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CROP YIELD LITERATURE REVIEW FOR AgRISTARS CROPS CORN, SOYBEANS, WHEAT, BARLEY, SORGHUM, RICE, COTTON, AND SUNFLOWERS

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CROP YIELD LITERATURE REVIEW FOR AgRISTARS CROPS CORN, SOYBEANS, WHEAT, BARLEY, SORGHUM, RICE, COTTON, AND SUNFLOWERS

Job Order 73-312

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

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1. INTRODUCTION

Crop response models used in the monitoring of large area crop production by the National Aeronautics and Space Administration (NASA) currently are being coordinated through the Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program. Pertinent areas of the program include classification and acreage estimation of field crops, estimation of yield for each crop, and detection of episodic events significantly influencing crop production. AgRISTARS is a 6-year NASA program in cooperation with 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 of, cost of, 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:

a. Early Warning/Crop Condition Assessment (EW/CCA)

b. Foreign Commodity Production Forecasting (FCPF)

c. Yield Model Development (YMD)

d. Supporting Research (SR)

e. Soil Moisture (SM)

f. Domestic Crops and Land Cover (DCLC)

g. Renewable Resources Inventory (RRI)

h. Conservation and Pollution (C/P)

The program is structured so that crop yield is an integral part of the system. Many of the above mentioned projects are geared to aid in the economics of production and prediction of deterrents to potential yield.

This report reviews the technical literature pertaining to the effect of environmental factors and crop responses on the yield for eight AgRISTARS crops: wheat, barley, corn, soybeans, sorghum, cotton, rice, and sunflowers. The state of the art in modeling the yield of these crops using nonremotely sensed data will be evaluated. It should be recognized, however, that the information contained in this report is fundamental to the application of remote sensing to the yield estimation problem. The proper choice of spectral variables for study can be made only through the identification of critical events encountered during crop growth and a knowledge of the duration of these events in a crop's development.

Yield models may be used to assess yield in grain production forecasting systems and to estimate the effects of potential yield detractants such as drought stress and pest problems. The large area prediction of crop yields may be attempted by three methods: adjusting historical yield trends for year-to-year weather fluctuations; simulating crop growth and yield production through the use of meteorological models; and estimating yield from changes that occur in the crop spectral signatures during the growing season. Currently, the most common method of large area yield prediction is that of adjusting historical yield trends for annual variations in weather.

In modeling crop yields, one must consider the four major factors that influence final yield: weather, crop, soil, and culture. Weather factors include rainfall, solar radiation, air temperature, windspeed, and humidity. Crop factors, which are more complicated and difficult to obtain than weather factors, include photosynthesis and transpiration, leaf area index (LAI), plant water stress, and phenology. Soil factors play an important role because soil characteristics combine with the hydrological balance to determine water and nutrient availability. Cultural factors include crop varieties, soil and water management, fertilization, and pest and disease control measures. Most models which predict yield incorporate at least two of the above factors.

The models discussed in this report may be classified under four different approaches: multiple regression, multifactorial, law of the minimum, and general physiological. Most of the yield prediction models used in large area forecasting are multiple regression or multifactorial types that account for some of the physiological responses of the crop to soil and environmental factors. Both the law of the minimum and general physiological models to some extent employ multiple regression and multifactorial methods for parameter estimation.

The general problems involved in modeling crop yield are considered in section 2. Details of major environmental, crop, and cultural factors are discussed in section 3. A description of each crop of interest is given in section 4. Specific models and their application to specific crops are discussed in section 5. Recommendations for improvements of agrometeorological and general physiological yield models are given in section 6.

2. MODELING CROP YIELD

2.1 MODEL TYPES

Although many crop yield models fail to fit neatly into any one type, most of these generally may be classified as one of the following three types:

1. Statistical models — use the least squares technique to choose variables and significant interactions and to evaluate coefficients
2. Realistic physiological models — involve detailed simulation of many plant processes [Plant physiological theories are used to choose variables and interactions, and experimental data are used to evaluate coefficients (ref. 1).]
3. General physiological models — involve simulation of a few plant processes from a few variables based on physiological principles, theories, and experimental data to evaluate coefficients (ref. 1)

These three basic model types will be evaluated for the AgRISTARS program. Statistical models include the Feyerherm model (ref. 2), and models by Baier, Haun, Nelson and Dale, and Thompson (refs. 2-8). Although these models are easier to develop than physiological models, their development requires several years of data, and they are dependable only within the range of conditions of the developmental data set. Because most meteorological variables are highly intercorrelated, statistical models include variables and interactions which do not directly affect the modeled responses.

Realistic physiological models are the most complex to develop and test (ref. 9). Their primary application is in evaluating plant physiological theories (ref. 1). These models either require detailed plant information at the field level (leaf size distribution, leaf angle distribution, light penetration in the canopy, leaf resistance to transpiration, and leaf water potential curves), or they make very specific assumptions about plant responses to the environment and generate detailed predictions about the canopy structure. In the former case, such detailed information is not available to run the model operationally. In the latter case, testing and evaluation of the model is time consuming (ref. 9).

Some realistic physiological models may be simplified into general physiological models. Realistic models have been developed by de Wit et al., Duncan et al., Stewart, and Monteith (refs. 10-13).

General physiological models may be simplified from realistic physiological models or be based on experimental data for a few key physiological processes (ref. 1). This model type covers a wide range of models including law-of-the minimum models (refs. 14-20), and has greater potential for accuracy and stability over a broader range of environmental conditions than have statistical models.

2.2 YIELD MODELING PROCESS

Figure 2-1 shows how crop yield is controlled by meteorological variables, crop variables, and soil variables. Phenology (including planting date) modulates the effects of weather variables on growth and yield in terms of the sequence of weather that is applied to the crop at each stage of growth. Varietal characteristics affect the crop's response to each of the variables. Incoming solar radiation which is intercepted by the crop canopy (stand quality) determines how much water is removed from the soil and how much is available to maintain photosynthesis, leaf area expansion, translocation, and mineral uptake from the soil. The plant growth processes interact with soil water and soil minerals to produce grain yield.

For a statistical model, these and other correlated variables (rain days, days from planting, and average temperature) are regressed against yield. If the range of conditions is not too extreme, the resulting equation would predict yield both in the developmental data set areas and for other areas with similar environments.

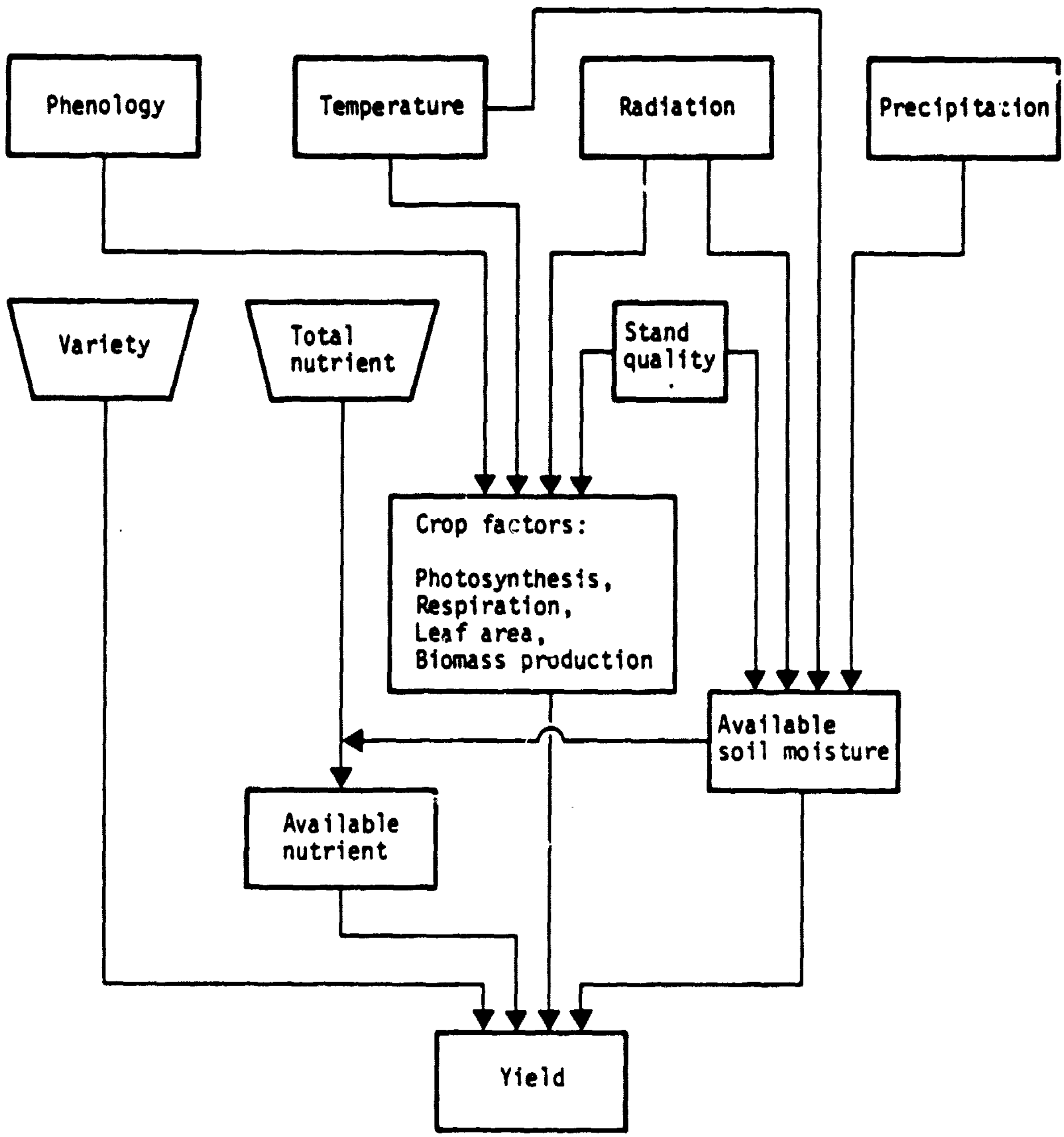


Figure 2-1.— Schematic flow chart showing crop yield resulting from interaction of environmental factors and crop responses.

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). One may use the output of the model to evaluate the theories of plant physiology on which the model is based.

To predict yield, a general physiological model requires meteorological data and some crop information including phenology data. For such a model, the following examples indicate the type of data needed and describe the function of each data point.

1. Requirements for interactive submodels for each growth stage calculated on a daily basis
   a. Photosynthesis — function of intercepted light, water stress, and temperature stress
   b. Respiration — function of photosynthesis, temperature, and accumulated biomass
   c. Net growth — difference between photosynthesis and respiration
   d. Leaf growth — function of net growth, temperature, and water stress
   e. Light interception — function of accumulated leaf growth and solar radiation
   f. Available water — function of rainfall, canopy evapotranspiration, temperature, and available water remaining from the preceding day
   g. The daily net growth is then partitioned into the various vegetative and reproductive plant organs using a phenology-based morphology submodel.
2. In a general physiological model based on the law of the minimum (see section 5.1.4), yield may be limited by
   a. Net photosynthesis during grain filling
   b. Available nitrogen (and possibly phosphorus or other minerals)

c. Available water at various stages

d. Temperature stress at various stages

Submodels are used to estimate photosynthesis as limited by previous development, light, temperature, or available water and to estimate available water from a soil moisture budget using whatever level of data is available.

3. FACTORS THAT INFLUENCE YIELD

3.1 RESPONSE OF PHYSIOLOGICAL PROCESS TO ENVIRONMENT

Weather is a major influence on crop production. Knowledge of climatic conditions is important for two main reasons. First, such knowledge aids those interested in choosing cultivars that are climatically adapted to a specific area; and, second, it provides agronomists and crop physiologists with the information needed to take into account the effects of weather variables on the growth and yield of crops. Crop growth and development, as well as yield, are affected by weather in different ways and at different times during the growth cycle. However, statistical approaches to relate final yield to weather variables have failed to produce consistent relationships (ref. 21). Such studies have provided little insight into the influence of weather on the physiological and developmental processes which ultimately determine yield, although the incorporation of some physiological realism has been attempted recently (refs. 2 and 22).

3.1.1 CONVERSION OF RADIATION INTO DRY MATTER PRODUCTION AND YIELD

3.1.1.1 Interception

Monteith (ref. 13) has demonstrated that early in the growing season the rate of dry matter production in barley and wheat is proportional to the amount of radiation intercepted. Similar results showing a linear response have been obtained for corn (ref. 23), soybeans (ref. 24), and wheat (ref. 25). Some researchers have also shown that final dry weights of crops depend on the total amount of radiation intercepted during the growing season (refs. 24 and 26).

The fraction of radiation intercepted by a crop depends primarily on its LAI (refs. 24 and 27). More than 80 percent of the incident photosynthetically active radiation will be intercepted by most crops that reach an LAI of four to five. Therefore, it is evident that environmental factors which restrict the rate of leaf expansion will also limit the dry matter production.

3.1.1.2 Photosynthesis

The rate of dry matter production and yield depends on a balance between the processes of photosynthesis and respiration. A high rate of photosynthesis accompanied by a high respiration rate or a high root-shoot ratio would result in comparatively low yields. On the other hand, certain varieties with low photosynthesis rates may produce high yields. Evans (ref. 28) showed evidence of this in high- and low-yielding wheat varieties. The three primary environmental factors which influence net photosynthesis in a crop are radiation, temperature, and a complex plant water-stress effect.

The hourly and diurnal rates of net photosynthesis have been shown to be linearly related to intercepted radiation for cotton and corn (ref. 29). For crops grown in climates where they are well adapted, intercepted radiation may be one of the primary determinants of photosynthetic productivity during the vegetative stage of growth. In later stages of plant development, the leaf surface may be less responsive to intercepted radiation.

The efficiency of solar radiation utilized by crops varies with several factors. Generally, a crop stores less than 1 percent of solar radiation as energy in biomass. This efficiency may be largely determined by the response of plants to radiation, C_3 plants becoming light saturated at lower light intensities than C_4 plants. Light saturation implies that limitations of photosynthesis are due to the supply of CO_2 or internal physiological conditions. The lack of photorespiration by C_4 plants accounts for part of their higher photosynthetic efficiency. Under cool, cloudy conditions, C_3 plants have a photosynthetic advantage over C_4 species; whereas, under hot, bright conditions, the reverse generally is true.

The relationship of photosynthesis to irradiance can be considerably modified when the crop is under a water stress. The degree of water stress and the pattern in which the stress develops are very important in assessing the effects of water stress on photosynthesis (ref. 30). A decrease in photosynthesis may be due to stomatal closure which has been shown to limit photosynthesis in water stressed leaves (ref. 31). Even when soil water potential remains high throughout most of the day, stomatal closure has been shown to occur in wheat (ref. 31) and cotton (ref. 29) under high irradiance conditions.

