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This computer model predicts crop growth and yield as a function of soil and weather factors. When the program is used for scheduling irrigation, the required depth and timing of irrigation water for any planting date is determined by simulating the effects of incremental supplements of water. The "best" resultant irrigation scheduling is indicated for any given pre-selected yield level. The computer program is useful for estimating probabilities of management effects on soybean yield from historical weather data at any selected site. The program does not eliminate the need for field trials, but it can be used to identify the more promising varieties, planting dates, and water management practices. Thus, field work can be concentrated on problem areas, with a result savings of time and money.

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PREDICTING SOYBEAN GROWTH AS AFFECTED BY WATER MANAGEMENT

By

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Department of Agricultural and Irrigation Engineering
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PREDICTING SOYBEAN GROWTH AS AFFECTED BY WATER MANAGEMENT

By

R. W. Hill[1], K. H. Ryan[2], D. R. Johnson[3]

Abstract

A computer program is presented which illustrates a strategy for determining soybean yield as influenced by water management. The application of the program can be demonstrated by use of a model which predicts crop growth and yield as a function of soil and weather factors.

The program requires a measurement of the amount of soil water in storage at the beginning of the season; available soil water storage in the root zone, and daily values of rainfall, irrigation, maximum and minimum temperatures and specific parameters for each variety that relate phenology to weather data. Determination of the phenologic state is based on phenology equations developed at the University of Missouri by D. J. Major and D. R. Johnson. The example presented utilizes three sites, three soybean varieties, and five years of data. From any pre-selected planting date, the program predicts yield as a function of relative transpiration during each of the following periods: emergence to begin flowering, begin flowering to begin podfill, begin of podfill to end of flowering, and end of flowering to maturity.

When the program is used for scheduling irrigation, the required depth and timing of irrigation water for any planting date is determined by simulating the effects of applying supplemental water in incremental

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amounts. The "best" resultant irrigation scheduling is indicated for any pre-selected yield level.

The program is useful for estimating probabilities of management effects on soybean yield from historical weather data at any selected site. The program does not eliminate the need for field trials, but it can be used for identifying the more promising varieties, planting dates, and water management practices. Thus, field work can be concentrated on problem areas with a resultant savings of time and money.

KEY WORDS: Water management, models, soybean yield model, irrigation, soil water model.

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PREDICTING SOYBEAN GROWTH AS AFFECTED BY WATER MANAGEMENT[1]

By

R. W. Hill[2], K. H. Ryan[3], D. R. Johnson[4]

Introduction

Staff members at Utah State University are involved in programs which provide transfer and adaptation of technical expertise in on-farm water management to some of the developing countries (Keller, Peterson, and Peterson (1973). This experience has illuminated the need for an organized means of identifying and efficiently transferring appropriate portions of our technical agricultural production capabilities to other areas of the world. This requires storing pertinent crop-water-soils and other agricultural production data in a retrievable form.

Appropriately designed computer programs can access this data for supplying recommended farm management practices and identify research needs at any given site. The work reported herein is a part of a continuing effort to identify non-site specific estimating techniques for crop production factors particularly related to water management practices. A similar but simpler example related to corn was presented by Hill, et al. (1974).

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Irrigation and tillage practices are commonly used to maximize production with a given set of soils, climate, water resources, and plant materials. Production may also be improved by selecting varieties and planting dates that will maximize the effects of naturally occurring rainfall.

The objective of this study was to develop a model which combines the influence of day length and temperature on soybean development with a soil water model which predicts relative yield. The model depends upon stored information which describes the rate of development of selected soybean varieties as affected by average daily temperatures and day lengths. In this example varieties from three different soybean Maturity Groups (II, III and IV) were used. Maturity groupings are a relative measure of the required length of season for a particular variety. For example, Maturity Group I varieties are shorter season than Maturity Group II. The model predicts dates when each of five phenologic growth stages are reached by the crop for any given planting date, then it predicts yield changes as affected by soil water availability during the period between each of the growth stages.

Robertson (1973) has described some of the important background literature relative to the climate-crop growth stage part of the model. The soil-water part of the model has been described by Hanks (1974). He demonstrated its' usefulness in predicting the influence of soil type and irrigation frequency on corn yield.

