieval, D. P.; Martsolf, J. D.; Mckee, G. W.; Norman, J. M.; Tukey, L. D.: Project NE-48: The Dynamics and Energetics of the Soil-Plant-Atmosphere Continuum (SPAC). Annual Progress Report, the Pennsylvania Agricultural Experiment Station, 1976.

Garner, W. W.; and Allard, H. A.: Effect of the Relative Length of Day and Night and Other Factors of the Environment on Growth and Reproduction in Plants. J. Agricultural Res., vol. 18, 1920, pp. 553-606.

Gott, M. B.: Flowering of Australian Wheats and Its Relation to Frost Injury. Australian J. Agricultural Res., vol. 12, 1961, pp. 547-565.

Halse, N. J.; and Weir, R. N.: Effects of Vernalization, Photoperiod, and Temperature on Phenology Development and Spikelet Number of Australian Winter Wheat. Australian J. Agricultural Res., vol. 21, 1970, pp. 383-393.

Hanway, J. J.: Growth Stages of Corn (Zea mays L.). Agron. J., vol. 55, 1963, pp. 487-492.

Haun, J. R.: Prediction of Spring Wheat Yields From Temperature and Precipitation Data. Agron. J., vol. 66, 1974, pp. 405-409.

Hesketh, J. D.; Baker, D. N.; and Duncan, W. G.: Simulation of Growth and Yield in Cotton: Vol. II. Environmental Control of Morphogenesis. Crop Sci., vol. 12, 1972, pp. 436-439.

Hillman, W. S.: Photoperiodism and Vernalization.: Physiology of Plant Growth and Development. M. B. Wilkins, ed. McGraw-Hill (London), 1969.

Hodges, T.: Photosynthesis, Growth, and Yield of Sorghum and Winter Wheat as Functions of Light, Temperature, Water, and Leaf Area. Ph. D. Dissertation. Kansas State University (Manhattan, Kansas), University microfilm no. 78-21869, 1978.

Hodges, T.; and Kanemasu, E. T.: Modeling Dry Matter Production of Winter Wheat. Agron. J., vol. 69, 1977, pp. 974-978.

Hodges, T.; Kanemasu, E. T.; and Teare, I. D.: Modeling Dry Matter Accumulation and Yield of Grain Sorghum. Canadian J. Plant Sci., vol. 59, 1979, pp. 803-818.

Howell, R. W.: Agron. J., vol. 50, 1958, p. 664-667.

Hunter, R. B.; Hunt, L. A.; and Kannenburg, L. W.: Photoperiod and Temperature Effects on Corn. Canadian J. Plant Sci., vol. 54, 1974, pp. 71-78.

Ikeda, K.: Photoperiodic Control of Floral Initiation in Rice Plants I. Light Requirement During the Photoperiod. Proc. Crop Sci. Soc. Japan, vol. 43, 1974, pp. 375-381.

Janardhan, K. V.; and Murty, K. S.: Effect of Photoperiod on Panicle Emergence in Rice. Current Sci., vol. 36, 1967, pp. 382-383.

Kish, A. J.; Ogle, W. L.; and Loadholt, C. B.: A Prediction Technique for Snap Bean Maturity Incorporating Soil Moisture With the Heat Unit System. Agricultural Meteorology, vol. 10, 1972, pp. 201-210.

Knowles, P. F.: Morphology and Anatomy. Ch. 3. Sunflower Science and Technology, J. F. Carter, ed., American Soc. Agronomy (Madison, Wisc.), 1978, pp. 55-88.

Kondo, M.; Terasaka, A.; and Umino, M.: Experimental Studies on Photoperiodism in Rice. III. (Translation). Nogaku Kenkyu, vol. 33, 1942, pp. 1-24.

Landsberg, J. J.: Effects of Weather on Plant Development. Environmental Effects on Crop Physiology. 5th Long Ashton Symposium. Academic Press (London), 1975.

Lane, H. C.: Effect of Light Quality on Maturity in the Milo Group of Sorghum. Crop Sci., vol. 3, 1963, pp. 496-499.