In temperate species, optimum photosynthesis and growth occur when temperatures are between approximately 20° and 25° C (68° and 77° F); whereas optimum photosynthesis and growth occur between approximately 30° and 35° C (86° and 95° F) for tropical grasses, including corn (ref. 31).

The influence of temperature on photosynthesis depends on the light intensity and availability of CO_2. If these two factors are adequate, photosynthesis rates may increase when temperatures are higher than those in the optimum range.

3.1.1.3 Respiration

Respiration measurements, which are usually made during the night, have been shown to reflect on the photosynthesis experienced by the crop during the preceding day (ref. 33). On bright days, measured respiration rates were found to be approximately twice as high as those on dull days (ref. 34). Rapid respiration was associated with high levels of total soluble carbohydrates in the plants. The respiration rate is also shown to be strongly dependent on temperature (ref. 33) and can be expressed using a temperature coefficient (Q_{10}) as follows:

$$R_2 = R_1 Q_{10}^{(T_2-T_1)/10}$$

where R_2 and R_1 are the respiration rates at temperatures T_1 and T_2, respectively. The Q_{10} value is found to vary over a wide range with different shapes of the temperature respiration response curve (refs. 33, 35, and 36). This wide variation in Q_{10} values may be due to the influence of soluble carbohydrate levels which play an important part in governing rates of respiration.

McCree (ref. 37) divided total respiration into two components: maintenance (R_m) and synthetic (R_s) respiration. Maintenance respiration was directly related to total plant dry weight (W_t) and temperature, whereas synthetic respiration due to synthesis of new cellular material (ref. 38) was found to be a constant fraction of gross photosynthesis (P_g). The respiration rate (R_t) as suggested by McCree (ref. 37) is as follows:

$$R_t = aP_g - bW_t$$

where a is a constant determined experimentally and b is a function of temperature.

This approach has been tested for sorghum (refs. 19 and 37), clover (ref. 37), cotton (ref. 33), barley (ref. 39), and wheat (ref. 18). Maintenance respiration (bW_t), which is strongly linked to the metabolic activity of the plant cells, is thought to be independent of the photosynthesis rate under field conditions (ref. 40). A strong temperature influence on this component of respiration was observed by McCree (ref. 37) and was found to have a profound effect on dry matter production. Little is known, however, about the effect of temperature on synthetic respiration. It appears that, while the efficiency of conversion of gross photosynthate to plant material is not affected by temperature, the rate of conversion increases at higher temperatures.

3.1.2 LEAF AREA INDEX

3.1.2.1 Radiation Interception

In the absence of water deficit, mineral deficency, and other limiting factors, radiation and net photosynthesis are closely related in plant development. Baker (ref. 41) and Moss, Musgrave, and Lemon (ref. 42) have reported that 90 percent of the hourly fluctuations of net photosynthesis in a corn stand could be explained by light fluctuations alone. In addition, Murata and Iyama (ref. 43) found that increased correlation between radiation and photosynthesis rate occurred with an increase in the LAI. Therefore, one can expect a close relationship between the total radiation and growth of a dense crop where light interception is relatively high. However, under low leaf area conditions in which light interception is not efficient, the correlation breaks down.

Black (ref. 44) examined the relationship among solar radiation, LAI, and crop growth rate for subterranean clover. He found that, at any given radiation intensity, the growth rate increased to a maximum with LAI and declined thereafter. With increasing levels of radiation intensity, growth rate peaks shift to higher LAI levels, and the saturation light intensity and the compensation point are altered with increasing LAI. The optimum LAI may be defined as the level at which the lower leaves in the canopy are just above the compensation point. When the upper and lower leaves intercept approximately the same light intensity (as when the upper leaves are vertical), the intercepted light is used most efficiently. Thus, under the same light intensity and LAI, the rate of photosynthesis varies with the extinction coefficient of the crop canopy.

Crops such as corn and sorghum require a high LAI to intercept light efficently. This requirement is usually accomplished by planting to achieve high plant population, the upper limit being set by the leaf angle. With increasing leaf angles, a higher LAI can be accommodated. The rate of planting required for maximum canopy photosynthesis rate and, presumably, yield for a given genotype is set by the LAI per plant and the angle or aspect of the leaves.

3.1.2.2 Temperature Effects on Leaf Extension

In a study of barley and its environment, Biscoe et al. (ref. 39) reported that, during the early part of the growing season, barley plants exhibited a linear relationship of leaf extension rate to temperature. Further, day and night extension rates were found to have the same response rate. However, later in the season when day lengths were longer, a simple linear relationship of the leaf extension rate to temperature no longer occurred. There were cases when the leaf extension rate at similar temperatures was slower in the afternoons than in the morning, possibly because of water stress. On a geographic scale, the response of tropical plants at temperatures above 15° C (59° F) was greater than that of temperate plants. For the tropical plants, however, extension growth ceased at temperatures of 10° C (50° F) and below (refs. 45 and 46) whereas leaf extension of wheat is reported to occur at temperatures as low as 1° C (34° F). (See ref. 47.)

3.1.2.3 Water-Stress Effects on Leaf Extension

As discussed in section 3.1.1.2, stomatal closure may cause a reduction of photosynthesis in water-stressed plants (ref. 30). Plant water stress also reduces the leaf extension rate. Biscoe et al. (ref. 39) studied the relationship between leaf extension rate and water potential gradient in the soil and leaves of barley plants. Their studies show that when plants are under water stress, there was no significant relationship of the leaf extension rate to increasing temperatures. In the absence of water stress, a slower leaf extension rate was observed in the afternoons. Boyer (ref. 48) and Acevedo et al. (ref. 49) reported similar results from studies conducted in environment-controlled chambers.

It should be noted that the lack of a uniform concept of water stress often results in inconsistent reports of studies conducted both in the field and in environment-controlled chambers. Such inconsistencies may appear when researchers involved in the studies fail to specify the method by which water stress was induced and the development stage at which stress occurred.

3.1.2.4 LAI and Dry Matter Production

The dry matter accumulation of a crop is highly dependent upon development of the crop's total leaf area (ref. 50). As the ratio between total leaves and nonphotosynthesizing organs changes with crop development, the optimum LAI should change accordingly. Watson (ref. 51) reported that seasonal changes in net photosynthesis were somewhat independent of the LAI development pattern. For example, the LAI of wheat and barley in moist regions reached a maximum value of about three by the rapid-shoot elongation stage. By the ear emergence stage, however, the LAI dropped to half of its peak value and was near zero by harvest. Thus, seasonal variation of the LAI has an important bearing on planting date. Ideally the maximum LAI should be developed when climatic conditions are most favorable for photosynthesis.

3.1.3 PARTITIONING OF DRY MATTER INTO YIELD COMPONENTS

In the agronomic sense, yield is equivalent to only a fraction of the total dry matter production, and this fraction may change with environment and plant variety. By component analysis, the yield (Y) for most cereal crops could be expressed as follows (ref. 52):

$$Y = N_e N_g W_g$$

where N_e is the number of ears per unit ground area, N_g is the number of grains per ear, and W_g is the mean weight per grain at harvest. The number of grains is normally determined by the time of anthesis, while grain growth takes place after anthesis (ref. 53).

The mean grain weight changes approximately linearly with time (ref. 54) and enables grain growth to be analyzed in terms of rate and duration. Because the crop growth rate normally decreases during the period of grain growth (refs. 39 and 55), the constant rate of grain growth implies that the two processes may be relatively independent of each other. Hence, during the grain-filling period, short-term changes in the rate of dry matter production have no direct effect on the rate of grain growth. Increasing temperatures (up to a limit) tend to increase the rate of grain growth but shorten the duration, and the net effect may be a constant mean weight per grain. Severe water stress, which is another influencing factor, shortens the duration of grain growth (ref. 56). Hence, except under conditions of extreme temperature or water stress, the mean grain weight is a relatively conservative characteristic for most cereals. In general, evidence suggests that the number of grains per unit ground area is a major determinant of yield in wheat and barley (ref. 54).

The number of grains per unit ground area which a crop will produce is determined shortly after anthesis in barley and other cereal crops (refs. 53 and 57). Adverse weather conditions during the 3 weeks prior to anthesis can affect yield in temperate cereal crops. During this period, both the number of ears per unit ground area and the number of grains per ear are determined (ref. 54). Salter et al. (ref. 58) have shown that water stress at this time causes a severe reduction of yield. In controlled environment studies, Cock et al. (ref. 59) have shown that increased dry matter production during the critical period before anthesis resulted in a higher number of grains and, also, higher yields. Experiments with wheat and barley also have shown that during this period the rapidly growing stem and ear compete for assimilates (refs. 54 and 60). It is possible, however, that rapid dry matter production by the crop may actually lessen the competition and allow more grain to develop. In addition, climatic factors affecting dry matter production would be expected to affect yield.

Agronomic yield studies conducted in the past reveal that cool summers have favorably affected yield in most cereal crops (refs. 61-62), while warm temperatures have unfavorably affected yield perhaps by stimulating the rate at which a plant goes through a development phase. The effect of high temperature on photosynthesis is quite insignificant compared to its effect on yield through the shortening of the development period. On the other hand, cooler weather lengthens the duration of growth up to the flowering stage (ref. 63), thus increasing yields. Chang (ref. 64) reported that productivity in temperate regions of the world is higher than in tropical regions. Two factors may account for this. First, the tropical region's high night temperature, which accelerates respiration, is a disadvantage. Second, during the normal growing season, the radiation in the Tropics is lower than that of the Temperate Zones. The Tropics, of course, have the advantage of year-round production.

3.2 WATER-STRESS EFFECTS ON YIELD

In considering the general effects of water stress on growth and development relating to specific problems of grain formation and yield, three time periods are of special importance. The period of floral initiation through inflorescence development determines the potential number of grains. During the period from anthesis to fertilization, the potential is realized. Finally, during the grain-filling stage, grain weight progressively increases. Although many aspects of yield development are common to cereals, it is hardly appropriate to generalize the effects of water stress on grain yield.

3.2.1 WATER STRESS AND INFLORESCENCE DEVELOPMENT

Gates (ref. 65) has shown that moisture stress greatly reduces the rate of appearance of floral primordia. In barley development (ref. 66), if the stress is mild and the period of stress is relatively brief, the rate of primordial initiation (upon relief of stress) is more rapid than the rate in the control plants, and the total number of spikelets formed may be unaffected. Under severe or prolonged stress, the number of spikelets is substantially reduced, as is the potential number of grains per ear. On the other hand, work done by Whitman and Wilson (ref. 67) studying the effects of water stress on sorghum development suggested that the development of the inflorescence could be suspended during stress and resumed after rewatering. This would then result in a flowering head not significantly different from that of control plants.

Volodarski and Zinevick (ref. 68) claim that a somewhat similar phenomenon occurs in corn development, with retardation of ear initiation during water stress being completely reversible. Unfortunately, the degree of water stress imposed on plants in the studies was not well defined. This presents great difficulty when comparing water stress effects on development and yield for different crops. In order to make a good assessment of its effects on yield, it is vital to know the degree of water stress and the manner in which stress was induced.

3.2.2 WATER-STRESS EFFECTS ON FERTILIZATION

If water stress is present at anthesis, fertilization and grain set in most cereals may be markedly reduced. Corn at this stage is reported to be very sensitive (refs. 69-70), with yield reductions of over 50 percent caused by relatively brief periods of wilting. Robins and Domingo (ref. 69) suggested that in corn development water stress may have resulted in disrupting the growth of pollen from the stigma to the ovules rather than in the dehydration of the pollen. This effect may be expected to be more pronounced in corn than in other cereals because of the length of the silk through which the pollen must grow. Species that flower over an extended period because of progressive flowering of tillers which develop after the main stem are somewhat protected from isolated periods of stress. If stress occurs early in the vegetative period and interferes with spikelet development on the main stem, the plant may compensate by increasing tiller development. Also, the total number of grains per plant may be little affected by a stress which severely reduces the number of main stem grains, although tillers of these plants may not have as many spikelets as a nonstressed main stem (ref. 71).

3.2.3 WATER-STRESS EFFECTS ON GRAIN FILLING

Water stress at the time of fruit set, especially in determinate species such as annual cereals, decreases the number of seed (ref. 72). In their study of the effects of water stress on corn, Robins and Domingo (ref. 69) found that maximum reductions in yield occurred when water stress takes place during the tasseling stage. Denmead and Shaw (ref. 70) found that water stress at the silking stage resulted in a yield reduction of about 30 percent. Asana and Basu (ref. 73) show that similar effects were observed for wheat. As revealed in their study, active photosynthesis after fruit set was an important determinant of final yield. As water potential drops significantly below fully turgid values, water stress causes a significant and progressive decrement in most processes concerned with plant growth.

Plant water stress has the greatest effect on yield during the postflowering stages. The two sources for assimilates during the grain-filling period are photosynthesis in the ear and remaining leaves, and translocation of material stored elsewhere in the plant. The greatest contribution is usually from photosynthesis after anthesis by the ear, leaves, and stem (refs. 74-76). Asana (ref. 77) demonstrated that in wheat development, virtually all the increase in dry weight after anthesis is associated with grain filling. It is quite clear that a large reduction in photosynthesis due to water stress at this time can lead to a large reduction in yield. On the other hand, there is also evidence of an upper limit to grain size and rate of grain filling in any one phenotype so that surplus photosynthate may be available in nonstressed plants. Buttrose and May (ref. 78) demonstrated that in barley development, water stress may not lead to reduced grain weight until any surplus photosynthate is eliminated.

In conclusion, it is difficult to make general statements about the relative sensitivity of different growth and development stages of different crops to periods of water stress. There are several reasons: the lack of in-depth information available concerning the effects of water stress, the difference between the plant species, and the fact that compensatory effects can take place from one growth stage to another. Over all, it is apparent that maximum yields are likely to be obtained only if an adequate water status is maintained throughout the life of the crop. Mild or relatively brief stress can usually be remedied. In general, it appears that the preflowering stage is most tolerant to water stress. By comparison, severe stress at almost any stage between floral initiation and maturity is likely to result in marked yield reduction.

3.3 INFLUENCE OF DEVELOPMENT RATE ON YIELD

The influence of plant development on yield is mainly through the effects of weather on the development rate of the crop. A detailed discussion of this has been presented in a recent report on crop phenology models by Hodges and Doraiswamy (ref. 79). As discussed by Hodges and Doraiswamy (ref. 79), both prolonging and accelerating the development process by environmental conditions will affect yield.