Plant Development Prediction

During plant growth, from seeding to harvest, the influence of various environmental conditions depends upon the sensitivity of each particular growth stage. Some of the important factors that influence

crop growth are:

1. Weather (temperature, precipitation, radiation, wind, humidity)

2. Soil (water status, fertility, toxicity, salinity)

3. Plant (crop, variety, preconditioning, population, planting date)

4. Pests (diseases, insects, weeds)

5. Daylength and elapsed time

Information describing crop response in terms of these factors must be identified before a model can predict crop growth and yield. A conceptual basis for handling the resulting complex relationships is presented by Keller, Peterson and Peterson (1973). They suggest that crop response to environmental conditions can be expressed as the interaction of two multi-dimensional vectors, agricultural environment, $\overline{E}$, and production materials, $\overline{M}$. The crop response vector, $\overline{Rc}$, can thus be expressed as $\overline{Rc} = f(\overline{E}, \overline{M})$. For the purposes of the present model, $\overline{E}$ includes daily maximum and minimum temperatures, precipitation, radiation, daylength, irrigation and soil water properties. At the University of Missouri, Major et.al (1975), reduced the vector $\overline{M}$ to a scalor quantity M by an equation relating soybean development to temperature and daylength. Their equation is

$$M = \sum_{S_1}^{S_2} [a_1 (L_n - a_o) + A_2 (L_n - a_o)^2] \times$$

$$[b_1 (t_n - b_o) + b_2 (t_n - b_o)^2] \qquad [1]$$

in which

M = progression toward maturity which is equal to unity when current stage is completed

S_1, S_2 = phenological growth stages

L_n = day length for nth day in hours from sunrise to sunset

t_n = average temperature for nth day in °C

a_o, a_1, a_2 = regression coefficients of day length effects

b_o, b_1, b_2 = regression coefficients of temperature effects

The field experiments and analytical procedures used in determining regression coefficient values for several soybean varieties are described by Major, et. al. (1975).

Crop Yield Estimation

The other major portion of the model provides seasonal estimates of plant growth (yield) as influenced by soil water status. The soil water status is related to initial soil moisture, effective rain and irrigation, evaporation directly from the soil, transpiration from plants, and drainage. It is assumed that the only process directly influencing plant yield is the ratio of transpiration, T, to potential evapotranspiration, E_{tp}, for a reference crop such as alfalfa. Soil evaporation and drainage have an influence on water availability and thus indirectly affect transpiration; but the model assumes these processes do not directly affect yield.

Several investigators have examined the effect of water availability on soybean yield. Runge and Odell (1960) found that above normal precipitation during blooming and pod filling periods increased yields, whereas, abundant rainfall during early vegetative growth periods was detrimental to yield. Thompson (1970) reported essentially the same effects in an analysis of yield data from five states (Illinois, Indiana, Iowa, Missouri and Ohio) between 1930 to 1968. Shaw and Laing (1966) indicated that water stress during the bean filling stage and the last

week of pod development resulted in greater decreases in yield than stress during other periods. In an analysis of irrigation treatment effects on soybean yield in Kansas, Brady et. al. (1974) discovered that partial season irrigation (podding stage only) produced as much yield as full season irrigation and lodging increased when water was applied earlier in the season.

In view of these research observations, any equation linking soybean yield to water stress during the various phenologic stages should have different weighting factors for the growth period between each stage. To achieve this, the method suggested by Jensen (1968) was used. For soybeans the season was divided into five interstage growth periods and relative bean production computed by

$$\frac{Y}{Y_p} = \left(\frac{T_1}{T_{p1}}\right)^{\lambda_1} \cdot \left(\frac{T_2}{T_{p2}}\right)^{\lambda_2} \cdot \left(\frac{T_3}{T_{p3}}\right)^{\lambda_3} \cdot \left(\frac{T_4}{T_{p4}}\right)^{\lambda_4} \cdot \left(\frac{T_5}{T_{p5}}\right)^{\lambda_5} \qquad [2]$$

in which

T_i = cumulative transpiration in growth period i

T_{pi} = cumulative potential transpiration which occurs when soil water is not limiting during growth period i

Y_p = potential bean yield when tranpiration is equal to potential transpiration

λ_i = an exponent to allow for weighting growth period i

Y = the estimated bean production for any situation where T_i does not necessarily equal T_{pi}

i = 1,2,...5 representing the five periods of growth described below.