Large, E. C.: Growth Stages in Cereals: Illustrations of Feekes' Scale. Plant Pathology, vol. 3, 1954, pp. 128-129. [Primary source — Feekes, W.: DeFarwe in Haar Millieu. Vers. XVII Tech. Farwe Comm. (Groningen, Germany), 1941, pp. 560-561.]

Lawn, R. J.; and Byth, D. E.: Response of Soybeans to Planting Date in South Eastern Queensland. I. Influence of Photoperiod and Temperature on Phasic Development Patterns. Australian J. Agricultural Res., vol. 24, 1973, pp. 67-80.

Lewis, C. F.; and Richmond, T. R.: Cotton As a Crop. Advances in Production and Utilization of Quality Cotton. Principles and Practices, E. C. Elliot et al., eds. Iowa State University Press (Ames), 1968.

Lindsey, A. A.; and Newman, J. E.: Use of Official Weather Data in Springtime-Temperature Analysis of an Indian Phenological Record. Ecology, vol. 37, 1956, pp. 812-823.

Loomis, R. S.: Summary, Section I. Dynamics of Development of Photosynthetic Systems. Prediction and Measurement of Photosynthetic Productivity. Proc. IBP/PP Technical Meeting (Trebon), Sept. 14-21, 1969.

Low, A.; Hesketh, J.; and Muramota, H.: Some Environmental Effects on the Varietal Node Number of the First Fruiting Branch. Cotton Growing Rev., vol. 46, 1969, pp. 181-188.

Maas, S. J.; Arkin, G. F.; Bremer, J. E.; and McFarland, M. J.: Sorghum Advisory Pilot Project: Application of Operational Weather Forecasts to Predicting Management-Oriented Crop Status. Preprint Volume, 14th Conference on Agriculture and Forest Meteorology and 4th Conference on Biometeorology, April 2-6, 1979 (Minneapolis, Minn.). American Meteorological Society.

Major, D. J.: Soybean Development. Proc. of the 1978 LACIE Corn-Soybean Seminar. NASA/JSC (Houston, Tex.), Oct. 1978.

Major, D. J.; and Johnson, D. R.: A Review of the Effect of Daylength and Temperature on Development of Soybeans (Glycine max (L.) Merrill). Agriculture Canada Research Station, LRS Mimeo Report 2 (Lethbridge, Alberta, Canada), Feb. 1977.

Major, D. J.; Johnson, D. R.; and Luedders, V.D.: Evaluation of Eleven Thermal Unit Methods for Predicting Soybean Development. Crop Sci., vol. 15, 1975, pp. 172-174.

Major, D. J.; Johnson, D. R.; Tanner, J. W.; and Anderson, I. C.: Effects of Daylength and Temperature on Soybean Development. Crop Sci., vol. 15, 1975, pp. 174-179.

Martin, J. H.; and Leonard, W. H.: Principles of Field Crop Production. Second ed. The MacMillian Company (New York), 1967.

Mauney, J. R.: Floral Initiation of Upland Cotton Gossypium hirsutum L. in Response to Temperatures. J. Experimental Botany, vol. 17, 1966, pp. 452-459.

Mauney, J. R.: Morphology of the Cotton Plant. Advances in Production and Utilization of Quality Cotton: Principles and Practices, E. C. Elliot et al., eds. Iowa State Univ. Press (Ames), 1968.

Mauney, J. R.; and Phillips, L. L.: Influence of Daylength and Night Temperature on Flowering of Gossypium. Botanical Gazette, vol. 124, 1963, pp. 278-283.

Miller, F. R.; Barnes, D. K.; and Cruzado, H. I.: Effect of Tropical Photoperiods on the Growth of Sorghum When Grown in 12 Monthly Plantings. Crop Sci., vol. 8, 1968, pp. 499-502.

Monteith, J. L.: Light Distribution and Photosynthesis in Field Crops. Annals of Botany (N.S.), vol. 29, 1965, pp. 17-37.

da Mota, F. S.: Soybean and Weather. World Meteorological Organization, Tech. Note 160. Secretariat of the WMO, Geneva, 1978.