The major environmental parameters that influence phenology include radiation, day length, and temperature. The soil water budget and the planting date are also important in the final assessment of yield. However, for large area yield estimation, the planting date is the most important variable and the most difficult to obtain. Economic, social, and climatic factors prompt a farmer to plant at a particular date. The planting date initiates the biological clock that determines the development rate and the factors that will affect development at each stage of the plant's life cycle. When the wet and dry spells in the weather pattern during the growing season are quite predictable, choosing a planting date to fit appropriate stages of development may be very beneficial to crop production.

Between an upper and lower critical temperature, the plant development rate increases with temperature. Above the critical temperature, however, the development rate decreases with increasing temperature (ref. 80). When the temperature range is above that normally encountered in the field, development is hastened, resulting in short growth stages and early maturation. Early maturity usually means reduced yields because of less time for grain filling. In the case of winter wheat, the vernalization process requires a period of low temperatures before floral initiation can occur.

While severe soil moisture stress delays development of most cereal crops, the degree and duration of moisture stress will have different effects on various crops. For instance, if plant water stress develops gradually during early stages of development, the plant may be adapted to withstand a greater degree of water stress at later stages of development. Or, if the plant water status reaches a point where the plant is unable to meet the demands of the atmosphere, transpiration is reduced through stomatal closure. This control mechanism may raise plant temperature to damaging levels, causing a simultaneous reduction of photosynthesis. If such a process occurs at a time when photosynthate supply is limiting grain size, yield may be directly affected.

3.4 SOIL FERTILITY EFFECTS ON YIELD

Historically, crop production has been increased through the use of fertilizers and the selection of varieties capable of responding to increased soil fertility. The selection of the proper rate of plant nutrients depends on a knowledge of the nutrient requirements of the crop and the nutrient-supplying power of the soil. Up to a given point, increasing the amount of a nutrient (e.g., nitrogen) will increase the elemental content of the plant, as well as the yield. One of the problems in the interpretation of plant analysis is that of obtaining a balance among nutrients. For example, under any given set of environmental conditions, a plant will take up a fixed number of cations and a fixed number of anions. An increase in one cation or one anion means a decrease in other cations or anions (ref. 81). This tendency toward a nutritional balance complicates the procedure of using the actual quantity of a given element as an indication of adequacy or deficiency.

Crops are fertilized in order to supply the nutrients that are not present in sufficient quantities in the soil. The major factors which influence the selection of application rate and placement of fertilizer include crop characteristics, soil characteristics, expected rainfall, and anticipated yield. Fertilizer uptake by the crop will vary considerably depending on a number of factors such as yield level, existing nutrient supply in the soil, fertilization, and available soil moisture. The stage of development is also a consideration. Vegetative growth is considerably more responsive to nitrogen fertilizer than is reproductive growth (grain yield). Accordingly, nitrogen fertilizer should be applied in order to give maximum encouragement to reproductive growth.

A list of nutrient requirements for corn, soybeans, wheat, and barley is presented in table 3-1. As indicated in the table, corn takes up large quantities of nitrogen and potassium in relation to phosphorus. Superphosphate and potash generally increase soybean yield in soils which are deficient in plant food elements. Nitrogen fertilizers are seldom necessary when the soil is innoculated with appropriate soybean nodule bacteria or when the soybeans follow a crop that was well fertilized. Additionally, lime application on highly acid soils stimulates nodulation and promotes increased yields, as well as a higher nitrogen content in both vegetation and seed.

Wheat responds profitably to nitrogen application in soils of humid or irrigated regions. Reasonably, nitrogen applications of 45.36 to 136.08 kilograms (100 to 300 pounds) per acre are often beneficial to wheat yields on sandy soils in semiarid regions except during dry seasons. Heavy applications of nitrogen often reduce wheat yields not only by increasing plant lodging, but also by delaying maturity of the crop so that it is subject to greater damage from rust (ref. 81). In humid regions where winter wheat is grown, it is

TABLE 3-1.– APPROXIMATE UTILIZATION OF NUTRIENTS BY SELECTED CROPS

[From reference 8 (Source of data: American Potash Inst., National Plant Food Inst.)]

Plant	Yield, bushels per acre	Nitrogen, lbs.	Phosphorus, lbs.	Potassium, lbs.	Magnesium, lbs.	Sulphur, lbs.
Corn	150	135	22	30	20	14
Soybeans	50	160	18	58	18	10
Wheat	60	75	15	12	9	5
Barley	100	110	18	30		

customary to apply, in the fall during seed bed preparation, a mixed fertilizer that contains some nitrogen (ref. 81). Additional nitrogen is applied as a top dressing in early spring. The response of barley to nitrogen fertilizer is similar to that of wheat when soil moisture is adequate.

3.5 EFFECTS OF DISEASES AND PESTS ON YIELD

As with plants, climate affects the development and survival of pathogens and pests both directly and indirectly. The direct effects may be short term and pertain to the ways in which the optimum survival conditions are determined by the daily interaction of energy transfer and metabolism between the pests and the environment. The long-term effects are those in which the integrated short-term results are successful survival and reproduction of the population. Climatic factors may hinder or enhance the appearance, spread, and continuation of diseases and pests

The presence of disease in plant communities, the rate of spread, and the extent of potential damage are probably the result of soil wetness and exchange of light and heat at different stages in the plant's complex life cycle. Waggoner and Horsfall (ref. 82) summarized the role of weather in the spread of diseases and the degree to which disease damage is irreversible. In a study on fungal diseases, these authors suggested that most fungal diseases are more dependent on the degree and duration of wetness than on temperature in the warm season. Most researchers who have studied plant diseases have found it difficult to assess other effects of diseases on yield for a given range of climatic conditions because of the unavailability of adequate methods of analysis.

The development and survival of insects in major agronomic crops have been investigated for several decades. These studies show that the overall effect of the potential damage and reduction in yield may be attributed primarily to the complex interactive effects of the soil-plant-atmosphere continuum. Soil factors such as limitations in (and sometimes abundance of) water and/or nutrients may be primary influences on plant susceptibility. Plant vigor affects plant susceptibility to parasites. The development rate and survival of parasites also depend on seasonal environmental changes. Yield loss depends partly on the crop growth stage at which parasite attack occurs. Therefore, parasite activity and yield loss depend on the time at which the infestation occurs. It may be theorized that, if insect development is in synchrony with plant development, predictions of the amount of yield reduction as a result of pest damage could be made from a study of the environmental conditions surrounding the plant.

The complex relationship of disease and pest damage to yield reduction prohibits simplifying the interactive influences. In an endemic situation, choice of disease-resistant varieties, chemical treatment of seed and crops, and proper management practices may assure a certain degree of protection against drastic yield reductions. However, in an epidemic situation, a remedy may be more difficult to apply, and yield reduction may be inevitable.

4. DESCRIPTION OF CROPS

4.1 CORN

Corn is a tropical, warm season, short-day grass that accounts for approximately 14 percent of world acreage and 21 percent of world grain production (ref. 83). In 1977, 41 percent of the total world production of corn was in the United States. World trade in corn was 64.2 million metric tons (70.7 million tons), 71 percent of which was from the United States. Since corn is a major source of food for animals as well as for humans, much attention in the relevent agricultural service disciplines has recently been directed to the improvement and stabilization of corn production (ref. 84).

While most corn varieties are reported to have a short-day photoperiod response, certain varieties have been found either to be day neutral or to have very low photoperiod sensitivity (ref. 80). Although corn varieties are well adapted to a wide range of latitudes and altitudes, highest yields are reported for irrigated corn in areas with high solar insolation, hot days, and cool nights. Optimum growth of corn occurs at mean air temperatures of approximately 20° C (68° F). When mean air temperatures are above 26.5 C (80° F), yield is reduced.

The effect of water stress on corn yield varies depending on the stage of development at which it occurs. During moderate water stress, leaf elongation stops. Under more severe water stress, stomates close, transpiration is reduced, and leaf temperature increases, all of which may hasten or delay development. The effects of short periods of water stress on yield are greater if the water stress occurs during the brief stages of floral initiation and anthesis than if it occurs during longer stages.

4.2 SOYBEANS

The soybean is a temperate, warm season, short-day legume. The importance of soybeans in the United States and abroad has been growing and is expected to continue doing so. In 1977, the United States' export of soybeans and meal accounted for 66 percent of world soybean exports. Because it is a legume, the soybean requires very little nitrogen fertilizer; and, being a high protein crop, it is highly valued as a nutritional and inexpensive meat substitute in underdeveloped countries.

Determinate varieties of soybeans cease vegetative growth at the flowering stage, while indeterminate varieties continue vegetative growth during that stage. Indeterminate varieties are grown in about 60 to 65 percent of the area in the midwestern United States. Determinate varieties are grown in the poorer soils of the southern United States, which produce lower yields (ref. 85). The basic vegetative growth and developmental characteristics of soybeans are different from other major crops. For example, the basic vegetative period may be quite short, ending as early as 10 days after emergence.

There is little information on how temperature affects the developmental responses of soybeans. It is known, however, that as temperature increases the rate of development increases until an optimum is reached, at about 20° to 30° C (68° to 86° F); after that point, the rate of development decreases (ref. 85). High temperatures (over 38° C or 100° F) occurring early in the growing season may have adverse effects such as reducing the rate of node formation and the rate of growth of internodes (ref. 86). Varieties differ in their temperature requirements, and certain varieties are more adapted to higher temperature conditions than others.

Although the photoperiod may influence the reproductive and ripening phases of the soybean, it does not exert as strong an influence on these phases as it does on the juvenile phase. Nevertheless, the effects of temperature are important throughout the plant's life cycle. After the blooming and fertilization stages are complete, however, plant development appears to be mainly a function of temperature. The development of indeterminate varieties is more complex because the photoperiod also affects the duration of flowering and even maturity. For instance, the decreasing day lengths of fall may bring on maturity more quickly even though temperatures are decreasing.

Water is often the primary limiting factor in soybean production and, thus, is an important management concern. The rooting characteristics of the soybean depend on the physical properties of the soil, as well as its moisture conditions. Roots found in silt loam soils are usually extensive, both horizontally and vertically (ref. 87). Thus, the rooting habit of the plant allows it to extract water exceedingly well in many different soils. The long flowering period enables the plant to escape or survive short periods of drought stress. The failure of early flowers to set pods because of water stress may be remedied by an excellent pod set of late flowers if moisture becomes available. A moisture shortage during the pod-filling stage reduces yield more than does such a shortage during the flowering stage.

4.3 WHEAT AND BARLEY

Wheat and barley are long-day, cool season grasses which are grown throughout temperate regions. In recent years, wheat accounted for 24 percent of the world grain production and barley accounted for 9 percent (ref. 83). In 1977, the United States produced 14 percent of the world's wheat [382 million metric tons (421 million tons)] and 41 percent of the world trade in wheat. The highest yields for both wheat and barley are found in northern Europe and northwestern United States (LACIE data) because of mild winters, cool summers, and ample rainfall found in these areas (ref. 83).

In temperate latitudes, winter wheat is generally preferred since it tends to outyield spring wheat. Thus, in most of the U.S. Great Plains and in the Temperate Zones in Europe, winter wheat is widely grown. It requires a period of exposure to cool temperatures (several weeks) to initiate the reproductive portion of its life cycle. During this cool period, the plant goes into dormancy; growth is resumed in the spring.

Heat tolerance in wheat and barley is much lower than in corn or soybeans. Therefore, spring varieties are planted early enough to ensure that the crop can complete its vegetative growth before the onset of warm temperatures. In India, heat resistant varieties are also planted early to avoid flowering during the hottest part of the season (ref. 88). Barley varieties generally have slightly shorter growth periods than wheat, and they are planted later and mature earlier than wheat. Wheat is adapted to a wider range of climates than barley and thrives somewhat better in warmer climates.

4.4 SORGHUM

Grain sorghum is a warm season crop which is grown both in warm and hot regions with summer rains and in areas that are irrigated. A favorable temperature for growth is approximately 26° C (79° F). Sorghum can withstand extreme heat better than most other crops. Like corn, sorghum is a determinate C_4 species and produces a genetically predetermined number of leaves. Growth characteristics of grain differ little over large regional areas in the United States, as a result of insensitivity to photoperiod (ref. 17).

Grain sorghum is exceeded only by wheat, rice, corn, and barley in acreage of world crops (ref. 17). It is grown in areas where summer temperatures exceed 20° C (68° F) and the frost-free season is at least 125 days. Because grain sorghum can tolerate arid climates and adapt to water stress (ref. 89), it has become an important crop in marginal lands where other crops cannot be cultivated. The increase in worldwide sorghum production can be attributed to the breeding of higher yielding varieties with insect and disease resistance.

Intensive breeding within the last century has led to the development of hybrid cultivars adapted to the southwest United States. These cultivars are grown where the mean daily temperature exceeds 20° C (68° F), reaching 25° C (77° F) during the growing season. In tropical regions, the mean daily temperature exceeds 30° (86° F) during most of the growing season. Pasternak and Wilson (ref. 90) and Skerman (ref. 91) have shown evidence of plant damage caused by high temperatures occurring during the booting stage and at anthesis. Downes (ref. 89) conducted laboratory studies on the effects of high temperature on sorghum development. The fact that high day temperatures of 33° C (91° F) and high night temperatures of 28° C (82° F) resulted in low final yields in cultivars commonly grown in the United States suggests that low yields in tropical environments may reflect an adverse effect of high temperatures.

High day temperatures of 33° C (91° F) and night temperatures of 28° C (82° F) in the period between the germination and initiation stages were shown to have an adverse effect on ultimate yield and total dry matter production when compared with day temperatures of 27° C (81° F) and night temperatures of 22° C (72° F). When plants were grown at day temperatures of 33° C (91° F) and night temperatures of 28° C (82° F) until initiation and subsequently were subjected to day temperatures of 27° C (81° F) and night temperatures of 22° C (72° F), florets reached maturity but produced immature grain (ref. 89). Sorghum is an important crop in areas that are too hot and too dry for growing corn because certain sorghum genotypes can tolerate extreme heat (ref. 92). In general, plants resist or adapt to drought either by avoiding the development of severe water deficits or by tolerating severe deficits. It appears that both types of drought resistance exist among sorghum varieties (ref. 93).

Water stress during panicle development results in a reduced number of seeds but in some instances may be compensated by an increase in seed weight if stress is not too severe or prolonged. If water stress exists throughout the bloom period, both the number and size of seeds are reduced (ref. 94). One of the major effects of water stress during postanthesis is the reduction in dry matter production and subsequent reduction in the leaf area (ref. 95). Extreme water stress can also cause a reduction in leaf area because of leaf senescence. The effects of water stress are important in stages prior to bloom, during bloom, and during the grain-filling period. Although yield is not significantly affected by net assimilation prior to anthesis, the growth conditions may affect the grain yield potential by determining the number of grain and the utlimate magnitude of the storage capacity (ref. 96).

4.5 RICE

There are few crops as widely distributed throughout the world as rice. It is cultivated not only in the Tropics but also as far north as 49° N in Czechoslovakia. Environmental conditions in temperate rice-growing areas are considerably different from those of the Tropics and determine both the growth habits of the rice plant and the techniques of its cultivation. Its ability to germinate and thrive in water makes rice unique among cereals. The important factors for rice production are favorable temperature, a constant supply of fresh water for irrigation, and suitable soil (ref. 83).

Rice can be grown most successfully in regions that have a mean temperature of about 21° C (70° F) or above during the entire growing season. Rice yields are generally higher in warm temperate regions than in the humid Tropics where rice diseases and low soil fertility are prevalent. (Also, solar radiation is critical for yield if the water supply is not limited.)

Rice is the basic food for more than one-half of the world's population (ref. 97). Table 4-1 (ref. 98) contains a list of the leading rice-producing regions of the world. Approximately 90 percent of the agricultural lands cultivated for paddy are in the Far East and on the mainland of China. Most of the 295.4 million metric tons (324.5 million tons) of paddy produced in the world are grown for local consumption; only 3.8 percent of this production enters the export trade (ref. 99).

Temperature has a subtle and, in some respects, contradictory influence on the development, growth, and yield of rice. Water temperature is more important during germination than is air temperature. However, each of the hundreds of rice varieties has its own characteristic response to temperature, making it suitable for the local climatic conditions.

Being tropical or subtropical, rice requires daytime temperatures higher than 20° C (68° F) but below 35° C (95° F, ref. 100). The daytime optimum temperature is near 30° C (86° F) and night optimum around 20° C (68° F). The tillering rate of rice is inhibited by low temperatures (ref. 101), but the period for tillering is prolonged so that often the result is more tillers and more panicles than at higher temperatures. Low temperatures are also known to prolong the ripening period, reduce transpiration, and maintain green leaves, all of which contribute to the high accumulation of carbohydrates in the seed (ref. 98). However, low temperatures during the ripening stage lead to excessive shattering of grain during harvest, resulting in high grain losses.

TABLE 4-1.— WORLDWIDE POPULATION, AGRICULTURAL LAND, AND PADDY PRODUCTION IN 1972

[From reference 98.]

Region	Population, $\times 10^6$	Agricultural[1] area, 10^6 ha	Paddy area, 10^6 ha	Paddy yield, 100 kg/ha	Paddy production, $\times 10^6$ metric tons
Far East	1056	269	73.6	17.8	140.0
China (mainland)	801	111	33.8	30.9	104.3
South America	201	84	6.1	16.7	10.2
Africa	363	214	4.2	17.8	7.4
Near East	182	85	1.2	37.5	4.5
North and Central America	330	271	1.4	38.5	5.3
Europe	467	145	0.4	40.3	1.6
U.S.S.R.	247	233	0.4	38.9	1.6
Oceania	201	47	—	55.1	0.3
World total	3761	1457	131.2	22.5	295.4

[1]Excluding forest areas.

In inhibiting the development of rice, high temperatures between 35° to 40° C (95° to 104° F) have an effect similar to low temperatures. The number of tillers is increased during high temperatures, while panicle development is inhibited. At an optimum temperature of 30° C (86° F), shoot elongation is most rapid (refs. 102-104). The final number of tillers and panicles may not be a maximum; but, since the number of spikelets and tillers are inversely related, the result is maximum yield.

The main environmental characteristic which sets rice apart from other cereal crops is its water requirement. The optimum depth of water required is approximately 5 centimeters (2 inches). Thus, one of the problems in maintaining flooded conditions is an inadequate supply of irrigation water (ref. 98). The rooting depth of rice is shallow [15 centimeters (5.5 inches)], and water stress can develop quickly when the soil is drained.

The formation of tillers appears to be stimulated by the large diurnal variations of soil and water temperatures that appear during periods of shallow water. Exposure to warm water during the day followed by cool nights increases the number of tillers and ultimately the yield. The latter part of the vegetative period is the stage when water is most critical to the rice plant's life cycle (ref. 98). It corresponds to the stages extending from panicle primordial initiation to about 5 days after heading.

Evapotranspiration for rice approaches potential rates; and, during advection in smaller paddies, actual evapotranspiration may exceed potential rates. However, this is seldom the case in the humid Tropics where daily evapotranspiration during both the rainy season and the dry season are 4 and 5.5 millimeters (0.16 and 0.22 inches), respectively.

Rice is a short-day plant (ref. 105); and, since it originated at low latitudes, it has developed a great sensitivity to small changes in day length. Because initiation and panicle development are controlled by the photoperiod, all rice fields (even those representing the broadest range of planting dates) ripen at about the same date at the end of the wet season (ref. 98). High-yielding varieties have been bred to be insensitive to the photoperiod variations in the Tropics (ref. 106). This insensitivity serves to shorten the growing period and makes the varieties adaptable to carefully managed irrigation schemes in which rice can be planted year-round.

A proper balance between photosynthesis and nitrogen absorption is very important for optimum rice yields. Heavy nitrogen application will produce a vigorous growth of leaves. However, vigorous growth of a plant beyond certain limits increases mutant shading, which adversely affects yield (ref. 107). With adequate fertilizer application, high yields may be limited by the inabilities of the crop to assimilate solar energy and to form storage organs. Rice plants have a relatively high CO_2 compensation point which increases with increasing temperature.

Being a C_3 species, rice has a relatively high photorespiration rate. However, rice plant leaves lack the chlorophyllous parenchymatous bundle sheath which is a characteristic of plant species with high photosynthetic rates.

4.6 COTTON

Cotton is a short-day plant and nearly fits the classification of a tropical xerophyte. Climatic conditions for cotton are favorable when the mean temperature during the summer months is less than 25° C (77° F). The cotton production zone lies between latitudes 37° N. and 32° S. (ref. 108). The essentials for a good crop are freedom from frost during the growing season (180 to 220 days), an adequate supply of moisture (with a suitable seasonal distribution), and abundant sunshine. The most favorable growing conditions for cotton consist of a mild spring; a warm, moderately moist summer; and a dry, cool, prolonged autumn.

Cotton is grown commerically in 60 countries, with 8 major countries contributing 80 percent of the world's cotton. The average world production of cotton per year in 1964 was 10 million metric tons (11 million tons) of lint and 15 million metric tons (17 million tons) of seed. Cotton is grown mostly in the south-central and southeastern coastal plains of the United States (ref. 109). Two of the major varieties grown in these areas are the American-Egyptian, which is grown in dry areas, and the American Upland, which is indeterminate in growth habits and insensitive to day length (ref. 83).

Table 4-2 is a listing of average temperature and yield factors for five selected cotton-growing regions of the world. High yields are predominantly in areas with a high number of frost-free days and warm seasonal temperatures.

Air temperatures below 16° C (60° F) contribute little if anything to the growth of the cotton plant (ref. 109), and air temperatures in excess of 38° C (100° F) may be unfavorable. One growth characteristic usually associated with high air temperatures is early initiation of the squaring phase. The squaring phase is the period of time the plant requires for development from the initial budding to open bloom. When mean daily maximum temperatures approach 38° C (100° F), maturation requires less time; but bolls are smaller with both lint and seed somewhat undeveloped.

The extent to which temperature affects the plant depends to a critical degree on the moisture supply, and the effects of soil moisture on boll development often make temperature effects negligible. In arid regions where soil moisture supply is primarily from irrigation, total plant growth reaches its maximum when periods between irrigation are long (ref. 109).

Most of the water is removed from the soil before the cotton plant exhibits stress (ref. 110). Production of high-quality lint cannot occur if, at the early stages of plant development, the level of soil moisture is low enough to produce wilting. Less severe moisture shortages often stunt growth and cause shedding of squares and young bolls. Bolls maturing under drought conditions have lighter seeds, lower oil content, and reduced fiber length. Some cotton varieties have been bred and selected for drought tolerance; and, as a rule, the short-fibered varieties suffer less damage in quality under water stress than do the long-fibered varieties.

TABLE 4-2.— ANNUAL TEMPERATURE FACTORS AND YIELD OF COTTON FOR SELECTED REGIONS AND CORRESPONDING VALUES FOR THE CENTRAL COASTAL PLAIN

[From reference 109.]

Location	Number of frost-free days	Growing degree days[1]	Average temperature for 6 warmest months, °C	Yield, kg/ha
Tashkent, U.S.S.R.	200	2327	21	875
Leeton, Australia	299	2320	21	870
Lubbock, U.S.	215	2496	22	675
Phoenix, U.S.	270	4000	28	1100
Skop, Yugoslavia	180	2000	20	340
Israel	240	2307	23	1170

[1]Base temperature is 10° C.

The morphology of the cotton plant favors vegetative growth rather than reproductive growth. Baker and Hesketh (ref. 33) have shown that less than one-half of the total dry matter produced during the reproductive phase is directed toward reproductive growth. Possibly, the key to increased crop yields may be the adoption of practices which will bring the time sequence of dry matter production more closely into phase with that of reproductive sink development (ref. 33). Although it is clear that climatological factors play a major role in determining the size both of the source and of competing sink strengths, neither the relationships of these factors nor their interactions have been clearly established (ref. 109).

The nutrient requirements for cotton are not greatly demanding. About 75 percent of the cotton plant's total seasonal production of dry matter is stubble to be returned to the soil. During the seedling phase, the cotton plant needs comparatively high quantities of nitrogen, potash, lime, and magnesium (ref. 83). A low level of soil nitrogen causes plants to be stunted and woody, and mature leaves to turn yellow and shed prematurely. Because its growth is curtailed, the plant produces fruit too quickly; and total production of the plant is greatly limited.

4.7 SUNFLOWER

The sunflower grows well in most of the Temperate Zones of Europe, Africa, and North and South America (ref. 111). Identical sunflower cultivars are often adapted to this wide range of locations because of various morphological and physiological characteristics similar to those of the sunflower. In the United States, the sunflower is adapted in the Corn Belt region and is extensively grown in North Dakota. Future expansion will likely be on land located on the fringe of the present corn-, soybean-, and cotton-growing areas.

The cultivated sunflower ranks with the soybean, the rape, and the peanut as one of the four most important annual crops in the world grown for edible oil (ref. 111). In Russia and other eastern European countries, the sunflower is the main source of edible vegetable oil. In the last decade, production of sunflowers in the United States has increased tenfold. Food and Agricultural Organization (FAO) statistics (ref. 112) report that Russia was the leading country in sunflower production in 1977, with 6.5 million metric tons (7.2 tons) or 54 percent of the total 12 million metric tons (13.2 tons) produced worldwide. With 10 percent of the total sunflower production, the United States took second place.

The tolerance of the sunflower to both low and high temperatures contributes to the ease of its adaptation to different environments. Young plants are known to withstand freezing [-5° C (23° F)] until they reach the four- to six-leaf stages (ref. 83). While crops like corn and soybeans are killed by slight frost in the fall, temperatures must be less than -2° C (28° F) to kill maturing sunflower plants (ref. 111). High temperatures during seed formation were beneficial in increasing the oil concentration from 40 percent at 21° C (70° F) to about 57 percent at temperatures greater than 35° C (95° F). Photosynthesis in the sunflower is altered very little between 18° and 30° C (64° and 86° F). Other physiological effects of temperature have not been studied in detail.

The sunflower is an inefficient user of water, as indicated by its water requirement, which is greater than for corn, soybeans, and sorghum. Sunflowers are not highly drought tolerant, but they often produce satisfactorily under conditions that would cause other crops serious damage. This may be attributed to their extensive and heavily branched taproot system, which has a potential lateral spread and depth exceeding 2 meters (6.6 feet). This adaptation enables sunflower plants to extract more moisture than could most plants for a given volume of soil (ref. 113). The critical period for seed production begins about 20 days before flowering and ends about 20 days afterward (refs. 113-115). To affect yield, stress must be continuous for 5 weeks during this critical period. Drought affects oil yield most through the stress it inflicts on the plant during the 20 days after flowering (ref. 114). Drought also causes lower leaves to die prematurely, but this is significant to yield only if it occurs prior to flowering (ref. 116).

The sunflower is one of the few C_3 plants that does not become light saturated under field conditions. Most C_3 crops are light saturated at low intensities and are inefficient users of light. Photorespiration in sunflowers is reported to be over three times the rate of dark respiration (ref. 117). However, the net photosynthesis rate of the sunflower is almost equivalent to the rates of the C_4 species, suggesting a high potential for seed production. The optimum temperature for photosynthesis is reported to be between 30° and 35° C (85° and 95° F, ref. 122). Regarding the effects of water stress on photosynthesis, Boyer (ref. 48) reported that photosynthesis continued at high levels of moisture stress even though leaf growth was inhibited.

5. YIELD MODELS

5.1 INTRODUCTION

As discussed in section 3 of this document, yield is a complex function of crop genetic material, weather, soil, cultural practice, and plant response to environment in terms of timing of development. In its first steps toward yield, the plant grows and establishes a base. It then produces flowers and they are fertilized. Finally, the plant fills the grain. In each of these stages, the plant is sensitive to the environment, and each of these stages influences later stages.

The simplest models, discussed in section 2 as statistical models, ignore the complexity of plant growth and simply regress yield against weather, soil factors, and cultural factors. At a higher level of sophistication, there are models which use estimated or observed timing of growth stages to define weather variables in a multiple regression equation. The multifactorial models estimate yield as the product of several major factors or plant processes (such as transpiration) but still do not account for the effect of a plant response to one factor on the plant response to another factor. The realistic and general physiological models simulate a greater or lesser number of plant processes and interactions between the processes.

5.1.1 MULTIPLE REGRESSION MODELS

Many early efforts at modeling crop yields have involved multiple regression of yields on weather variables over a period of many years. Multiple regression models are fairly easy to develop if many years of data are available. Recently, a time or technology variable called trend, which takes into account increases in yield over the last 50 or 100 years, has been combined with weather variables in developing yield models. Using trend, as well as monthly average temperature and rainfall data, Thompson (refs. 6-8) developed a multiple regression model for yields of wheat, corn, and soybeans in the U.S. Great Plains.

5.1.1.1 Multiple Regression Model Variables

In developing the multiple regression model for corn, Thompson (ref. 6) used the following variables:

$$\begin{aligned}\text{Yield} = {} & 0.898\ (\text{Time 1}) + 3.819\ (\text{Time 2}) - 0.715\ (\text{Time 2})^2; \\ & - 0.101\ (\text{P Precip}) - 0.014\ (\text{P Precip})^2 - 0.275\ (\text{June Temp}); \\ & - 0.297\ (\text{June Temp})^2 + 2.922\ (\text{July Precip}) - 0.373\ (\text{July Precip})^2; \\ & - 0.757\ (\text{July Temp}) - 0.092\ (\text{July Temp})^2 + 0.397\ (\text{Aug Precip}); \\ & + 0.450\ (\text{Aug Precip})^2 - 0.282\ (\text{Aug Temp}) - 0.109\ (\text{Aug Temp})^2 + 40.03\end{aligned}$$

where Time 1 and Time 2 are trend variables, and P Precip is preseason precipitation.