Neild, R. E.; and Seeley, M. W.: Growing Degree Days Predictions for Corn and Sorghum Development and Some Applications to Crop Production in Nebraska. The Univ. of Nebraska Agricultural Experiment Station, Res. Bull. 280. Institute of Agriculture and Natural Resources (Lincoln), 1977.

Nuttonson, M. Y.: Some Preliminary Observations of Phenological Data As a Tool in the Study of Photoperiodic and Thermal Requirements of Various Plant Material. Vernalization and Photoperiodism Symp. Chronica Botanica (Waltham, Mass.), 1948, pp. 129-143.

Owen, P. C.: The Effects of Temperature on the Growth and Development of Rice. Field Crop Abstracts, vol. 24, 1971, pp. 1-8.

Passioura, J. B.: Sense and Nonsense in Crop Simulation. J. Australian Inst. Agricultural Sci., Sept. 1973, pp. 181-183.

Phinney, D. E.; and Trenchard, M. H.: Rederivation of the Winter Wheat Adjustable Crop Calendar Based on Crop Reporting District Data. Lockheed Electronics Company, Inc., Tech. Memo. LEC-10692, 1977.

Prine, G. M.; Guilarte, T. C.; and Duncan, W. G.: Corn Maturity Dates for Different Florida Locations and Planting Dates Based on Growing Degree Days. Proc. Soil and Crop Sci. Society of Florida, vol. 34, 1975, pp. 134-137.

Ragland, J. L.; Hatfield, A. L.; and Benoit, G. R.: Photoperiod Effects on the Ear Components of Corn (Zea mays. L.). Agron. J., vol. 58, 1966, pp. 455-456.

Rasmussen, V. P.; and Hanks, R. J.: Spring Wheat Yield Model for Limited Moisture Conditions. Agron. J., vol. 70, no. 6, 1978, pp. 940-944.

Robertson, G. W.: A Biometeorological Time Scale for a Cereal Crop Involving Day and Night Temperatures and Photoperiod. Int. J. Biometeorol., vol. 12, 1968, pp. 191-223.

Robinson, R. G.: Production and Culture. Ch. 4. Sunflower Science and Technology, J. F. Carter, ed. American Society of Agronomy (Madison, Wisc.), 1978, pp. 89-144.

Robinson, R. G.: Sunflower Phenology-Year, Variety, and Date of Planting Effects on Day and Growing Degree-Day Summations. Crop Sci., vol. 11, 1971, pp. 635-638.

Salisbury, F. B.; and Ross, C.: Photoperiodism and the Physiology of Flowering. Plant Physiology. Wadsworth Publishing Co., Inc. (Belmont, Calif.), 1974.

Satake, T.; and Yoshida, S.: Critical Temperature and Duration for High Temperature-Induced Sterility in Indica Rice. Japanese Agricultural Res. Quart., vol. 11, 1977, pp. 190-191.

Satake, T.; and Yoshida, S.: A Mechanism of Ste ty Caused by High Temperature at Flowering Time in Indica Rice. Japanese Agricultural Res. Quart., vol. 11, 1977, pp. 127-128.

Satake, T.; and Yoshida, S.: High Temperature-Induced Sterility in Indica Rices at Flowering. Japanese J. Crop Sci., vol. 47, 1978, pp. 6-17.

Shaw, R. H.: Growing Degree Units for Corn in the North Central Region. Iowa State Univ. Agri. and Home Ec. Exp. Station, Res. Bull. 581 (Ames), 1975.

Slatyer, R. O.: Physiological Significance of Internal Water Relations to Crop Yield. Physiological Aspects of Crop Yield, J. D. Eastin et al., eds. American Society of Agronomy, Madison, Wisc., 1969.

Spector, W. S.: Handbook of Biological Data. Philadelphia: Saunders, 1956.

Stanhill, G.: Cotton. Vegetation and the Atmosphere, Vol. II. Case Studies, J. L. Monteith, ed. Academic Press (New York), 1976, pp. 121-150.