In developing the model for soybeans, Thompson (ref. 8) used the same weather variables as he used for the corn models. For wheat, Thompson (ref. 7) used August through March precipitation, two trend variables, and precipitation and temperatures for April, May, June, and July. For spring wheat and winter wheat, separate models were developed for each state and for major foreign wheat producers. Eventually, the wheat models were adapted for use in the LACIE project to predict spring and winter wheat yields from 1975 through 1978 (ref. 119).

5.1.2 PHENOLOGICALLY ADJUSTED MULTIPLE REGRESSION MODELS

Some researchers have recognized the importance that year-to-year variations in the planting date and the dates of various growth stages have on the effect of weather variables on crop yields. For example, stress during flowering has a different effect on yield than stress during grain filling. Numerous regression models have been developed which use the rate of plant development or the dates of growth stages in estimating yield (refs. 4 and 119-122). Some models use either observed or modeled dates of growth stages to accumulate and average weather variables; i.e., use flowering-to-dough stage average temperatures rather than July average temperatures.

Haun (ref. 4) developed universal models for spring and winter wheat using the modeled rate of plant development up to boot stage as an input variable into a multiple regression yield model. The models estimate a daily soil moisture budget from initial soil moisture, daily precipitation, potential evaporation. Potential evaporation was estimated by the Thornthwaite method (ref. 123) using long-term average monthly temperatures and daily maximum and minimum temperatures. For yield estimates, twenty weekly equations are used for each crop, each equation using the meteorological data accumulated thus far.

Feyerherm et al. (ref. 122) developed spring and winter wheat yield models for the U.S. Great Plains based on a modified Robertson spring wheat phenology model (ref. 14), a planting date model (ref. 2), and a modified soil moisture budget model (ref. 124). In his yield equation, Feyerherm splits trend into varietal yielding ability and nitrogen application and also uses about 20 (for spring wheat) to 30 (for winter wheat) phenology-based weather variables calculated from daily maximum and minimum temperatures and precipitation. Feyerherm also adapted his models to the wheat-growing areas of the U.S.S.R.

For corn in Iowa, Illinois, Indiana, Missouri, Kansas, and Nebraska, Runge and Benci (ref. 121) developed a multiple regression model centered around average pollination date. The model uses 6 weeks of meteorological data before the average pollination date and 4 weeks of data after that date. The model uses available soil moisture at planting, weekly totals of precipitation, weekly mean maximum temperature, and week number (1 to 10) combined into 14 variables, each of which is summed over the 10-week period. Available soil moisture at planting was estimated from preseason precipitation in dry areas and from soil survey data.

Because the model was developed on high-yielding experimental fields, differences between reported and predicted county yields were attributed to farmer technology levels. Average farmer technology levels for each state during each year from 1968 through 1972 were calculated by dividing reported county yields (weighted for county corn acreage) by predicted county yields (weighted) for county corn acreage) and summing across each state. The average farmer technology level in each state behaves quite erratically from year to year, indicating that it includes a large component of something else, probably weather.

The Earth Satellite Corporation (ref. 125) developed a regression model for predicting yield of spring wheat in the U.S. Great Plains. The model estimates yield on 23.2 by 23.2 kilometer cells in 4 states. It combines weather-satellite and weather-station data to estimate growth stages, soil water balance, and yield for spring wheat in Montana, North Dakota, South Dakota, and Minnesota.

Six-hour precipitation is estimated for cells in each of the four areas from weather-station observations and satellite measurement of cloud density and cloud type, using an equation adopted from Follansbee (ref. 126).

$$Pe = K_1Cb + K_2Ns + K_3Cc$$

where Cb, Ns, and Cc represent percentages of cumulonimbus, nimbostratus, and cumulus congestus clouds, and K_1, K_2, and K_3 are coefficients.

The equation is adjusted each week by a factor calculated from the sum of the precipitation (Pr) reported at weather stations in an area divided by the precipitation (Pe) calculated. If the adjustment factor (F) is three times greater or one-third less than the value from the Follansbee equation, then it is set to 1.0. When only infrared satellite data is available, a simpler equation is used:

$$Pe = K_4BF$$

where B is the infrared brightness scaled from zero to one, and K_4 is a coefficient.

For estimating soil moisture, the model uses Baier and Robertson's (ref. 124) versatile soil moisture budget. Potential evapotranspiration (PET) is calculated from the Penman (ref. 127) equation which is as follows:

$$(PET) = \frac{[\Delta R_n + .64f(w)(e_s - e_a)]}{(\Delta + .64)}$$

where net radiation (R_n) is estimated from solar radiation, surface albedo (a function of the crop growth stage), satellite estimates of cloud cover and type, and satellite estimates of long-wave radiation from the earth's surface. As indicated in the equation, Δ is the slope of the saturation vapor pressure versus the temperature curve, e_s is the saturation vapor pressure at air temperature, e_a is the actual vapor pressure (interpolated from temperature and dew-point data), and f(w) is a function of wind speed. Available soil moisture capacity (AWS) and daily plant water stress (S) are calculated from moisture soil moisture (AW) and the following:

$S = AW/0.7AWS \qquad AW \leq 0.7\ AWS$

$S = 1 \qquad AW > 0.7\ AWS$

Actual evapotranspiration (T) is estimated from PET and various soil and plant factors following an estimation of the soil moisture using Baier and Robertson's (ref. 124) soil moisture budget.

At the cell level, yield is estimated with multiple regression equations (one for each state) from the number of years and the average daily water stress from planting to ripe. The model has since been disavowed by the company because they claim to have a better unpublished model.

5.1.3 MULTIFACTORIAL MODELS

Some factors can cause zero yields or very low yields even when all other factors are optimal. The multifactorial models account for this by weighting each factor with an exponent and then multiplying all factors together as follows:

$$\frac{\text{Yield}}{\text{Potential yield}} = (X)_1^{\lambda_1}(X)_2^{\lambda_2}\cdots(X)_N^{\lambda_N}$$

where each X_i is a single variable or combination of variables averaged or summed over a time period or growth stage. The λ's are weighting exponents and can be evaluated by multiple regression after a logarithmic transformation of the data set.

Several scientists have worked on a yield model for water-limiting conditions. The model estimates grain yield as a function of varietal potential yield and the ratio of transpiration to potential transpiration. This model is based on the following equation, which was proposed by de Wit (ref. 128).

$$\frac{Y}{Y_p} = m\frac{T}{T_p}$$

where Y is biomass production, Y_p is potential biomass production, T is transpiration, T_p is potential transpiration, and m is a crop and growth stage constant. Eventually, Hanks (ref. 129) adapted the model for corn; Rasmussen and Hanks (ref. 130) adapted the model for spring wheat; Rasmussen et al. (ref. 16) adapted it for winter wheat; and Hill, Johnson, and Ryan (ref. 131) adapted it for soybeans. The researchers who adapted this model for various crops and conditions have used several approaches in calculating crop water use.

5.1.3.1 CORN

In the model developed by Hanks (ref. 129), potential transpiration (T_p) and potential soil surface evaporation (E_p) are estimated from free water evaporation (E_o) and crop growth stage.

$$T_p = aE_o$$

$$E_p = b(E_o - T_p)$$

where a and b are dependent growth stage crop factors, and growth stages which are calculated by using a growing degree day (GDD) equation by Gilmore and Rogers (ref. 132). Growth stages used by the model developers are (1) Emergence to tasseling, (2) tasseling to silking, (3) silking to milk, and (4) milk to maturity.

Actual transpiration T and actual soil surface evaporation E are calculated from available soil moisture capacity (AWS), available soil moisture (AW), days since the last rainfall or irrigation (p), potential transpiration T_p, and potential soil evaporation E_p as follows:

$$T = (T_p AW)/.5AWS \text{ for } AW \leq 0.5AWS$$

$$T = T_p \text{ for } AW > 0.5AWS$$

$$E = E_p/p^{1/2}$$

Available soil moisture AW is calculated from the daily soil water budget of the previous day's AW (AW_{t-1}), rainfall or irrigation (P), actual transpiration T, potential soil surface evaporation E_p, and drainage (D). This calculation may be stated as follows:

$$AW_t = AW_{t-1} + P - T - E_p - D$$

A root growth function which is dependent upon growth stage is used to determine the soil depth (D_{root}) over which available soil moisture SWS is calculated as follows:

$$D_{root} = D_{plant}(D_{max} - D_{plant})/\left[1 + \exp^{(c-d-t/t_{max})}\right]$$

where D_{plant} is planting depth, D_{max} is maximum rooting depth, t_{max} is days to reach the maximum rooting depth, t is days from planting, and c and d are empirical constants.

Finally, grain yield (Y_{grain}) is calculated from varietal potential yield (Y_p), transpiration T and potential transpiration T_p of each growth stage, and growth stage weighting exponents λ_1, λ_2, λ_3, and λ_4. The calculation may be stated as follows:

$$Y_{grain}/Y_p = (T/T_p)_1^{\lambda_1}(T/T_p)_2^{\lambda_2}(T/T_p)_3^{\lambda_3}(T/T_p)_4^{\lambda_4}$$

For input data, the model requires daily precipitation, irrigation, free water evaporation, GDD's from maximum and minimum temperatures, crop-dependent growth stage factors a and b, and growth stage weighting exponents λ_i for each growth stage. Also, for the root growth function, planting depth D_{plant}, maximum rooting depth D_{max}, days to reach maximum rooting depth T_{max}, and empirical constants c and d are needed. Model output consist of daily estimates of available soil moisture AW, transpiration T, and evaporation E, and a crop yield estimate.

Shaw (ref. 133) also developed a multifactorial model for estimating corn yields in Iowa that exist primarily under water-limiting conditions. The model calculates a soil water budget, the daily evapotranspiration, and a water stress index from daily precipitation and class A pan evaporation (E_0). For growth stages, the model uses historical averages adjusted for planting date or silking date if available.

Look-up curves and look-up tables are used to determine soil water extraction distribution by depth for different dates, the ratio of potential evapotranspiration PET to pan evaporation E_0 for different dates, and the ratio of actual evapotranspiration T to PET for different amounts of available soil moisture.

A current stress index (SI) is calculated for 5-day intervals from 40 days before silking to 45 days after silking:

$$SI = 1 - (T + asf)/PET \text{ for } T + asf \leq PET$$

$$SI = 1 \text{ for } T + asf > PET$$

where asf is adjusted surface evaporation.

$$asf = 0 \text{ for } E_0 > 7.6 \text{ mm and } E_0 \times \frac{PET}{E_0} \times \frac{T}{PET} \leq 0.1 \text{ mm}$$

Also,

$$T + asf = 0.13 \text{ cm for } T + asf > 0.13 \text{ cm}$$

Weighting factors ranging from 0.50 to 2.00 are assigned to each 5-day period.

Shaw made some additional adjustments to the model as follows:

1. If two or more consecutive 5-day periods have SI values > 4.50, the weighting factor is increased by 1.5 for each period.
2. If two or three 5-day periods before silking have SI values > 3.0, these periods are multiplied by 1.5.
3. If the periods immediately before and after silking have SI values > 4.50, yield is set to zero.
4. If the rooting zone is not fully saturated sometime in May or June, the rooting depth is increased by 40 percent.

Additionally, it appears that some adjustment is necessary for excess moisture conditions.

5.1.3.2 Spring Wheat

In adapting the model for spring wheat, Rasmussen and Hanks (ref. 130) derived new values for a, b, and λ for each growth stage and for c and d. For spring wheat, the stages are emergence to booting, booting to heading, heading to soft dough, and soft dough to maturity.

5.1.3.3 Winter Wheat

In adapting the model for winter wheat, Rasmussen et al. (ref. 16) estimated potential evapotranspiration PET using the following equation developed by Priestly and Taylor (ref. 134):

$$PET = \alpha[S/(S + \gamma)]R_n$$

where α is a crop-specific and location-specific constant, γ is the psychrometric constant (mb/k°), S is the slope of the saturation vapor pressure curve at mean temperature (mb/k°), and R_n is the daily net radiation (mm/day). R_n is estimated from solar radiation (R_s) in mm/day and two regression equations:

$$R_n = 0.959R_s - 3.61 \text{ (until jointing)}$$

$$R_n = 0.926R_s - 2.70 \text{ (after jointing)}$$

Actual soil surface evaporation E is estimated in two phases: a constant-rate, energy-limited phase, and a falling-rate phase over a period of t days after stage 1 evaporation.

$$E = (\tau/\alpha) \text{ PET} \qquad \Sigma E_0 \leq U$$

$$E = Ct^{1/2} - C(t - 1)^{1/2} \qquad \Sigma E_0 > U$$

where $\tau = e^{-0.737LAI}$, and C (mm/day) and U (mm/day) are soil factors calculated from field lysimetric experiments and laboratory experiments, respectively.

When available soil moisture AW $\geq$ 0.35AWS the available soil moisture capacity, transpiration is calculated as follows:

$$T = 1.56(1 - \tau)[S/(S + \gamma)]R_n \qquad \text{(crop cover > 50 percent)}$$

$$T = (\alpha - \tau)[S/(S + \gamma)]R_n \qquad \text{(crop cover} \leq \text{50 percent)}$$

When AW < 0.35AWS, transpiration T is multiplied by a water stress factor (K_s), where K_s = AW/0.35AWS.

Finally, Rasmussen et al. (ref. 130) estimated yield (metric tons/hectare) from $[\Sigma(T/PET)]^\lambda$ as

$$\text{Yield} = 0.192(T/PET)_1^{0.172}(T/PET)_2^{0.104}(T/PET)_3^{0.646}$$

where 1, 2, and 3 refer to growth stages (1 is emergence to jointing, 2 is jointing to heading, and 3 is heading to soft dough). These growth stages are calculated by using a modified version of the Robertson's (ref. 14) spring wheat phenology model.

Input data to the model include initial soil moisture, α for the crop and location, soil factors C and U for the soil type, planting date, and daily values of rainfall, solar radiation R_s, maximum and minimum temperatures, and LAI. Model output include daily values of evaporation E, transpiration T, soil moisture content, growth stage, and a final yield estimate.

5.1.3.4 SOYBEANS

The Hanks corn model (ref. 129) was adapted by Hill, Johnson, and Ryan (ref. 131) for estimating soybean yield. They estimated potential evapotranspiration with the Jenson-Haize equation (ref. 135), which uses daily temperatures and solar radiation. Potential transpiration T_p and potential soil surface evaporation E_p are estimated from free water evaporation E_0, adjustment factor (f), and crop-stage-specific constants K_c and K_s for crop and soil, respectively.

$$PET = f(T_{max}, T_{min}, R_s)$$

$$T_p = K_c PET$$

$$E_p = K_s PET$$

For this model, actual transpiration T (mm/day) was estimated using the Hanks (ref. 129) calculations:

$$T/T_p = AW/0.5AWS \text{ for } AW \leq 0.5AWS$$

$$T/T_p = 1 \text{ for } AW > 0.5AWS$$

Soil surface evaporation E is estimated as a function of potential soil surface evaporation E_p and days since last rainfall or irrigation p as follows:

$$E = E_p/(2^{p-1})$$

For late soybean plantings, the total biomass is very small (because of the control of day length on flowering) and appears to limit bean yield. This biomass effect is estimated as a seasonal yield factor (SYF):

$$SYF = 1 \text{ for } T \geq T_{pth}$$

$$SYF = (T/T_{pth})^g \text{ for } T < T_{pth}$$

where T_{pth} is transpiration required for adequate biomass production, and g is a constant weighting factor.

According to Major et al. (ref. 136), there are five soybean growth stages: (1) planting to emergence, (2) emergence to beginning flowering, (3) beginning flowering to beginning pod fill, (4) beginning pod fill to end flowering, and (5) end flowering to physiological maturity. Excess moisture during the second and third stages reduces soybean yield. This effect is modeled as a lodging factor (LF):

$$LF = 1 \text{ for } TRA < TR23 < TRB$$

$$LF = TR23/TRA \text{ for } TR23 < TRA$$

$$LF = \ln(1.0 - TR23 + TRB + C)/\ln(1.0 + C) \text{ for } TR23 > TRB$$

where $TR23 = (T_2 + T_3)/(T_{p2} + T_{p3})$, TRA is a lower threshold of TR23 ratio, TRB is an upper threshold ratio; C is an empirical constant, T_2 and T_3 are transpiration during the second stage of growth, and T_{p2} and T_{p3} are potential transpiration during that period.

Grain yield Y_{grain} is a weighted product of potential yield Y_p, transpiration ratios, lodging factor LF, and seasonal yield factor SYF.

$$Y_{grain}/Y_p = (T_3/T_{p3})^{\lambda_3}(T_4/T_{p4})^{\lambda_4}(T_5/T_{p5})^{\lambda_5} \times LF \times SYF$$

where λ_3, λ_4, and λ_5 are empirical weighting exponents.

5.1.4 LAW-OF-THE-MINIMUM MODELS

During the last century, Liebig proposed the law of the minimum (ref. 137), i.e., that plant growth was limited by only a single factor at any given time. However, it was not feasible to use this law until more recently when linear programming and statistical algorithms were developed to allow computer fitting of law-of-the-minimum models with several variables (refs. 137-139). Such models have been developed to estimate spring wheat yields (ref. 20) from nitrogen and weather factors and to estimate corn yield from nitrogen and phosphorus (ref. 140).

This type of model reflects the observation that some variables affect yield independently and may mask the effects of other variables (ref. 140). Thus, if seed storage capacity limited by stress at pollination holds yield at a lower level than does photosynthesis during grain filling, then increasing the photosynthetic rate during grain filling will not increase yield. As indicated in figure 5-1, if stress at pollination is at level a and photosynthesis rate during grain filling is at level b , then yield cannot exceed level A because there is no room in the grain for more material.

A second principle of the law of the minimum is that of "fixed proportionality of responses," which states that response to a variable may be shown in a simple linear equation whenever the variable is most limiting. Figure 5-1 shows how this second principle works. Thus, according to the law of the minimum (MIN), if yield (Y) is limited or controlled by factors U, V, W, and X, as shown in figure 5-2, then each of the diagonal lines indicates how yield is limited by either U, V, W, or X. Each of the horizontal lines is labeled with the level of U, V, W, or X that limits yield at each particular level. The upper horizontal line Y_{max} is the maximum possible yield. Actual yield will be the lowest value indicated by either U, V, W, X or Y_{max} and may be stated as

$$Y = MIN\left[Y_a + m_1U,\ Y_b + m_2V,\ m_3W,\ Y_c - m_4X,\ Y_{max}\right]$$

5.1.4.1 Corn

The equation used in Waggoner's model (ref. 144) is as follows:

$$Yield = MIN[1.02 + 0.243P,\ 1.82 + 0.0538N,\ 7.69]$$

where P is applied phosphorus, N is applied nitrogen, and all values are in kilograms per hectare. In addition, the yield predicted by the model for the experimental crop was shown to be the lowest value given by one of the three functions in the equation. Waggoner and Norvall (ref. 140) compared the law-of-the-minimum approach with quadratic, logarithmic, and square root models for corn, red clover, and alfalfa. They concluded that, for predicting corn yield, a simple law-of-the-minimum model was superior except in cases where nutrient substitution occurred at very low levels of fertility.

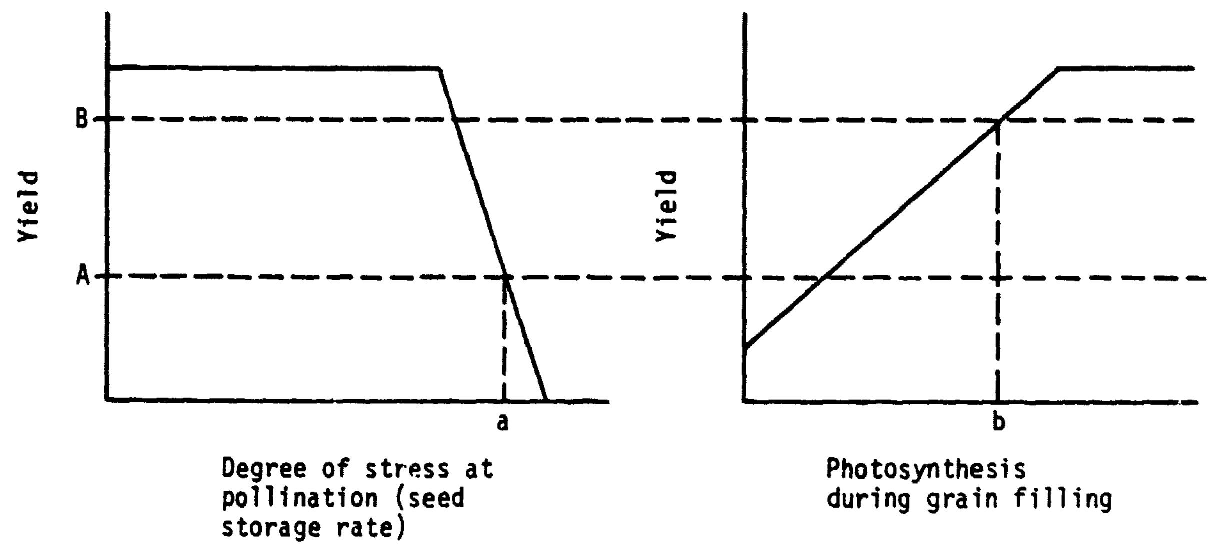


Figure 5-1.— Yield as a law-of-the-minimum function of seed storage capacity and photosynthesis during grain filling.

Fixed proportionality of responses

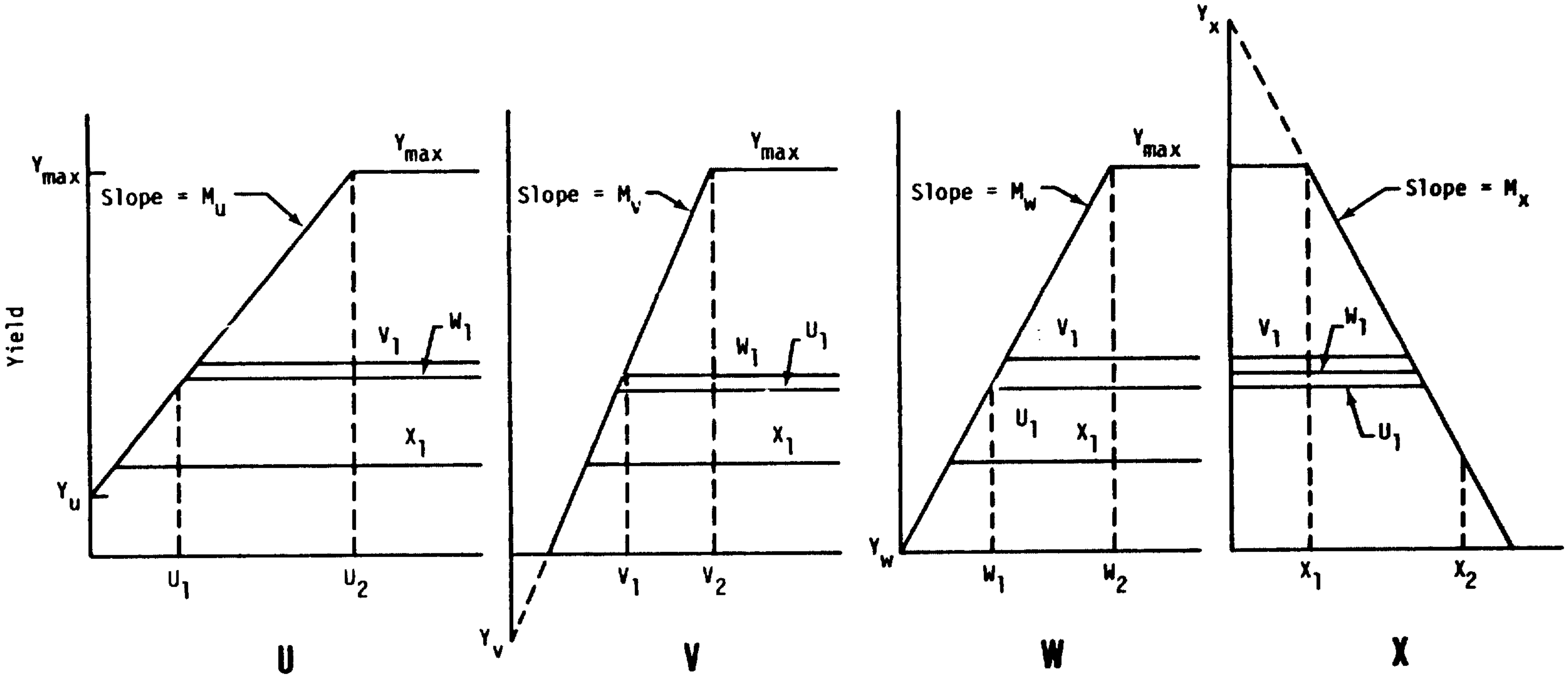


Figure 5-2.— Yield as a law-of-the-minimum function of u, v, w, x, and Y_{max} where Yield = $MIN[Y_u + M_uU,\ Y_v + M_vV,\ Y_w + M_wW,\ Y_x - M_xX,\ Y_{max}]$.

5.1.4.2 Spring Wheat

Cate and Phinney (ref. 20) have modeled crop reporting district (CRD) level spring wheat yields in the U.S. northern Great Plains as a function of available nitrogen during different stages of growth and of high temperature stress during the grain-filling period. Stages of growth were estimated using Feyerherm's (ref. 2) phenology model and planting date model. Total nitrogen (TN) is calculated by estimating soil nitrogen (NS) from historical yields and adding applied nitrogen (NA) in the CRD. Available nitrogen (AN) is then modeled as a function of soil moisture (RW), which transports nitrogen into the the plant, and total nitrogen. It may be stated that

$$NS = (Y/b*VYA - NA)/(1 + \%F/2)$$

where Y is yield; VYA is relative yielding ability of the varieties planted in the CRD as calculated by Feyerherm et al. (ref. 122); NA is applied nitrogen; %F is percent fallow land; and b is 0.321, which is the nitrogen uptake function where nitrogen is the only limiting factor (ref. 141).

Relative water availability RW is calculated as a function of estimated pan evaporation ($\hat{E}_o$) and precipitation (P) over each growth stage:

$$\hat{E}_o = \frac{n}{30} (0.2163 + 0.3473E_s - 0.2644E_n)$$

where n is the number of days in a stage, and E_s and E_n are vapor pressures associated with the average maximum and minimum daily temperatures respectively during a stage; E_s and E_n are calculated using the Clausius-Clapeyron equation. Further, RW is:

$$RW = [14 - (P - \hat{E}_o)]/14$$

where 14 is an empirical normalization constant which adjusts the range of RW from 0 to 1.0 in the U.S. spring wheat region. The equation for stating available nitrogen AN is:

$$AN = RW[NS(1 + \%F/2) + NA]$$

Yield Y, therefore, is calculated as the minimum of four functions:

1. Available nitrogen from planting to jointing (3.47 + 0.360AN)
2. Available nitrogen from jointing to heading (-2.24 + 0.490AN)
3. Available nitrogen from heading to maturity (11.06 + 0.349AN)
4. Average temperature ($\bar{T}$) from milk stage to maturity (102.09 - 1.055$\bar{T}$)

5.1.5 GENERAL PHYSIOLOGICAL MODELS

Hodges and Kanemasu (ref. 18) developed a general model for predicting overall growth of winter wheat. The model simulates canopy light interception, photosynthesis, and respiration on a daily basis from daily solar radiation (SR), maximum and minimum temperatures, and LAI. To estimate growth stages, the model used a modified version of the Robertson (ref. 14) spring wheat phenology model. Later, a yield estimation function (ref. 142) was added to the model. Total growth estimation by the model was quite good, but yield estimation was poor, reflecting a general lack of understanding of the partitioning process. Arkin et al. (ref. 17) developed a sorghum growth and yield model using numerous submodels to estimate the physiological processes.

5.1.5.1 Sorghum Growth and Yield Model

The sorghum model developed by Hodges et al. (ref. 19) considers two major aspects of yield: daily production of dry matter and partitioning of dry matter to the head and grain. The model developed by Arkin and Vanderlip (refs. 17, 143, 144, 145) considers daily production of dry matter, timing of plant physiological development, and growth of plant parts. Figure 5-3 (ref. 143) illustrates the various submodels that are required to generate the information required to produce the final yield. The details of the submodels have been discussed by Vanderlip and Arkin (ref. 143), Arkin et al. (refs. 17 and 144).