Steinberg, R. A.; and Garner, W. W.: Response of Certain Plants to Length of Day the Temperature Under Controlled Conditions. J. Agricultural Res., vol. 52, 1936, pp. 943-960.

Stewart, D. W.: Modeling Plant Atmosphere Systems. Impacts of Climatic Change on the Biosphere. CIAP Monograph 5. Part 2 _ Climatic Effects. Dept. of Transportation, Climatic Impact Assessment Program, Office of the Secretary of Transporation (Washington, D.C.), 1975, ch. 3, pp. 3-3-3-17.

Sumayo, C.; Kanemasu, E. T.; and Hodges, T.: Soil Moisture Effects on Transpiration and Net Carbon Dioxide Exchange of Sorghum. Agricultural Meteorology, vol. 18, 1977, pp. 401-408.

Thompson, H. E.: How a Soybean Plant Develops. Iowa State Univ., Cooperative Extension Service (Ames), 1971.

Tharp, W. H.: The Cotton Plant: How It Grows and Why Its Growth Varies. USDA/ARS Agriculture Handbook No. 178, 1965.

Tisdale, S. L.; and Nelson, W. L.: Soil Fertility and Fertilizers. Second ed. The MacMillian Company (New York), 1966.

Vanderlip, R. L.; and Reeves, H. E.: Growth Stages of Sorghum (Sorghum bicolor (L.) Moench.). Agron. J., vol. 64, 1972, pp. 13-16.

Vanderlip, R. L.; and Arkin, G. F.: Simulating Accumulation and Distribution of Dry Matter in Grain Sorghum. Agron. J., vol. 69, 1977, pp. 917-923.

Vergara, B. S.; Chang, T. T.; and Lilis, R.: The Flowering Response of the Rice Plant to Photoperiod — A Review of the Literature. Int. Rice Res. Inst. Tech. Bull. 8, 1969.

Vergara, B. S.; and Lilis, R.: Response to Photoperiod of Reported Long-day and Intermediate Varieties of Rice. Nature, vol. 216, 1967, p. 168.

Volodarski, N. I.; and Zinevich, L. V.: Drought Resistance of Corn During Ontogeny. Fiziol. Rast., vol. 7, 1960, pp. 176-179.

Waldren, R. P.; and Flowerday, A. D.: Growth Stages and Distribution of Dry Matter, N, P, and K in Winter Wheat. Agron. J., vol. 71, 1979, pp. 391-397.

Warren Wilson, J.: Effect of Temperature on Net Assimilation Rate. Annals of Botany, vol. 30, 1967, pp. 753-761.

Went, F. W.: The Physiology of Photosynthesis in Higher Plants. Preslia, vol. 30, 1958, pp. 225-249.

Went, F. W.: The Response of Plant to Climate. Science, vol. 112, 1950, pp. 489-494.

Whisler, F. D.; Landivar, J. A.; and Baker, D. N.: A Sensitivity Test of Weather Variables in the GOSSYM Cotton Simulation Model. Program and Abstracts: Workshop on Crop Simulation. Purdue University (West Lafayette, Indiana), May 15-17, 1979.

Whiteman, P. C.; and Wilson, G. L.: The Effects of Water Stress on the Reproductive Development of Sorghum vulgare Pers. Queensland Univ. Papers (Dept. of Botany), vol. 4, 1965, pp. 233-239.

Wiggens, S. C.: The Effect of Seasonal Temperatures on Maturity of Oats Planted at Different Dates. Agron. J., vol. 48, 1936, pp. 21-25.

Williams, C. D. W.: Deriving a Biophotothermal Time Scale for Barley. Int. J. Biometeorology, vol. 18, no. 1, 1974, pp. 57-69.

de Wit, C. T.; Brouwer, R.; and Penning de Vries, F. W. T.: A Dynamic Model of Plant and Crop Growth. Potential Crop Production, A Case Study, P. P. Wareing and J. R. Cooper, eds., Heineman Educational Books, Ltd. (London), 1971, p. 117-142.