5.1.5.1.1 Daily Dry Matter Production

The model runs on a daily input and output basis. The production of daily dry matter is calculated from (1) the development of the leaf area in response to temperature, (2) the computation of light interception from the calculated

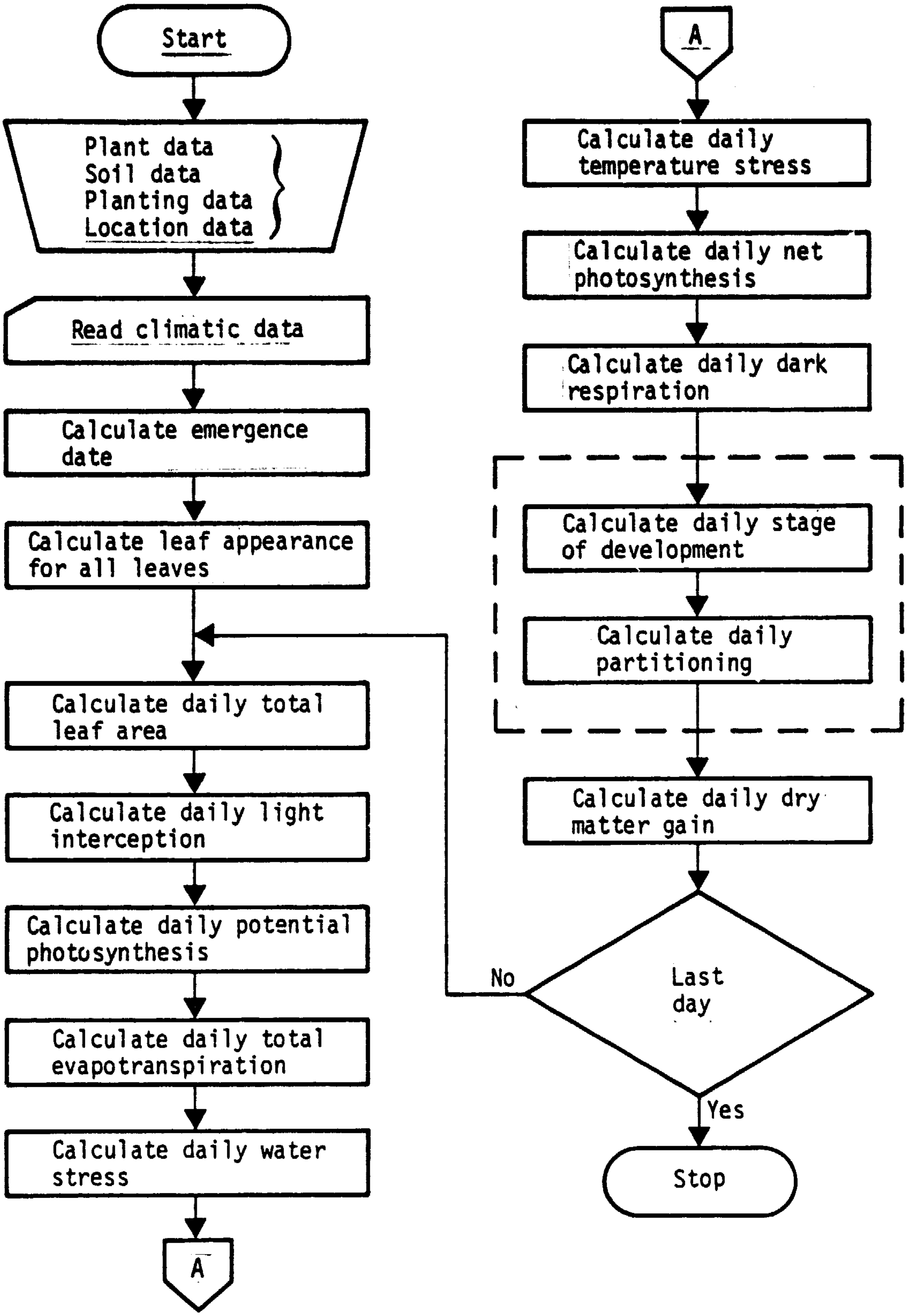


Figure 5-3.– A generalized flow diagram of the grain sorghum model. (From reference 143.)

leaf area, (3) arrangement of the plant, and (4) solar radiation, which gives net photosynthesis (see figure 5-4). Adequate fertility is assumed.

$$\text{Dry Matter (mg dm}^{-2}) = \frac{12}{44} \times \frac{1}{0.4} \times P.$$

where 12/44 is the ratio of the molecular weights of C and CO_2, respectively, 0.4 is the proportion of carbohydrate which is carbon, and P is net photosynthesis.

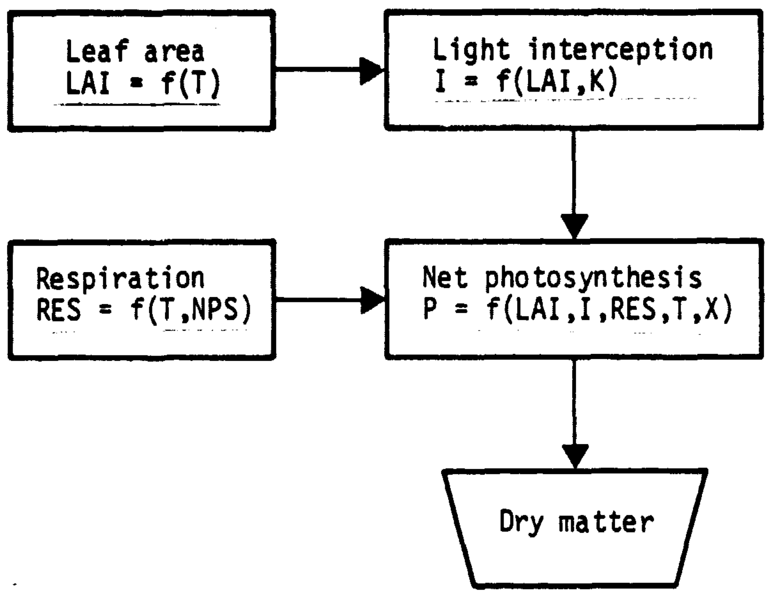
5.1.5.1.2 Timing of Plant Development

The development of the plant was assessed according to the development stages of sorghum suggested by Vanderlip and Reeves (ref. 145). Figure 5-4 describes the relative importance of the growth stages to dry matter partitioning. In observing the distribution of the dry matter accumulation to various parts of the plant, three stages of development were found to be of particular importance: Stage 3, growing point differentiation (GPD); Stage 6, half bloom; and Stage 9, physiological maturity (PM). These stages may be explained as follows:

Stage 3 — Growing point differentiation GPD occurs halfway between the period when the fifth leaf is fully expanded and the period when the flag leaf appears in the whorl.

Stage 6 — Half bloom is usually defined as the stage when one-half of the plants in the field are in full bloom. In the model, half bloom is estimated as the computed date the flag leaf was fully expanded, plus 0.86 times the computed days from Stage 3 to the appearance of the flag leaf (ref. 143). At Stage 5, which occurs several days before half bloom, maximum LAI occurs, indicating that approximately one-half of the total dry weight of the plant has been produced.

Stage 9 — Physiological maturity is not clearly defined. The amount of time required for grain filling has been found to be variety dependent. Also, hybrids have a relatively longer grain-filling period than do those varieties which have stronger parental lines. In this particular model, the number of days from emergence to Stage 9 was calculated in the submodel as 1.6 times the computed days from emergence to half bloom.



Legend:

T	Mean air temperature
K	Canopy extinction coefficient for light
NPS	Net exchange of CO_2 during day and night
X	Moisture stress
f	Adjustment factor

Figure 5-4.— Submodels for calculating the daily production of dry matter.

Both Stage 3 and the time of half bloom were based on the calculations of leaf number and leaf expansion.

5.1.5.1.3 Dry Matter Partitioning

The submodel used for partitioning dry matter is discussed in detail by Vanderlip and Arkin (ref. 143). Figure 5-5 shows the partitioning of dry matter at the three particular stages of development discussed in section 5.1.5.1.2. An assessment of the partitioning process at these stages is as follows:

Emergence to Stage 3: Leaves and roots. The partitioning was based on the modeling of the daily leaf-area development and the dry matter production. There are certain constraints in the model that allowed this relationship to the environmental conditions. The roots received at least 25 percent of the dry matter.

Stage 3 to 10 days afterward: Leaves, roots, and culm. The partitioning to the leaves was first priority in a manner similar to that described above. A ratio of 0.4:0.6 was the partitioning ratio of the remaining dry matter between the roots and culm, with at least 20 percent going to the roots.

Remaining period in Stage 3 to half bloom: Leaves, roots, culm, and head. After partitioning to the leaves, the remaining dry matter going to the roots, culm, and head was in the proportion of 0.20:0.45:0.35, respectively.

Stage 6 to maturity: Head. A short time (0.1 x time from emergence to anthesis) after anthesis, the entire amount of dry matter went into the grain. In addition, the culm weight was reduced to contribute some proportions to the yield and roots.

5.1.5.2 Model Limitations

Arkin et al. (ref. 144) have been evaluating the model for several years at a field level. The results have proven satisfactory at this level of application. A modified version of this model has also been evaluated satisfactorily by Hodges et al. (ref. 19). However, the model has some limitations which could be overcome if the following areas are addressed.

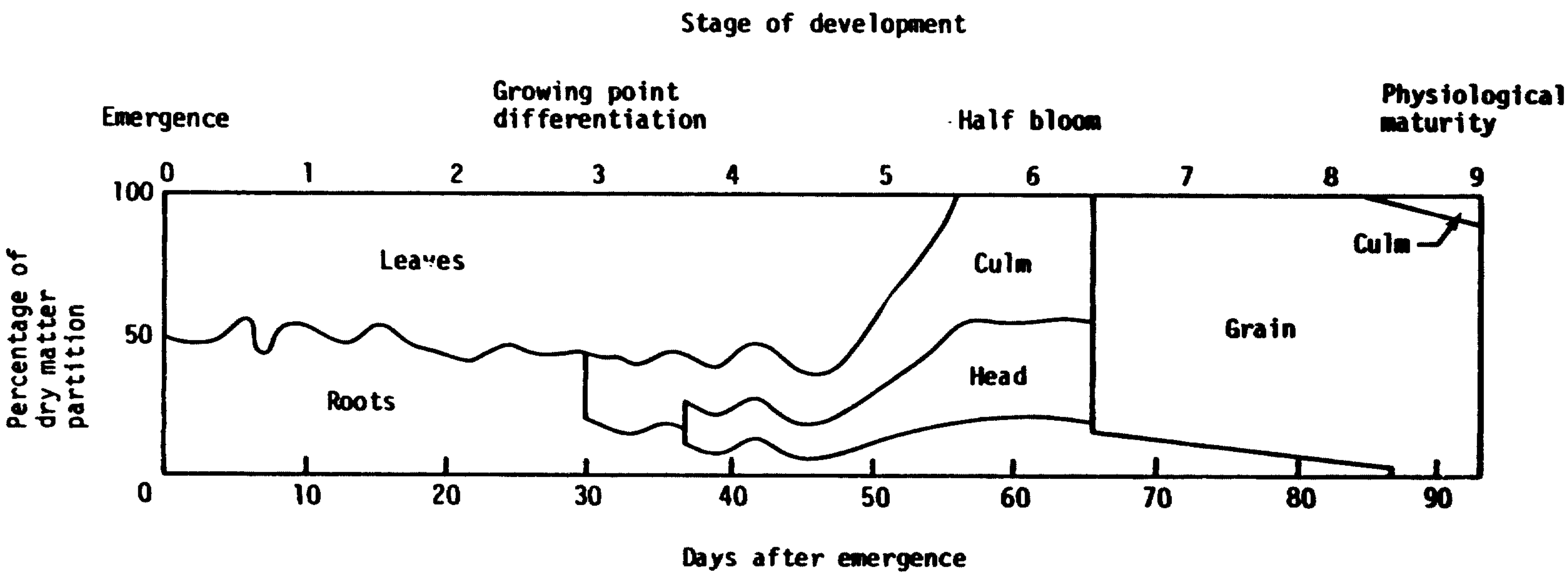


Figure 5-5.— Empirical partitioning of dry matter to the appropriate plant parts as a function of a given stage of development. (From reference 144.)

1. The timing of phasic deve .pment and the partitioning of dry matter need to be made more responsive to soil water, nutrients, and photoperiod.
2. Both water stress and nitrogen stress should reflect the rate of leaf appearance, leaf development, and leaf area.
3. The number of seeds and the rate of grain filling must be adequately modeled.

5.1.6 DISCUSSION OF MODELS

As discussed in section 3, several variables, acting through such basic physiological processes as photosynthesis, respiration, transpiration, translocation, leaf and root growth, differentiation, and maturation, influence crop yield in an intricate manner which becomes increasingly complex as the plant matures. For example, light affects differentiation and maturation as day length during photoperiod-sensitive stages; however, it affects photosynthesis as energy intercepted by a changing leaf area during all stages.

If one models the basic physiological processes and their interactions, one may have a general idea of the nature of the response well beyond the range of experimental data because one understands how a particular plant process responds to extreme conditions. Thus, models which simulate photosynthesis and respiration could predict biomass over a wide range of conditions (refs. 15 (refs. 15 and 17-19). Because the processes of shoot and floral development. which influence partitioning of biomass into grain, are poorly understood, yield simulation is not as advanced as biomass simulation (refs. 17 and 19).

Many researchers have attempted to estimate grain yield with statistical models which do not simulate basic physiological processes. These models fit yield to linear or higher order forms of each of the variables closely correlated with yield. Since yield responds to the effects of these variables or growth processes which are somewhat removed from the actual grain-filling process, extrapolation along a purely statistical yield response curve cannot be expected to reflect changes in the underlying growth processes. However, because these models can be developed quickly, they require little agronomic data beyond yield and, therefore, obtain good results in many situations.

Certain types of effects are not readily accounted for by each of the model types discussed above. The following cases indicate such effects.

1. Single variables such as periods of drought, periods of extremely high or low temperatures, flooding, or mineral shortage may cause large yield reductions. These unfavorable variables are probably the most serious source of error for the regression models discussed in sections 5.1.1 and 5.1.2.

2. The response of one factor is sometimes dependent on levels of other factors. For example, when water or nitrogen is limited, response to the other major variables will be reduced or eliminated. Similarly, under low temperatures, the photosynthesis response to light is reduced or limited, as happens in winter wheat during early spring (ref. 141). In multiple regression and multifactorial models, this type of problem is sometimes handled by "tweaking" the model; i.e., by adding a new term or restraint each time a new combination of variables appears in the data. In using a law-of-the-minimum model when water or nitrogen is limited, yield would be seen as limited by the nitrogen-water submodel except in those cases where some other factor was even more unfavorable. A law-of-the-minimum model could be used when the photosynthesis response to light is reduced or limited only if several submodels including photosynthesis were seen as limiting yield and if the photosynthesis submodel had both light and temperature among the possible limiting factors.

3. New varieties tolerant of increased population density and increased nitrogen fertilization (without barrenness or lodging) will produce increased yields from year to year under stable weather conditions (ref. 6-8). The multiple regression models discussed previously deal with this problem through one of the following methods: (1) projecting the rate of yield increase over the last 5 to 10 years into the current year as trend (refs. 6-8); (2) dividing trend into a varietal yielding ability factor and a cultural factor and projecting both into the current year

(ref. 122); or (3) considering only the last few years of data in which the trend is less important (refs. 120-121). When methods 1 or 2 are used, weather patterns lasting 3 or more years tend to be incorporated into trend, making the models less sensitive to weather. When method 3 is used, the model is not sensitive to technology and cannot be tested over the full historical record.

The more sophisticated models attempt to assign "trend" variability to appropriate factors by considering varietal yield potential (refs. 20, 122, and 129) and nitrogen fertilizer application (ref. 20). However, these models fail to account for the possible influence of such factors as the chemical and biological control of pest damage and the shifting of crops between more and less fertile soils as prices change.

5.2 MODEL EVALUATION BY CROPS

Models will be evaluated by crops for use in large area yield forecasting.

5.2.1 CORN GROWTH AND YIELD MODELS

Corn yields have been steadily increasing for the last 50 years in the Corn Belt. This increase primarily is caused by the development of hybrid varieties which are tolerant of high population density (without barrenness) and which respond to high levels of nitrogen fertilizer (without lodging or barrenness).

In addition to increasing corn production in the Corn Belt, irrigation has enhanced corn production by making it possible to grow corn in the U.S. Great Plains (western Kansas, eastern Colorado, Oklahoma) which would otherwise be too dry.

Other factors which limit yield are short growing season (northern United States and Canada), heat stress, mineral nutrients such as phosphorus and potassium, and pest and disease damage.

The corn models discussed in this report are listed in table 5-1. Of these models, the model by Hanks (ref. 129) is the most sound theoretically but is applicable only in areas where yield is limited by water stress. The Thompson corn model (ref. 6) has a wider area of application than the Hanks model and has been widely tested as well.

The corn models developed by W. R. Duncan of the University of Kentucky and Curry and Baker of Ohio State University need further evaluation. At the present time, it appears that development of a more accurate corn yield model depends upon development of a good phenology model.

5.2.2 SOYBEAN GROWTH AND YIELD MODELS

Although soybean yields have increased during the last few decades, the increase has not been as great as for corn. A primary reason for this limited increase lies in the difficulty in crossing soybean varieties, which in turn results in unavailability of hybrid soybean seed. Other important factors limiting soybean yield are water availability, low number of seeds, and reduced nitrogen fixation due to unfavorable soil acidity or mineral balance. Additional factors which sometimes limit yield are excessively high temperatures, length of growing season, and pest and disease damage.

The two soybean yield models which are discussed in this report (refs. 8 and 130) are summarized in table 5-2.

In addition to the models discussed, a soybean growth and yield model developed by Curry, Baker, and Streeter (ref. 146) is of interest. This model may fit into the general or realistic model type; however, more information is needed before it can be evaluated for the AgRISTARS program.

The Hill soybean yield model is a theoretically sound model for use in predicting water-stress-limited yields; unfortunately, this model may not be suitable in areas where water stress is not limiting. On the other hand, the Thompson model is a multiple regression model and, therefore, will probably be

TABLE 5-1.– CORN YIELD MODELS SUMMARIZED

Model type	Reference	Input data	Output data	Area	Comments
Multiple regression	Thompson (6)	Preseason precipitation June temperature July precipitation July temperature August precipitation August temperature	Grain yield	U.S. Corn Belt	
Multiple regression adjusted for growth stages	Runge and Benci (121)	Silking or planting date Available soil moisture capacity Initial soil moisture Weekly maximum temperature Weekly minimum temperature Weekly precipitation Weekly irrigation	Farmer technology level as indicated by state Grain yield	U.S. Corn Belt	Farmer technology levels are erratic from year to year. Apparently, factors other than farmer technology are included.
Multifactorial	Hanks (129)	Growing degrees per stage Planting depth Maximum rooting depth Days to reach maximum rooting depth Free water evaporation Available soil moisture capacity Initial soil moisture Daily precipitation Daily maximum temperature Daily minimum temperature Varietal yield potential	Growth stages Soil moisture budget Grain yield Yield effect of irrigation	General	Should be effective in areas where yield is almost always limited by available water.
Multifactorial	Shaw (133)	Silking or planting date Varietal yield potential Daily precipitation Daily class A pan evaporation Daily maximum temperature Daily minimum temperature	Weekly stress factor Grain yield	Iowa	

TABLE 5-2.— SOYBEAN YIELD MODELS SUMMARIZED

Model type	Reference	Input data	Output data	Area	Comments
Multiple regression	Thompson (8)	Preseason precipitation June temperature July precipitation July temperature August precipitation August temperature	Grain yield	U.S. Corn Belt	
Multifactorial	Hill et al. (131)	Daily precipitation Daily solar radiation Daily maximum temperature Daily minimum temperature Crop stage constants (K_c, K_s) Available soil moisture capacity Initial soil moisture Minimum transpiration for adequate biomass production Upper and lower transpiration thresholds Varietal yield potential Varietal growth stage coefficients	Growth stages Soil moisture budget Lodging factor Flooding factor Grain yield	General	Should be effective in areas where yield is almost always limited by available water.

unsuccessful in predicting extremely high or low yields or yields where only one factor is very limiting. With the Major et al. (ref. 136) phenology model available, it should be possible to develop an improved soybean model by identifying the factors limiting number of seed.

5.2.3 WHEAT AND BARLEY GROWTH AND YIELD MODELS

No models are available for predicting the yield of barley crops.

Wheat yields, and to a lesser extent barley yields, have increased steadily over the last 50 years. In many areas, however, yield is limited because of the use of varieties which mature before the driest or hottest part of the summer. Such varieties are greatly affected by water stress and heat stress. In areas of ample water, where nitrogen is frequently a limiting factor, the crop yield may be increased through nitrogen fertilization. Winter wheat cannot be grown in areas where the winter is not cold enough for vernalization to occur, nor can it be grown in areas where the winter is too severe for the crop to survive. For some varieties, the influence of excess moisture at a time near maturity reduces yield. Finally, pest and disease damage are sporodic yield-limiting problems for both wheat and barley.

The wheat yield models discussed in this report are summarized in table 5-3. The Thompson (ref. 7) spring and winter wheat models as adapted for use in the LACIE project have been widely used and tested (ref. 119) as have the CCEA models. In terms of the U.S. spring wheat region, the modified Thompson or CCEA models were slightly outperformed by the Feyerherm spring wheat model [better in two of five regions, overall root mean squared error (RMSE) 2.07/2.56 and bias -0.3/1.0] and substantially outperformed by the Cate-Phinney spring wheat model (better in three of five regions, overall RMSE 0.99/2.56 and bias 0.0/1.0, ref. 119). When the problems of modeling phenology of winter wheat are overcome, it should be possible to develop a winter wheat model similar to the Cate-Phinney spring wheat model. The model by Hodges and Kanemasu (ref. 18), however, will not be a candidate for large area yield forecasting until the growth partitioning problem is resolved.

TABLE 5-3.— WHEAT YIELD MODELS SUMMARIZED

(a) Spring wheat

Model type	Reference	Input data	Output data	Area	Comments
Multiple regression	Thompson (7)	Preseason precipitation April precipitation April temperature May precipitation May temperature June precipitation June temperature July precipitation July temperature	Grain yield	U.S. Great Plains Canada U.S.S.R.	As modified for LACIE (CCEA models), extensively tested.
Multiple regression with growth stages	Haun (120)	Planting date Fertilizer application Preseason precipitation Field capacity Initial soil moisture Long-term monthly average temperature Daily precipitation Daily maximum temperature Daily minimum temperature 20 sets of coefficients for weekly yield-prediction equations	Estimated rate of maturation Grain yield forecast weekly	General	
Multifactorial	Rasmussen and Hanks (130)	Daily free-water evaporation Daily precipitation Daily maximum temperature Daily minimum temperature Available soil moisture capacity Initial soil moisture Growing degrees for each stage Varietal yield potential Planting depth Maximum rooting depth Days to reach maximum rooting depth	Growth stages Soil moisture budget Grain yield	General	Should be effective in areas where yield is almost always limited by available water.

TABLE 5-3.— Continued.

Model type	Reference	Input data	Output data	Area	Comments
Multiple regression with growth stages	Feyerherm (2)	Daily maximum temperature Daily minimum temperature Daily precipitation Nitrogen applied Varietal yield potential Varietal distribution	Growth stages Soil moisture budget Grain yield	U.S. Great Plains U.S.S.R. Canada	Extensively tested. In some areas provides slightly better estimates than CCEA models.
Law of the minimum	Cate and Phinney (20)	Daily maximum temperature Daily minimum temperature Daily precipitation Historical yield record Applied nitrogen Latitude or day length Varietal yield potential	Growth stages Factor limiting each case Grain yield	U.S. Great Plains	Appears to be a substantially better model than the CCEA models or the Feyerherm models which it was tested against.

TABLE 5-3.— Continued.

(b) Winter wheat.

Model type	Reference	Input data	Output data	Area	Comments
Multiple regression	Thompson (7)	August-March precipitation April precipitation April temperature May precipitation May temperature June precipitation June temperature July precipitation July temperature	Grain yield	U.S. Great Plains Canada U.S.S.R.	As modified for LACIE (CCEA models), extensively tested.
Multiple regression with growth stages	Haun (120)	Long-term monthly average temperatures Daily precipitation Daily maximum temperature Daily minimum temperature Fertilizer application Field capacity Initial soil moisture Planting date Preseason precipitation 20 sets of coefficients for weekly yield prediction equations	Estimated rate of maturation Grain yield forecast weekly	General	
Multiple regression adjusted for growth stage	Feyerherm (2)	Daily maximum temperature Daily minimum temperature Daily precipitation Nitrogen application Varietal yield potential Varietal distribution	Growth stages Soil moisture budget Grain yield	U.S. Great Plains U.S.S.R.	Extensively tested. Provided poorer estimates than did the CCEA models.

TABLE 5-3.— Concluded.

Model type	Reference	Input data	Output data	Area	Comments
Multifactorial	Rasmussen and Kanemasu (16)	Daily precipitation Daily solar radiation Daily maximum temperature Daily minimum temperature Daily leaf area index Available soil moisture capacity Initial soil moisture α for location Planting date Varietal yield potential	Growth stages Soil moisture budget Grain yield	General	Should be effective in areas where yield is almost always limited by water availability.
General physiological	Hodges and Kanemasu (18); Hodges (142)	Daily precipitation Daily solar radiation Daily maximum temperature Daily minimum temperature Daily leaf area index Available soil moisture capacity Initial soil moisture α for location Planting date Varietal yield potential	Growth stages Soil moisture budget Biomass production Grain yield	General	

5.2.4 SORGHUM GROWTH AND YIELD MODELS

The Arkin-Vanderlip yield model (ref. 143) is the only model available for evaluating sorghum. Modified versions of this model have been tested on a limited scale (ref. 18) but not over large areas (1 to 5 acres) or for several years. The initial goal of the Arkin-Vanderlip model was to generate daily growth and development of the sorghum crop. The functions for the various processes in the model were derived from field and laboratory studies of the physiological and agronomic characteristics of the sorghum plant or crop. Therefore, the model is responsive to most environmental conditions that influence development and yield. The data requirements and output of the model are shown in table 5-4.

There are certain limitations to the model that need to be considered. The model is responsive to water and temperature stress only in the photosynthesis submodel. It is necessary to incorporate the effects of water, temperature, and nitrogen stress on the rate of leaf appearance and leaf development. These effects usually do not produce the same response at each stage of development.

The timing of phenological development is based on the rate of leaf appearance and LAI, and reliance on these factors may be sufficient when the model is used for varieties that develop a fixed number of leaves. Photoperiod responses are not incorporated because the model was developed for U.S. varieties that are insensitive to photoperiod levels such as those at the development site in Temple, Texas, and at nearby latitudes. However, one must include the photoperiod response if the model is to be useful in areas where sorghum varieties do exhibit this characteristic. And, finally, there is room for improvement in the submodel where dry matter is partitioned into various plant parts.

5.2.5 COTTON GROWTH AND YIELD MODELS

A cotton model (SIMCOT) was developed to combine the different processes and provide a logical tool for considering quantitative relationships (ref. 147). The model requires detailed information of soil and plant characteristics. The effects of plant moisture stress, environment evaporative demand, and

TABLE 5-4.— THE DATA REQUIREMENTS AND INFORMATION PERTAINING TO THE GENERAL-PHYSIOLOGICAL SORGHUM GROWTH MODEL OF ARKIN AND VANDERLIP

Input data required	Output data	Area applicable	Comments
Planting date	Leaf appearance	Tested in fields of 1 to 5 acres in Temple, Texas. Formed with field and laboratory data obtained from several sources around the United States. Also tested on fields in Kansas, Nebraska, Colorado, and Missouri.	Requires detailed plant data. Use of spectral data could provide some of the plant data such as leaf area index. Model needs to be tested over large areas.
Plant population	Dry matter		
Row width and direction	Leaf area index		
Leaf number	Net photosynthesis		
Maximum area of each leaf	Water stress factor		
Maximum temperature	Development stage		
Minimum temperature	Dry matter partitioning		
Solar radiation	Grain yield		
Precipitation			
Latitude			
Soil characteristics			
Initial available moisture			

diurnal temperature are considered on a day-to-day basis. The model provides a good partitioning function for photosynthates among parts of the plant at different growth stages. The results of the model are reported to be reasonably good, but it is unclear from the available literature (refs. 110 and 148) how the various components of the model are combined to obtain the final yield.

5.2.6 RICE AND SUNFLOWER GROWTH AND YIELD MODELS

No yield models are available.

6. RECOMMENDATIONS

Based on discussions in sections 3.4 and 5.2.1, a nitrogen curve for the crops of interest should be developed as the basis for further yield modeling efforts. Such a curve can probably be derived from the scientific literature. Additionally, after the phenology problems for certain crops discussed in an earlier technical memorandum (ref. 79) are solved, general physiological or law-of-the-minimum models should be developed. Because the number of seeds appear to limit soybean yield in many cases, factors controlling flower and pod abortion should be identified and quantified prior to new model development. The Cate-Phinney spring wheat model should be thoroughly tested and improvements should be made in several areas, especially in the soil moisture budget. Furthermore, for each crop of interest, a temperature and respiration response curve and a plant water-stress response curve can be developed from the scientific literature.

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APPENDIX A

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