The five growth periods used in Equation 2 are:

1. planting to emergence

2. emergence to begin flowering
3. begin flowering to begin pod fill
4. begin pod fill to end flowering
5. end flowering to physiological maturity

Some water stress during the vegetative stage and the first part of the flowering period may prevent luxuriant vegetative growth and subsequent lodging (Brady et. al. 1974) resulting in a yield increase. To properly manage irrigation to improve soybean yields, it is important that moisture stress effects on yield be identified, and we feel that such a research task is worthy of considerable effort.

Preliminary examination of the Missouri field data revealed that Equation 2 is not satisfactory for predicting yields with extremely late planting dates (after July 15) for which transpiration ratios are high but yield is very low. We hypothesized then, that this is the result of insufficient accumulation of dry matter. It seems reasonable that for each soybean Maturity Group there is a threshold value of accumulated tranpiration below which dry matter production would limit bean yields.

An equation was proposed by de Wit (1958) for relating dry matter accumulation to transpiration as

$$Y_d = \frac{mT}{E_o} \qquad [3]$$

in which

Y_d = actual dry matter accumulation

T = transpiration

E_o = average free water evaporation

m = a crop factor

For a given crop and year the relation of relative transpiration to relative yield of dry matter is

$$\frac{Y_d}{Y_p} = \frac{T}{T_p} \qquad [4]$$

in which

T_p = potential transpiration which occurs when soil water is not limiting

We adapted Equation 4 to our model by using a season yield factor given by

$$SYF = 1.0, \text{ if } T \geq T_{pth} \qquad [5]$$

or

$$SYF = \left(\frac{T}{T_{pth}}\right)^{\lambda_6}, \text{ if } T < T_{pth} \qquad [5b]$$

in which

SYF = seasons yield factor

T = actual accumulated transpiration for the season

T_{pth} = potential accumulated transpiration threshold value required for adequate dry matter production

λ_6 = a constant weighting factor

The values of T_{pth} for varieties representative of Maturity Groups II, III, and IV are determined from planting dates which gave adequately long growing seasons for each group. A discussion of the validity of Equations 3 and 4 is presented by Hill, et.al. (1974).

A factor was introduced to account for the potential loss in yield

caused by too much available water during growth periods 2 and 3

$$LF = 1.0; \text{ if } TRA<TR23<TRB \qquad [6]$$

or

$$LF = TR23/TRA; \text{ if } TR23<TRA \qquad [6b]$$

or

$$LF = \frac{\ln}{\ln} \frac{(1.0-TR23+TRB+C)}{(1.0+C)}; \text{ if } TR23>TRB \qquad [6c]$$

in which

LF = lodging factor

TR23 = ratio of actual to potential transpiration for growth periods 2 and 3

TRA = lower threshold transpiration

TRB = upper threshold transpiration

C = constant

Values for TRA, TRB and C were determined during the calibration process.

To estimate bean yield, we combined Equations 2, 5, and 6 to give

$$\frac{Y}{Y_p} = \prod_{i=1}^{5} \left(\frac{T}{T_p}\right)_i^{\lambda_i} \times SYF \times LF \qquad [7]$$

We found in the calibration process that λ_1, λ_2, and λ_3 were close to zero; therefore, the first three terms in Equation 2 were dropped because they were each nearly equal to 1.0 regardless of the T/T_p value.

Actual transpiration is related to the soil water status and potential transpiration. Hanks (1974) shows that model predictions of the effects of soil water stress on corn yield are relatively insensitive to the relationship between the existing and potential soil water storage. To relate actual to potential transpiration we use

$$T = \frac{T_p}{0.5} \cdot \frac{SWS}{AW}, \text{ if } \frac{SWS}{AW} < 0.5 \qquad [8]$$

and

$$T = T_p, \text{ if } \frac{SWS}{AW} \geq 0.5 \qquad [8b]$$

where

$$T_p = k_c E_{tp} \qquad [9]$$

in which

SWS = existing or remaining soil water storage

AW = total available water holding capacity of the soil

k_c = a crop factor which depends on the crop and growth stage

E_{tp} = potential evapotranspiration for a standard reference crop

Equations 8 and 9 are adapted to allow for daily estimates and different layers of soil. A root growth estimation is used which allows for root extraction to occur at increasingly deeper depths with time. It is assumed that there is a unique AW for a given soil condition, however, this may not always apply.

Soil evaporation since the last wetting is assumed to be related to potential soil evaporation by

$$E = \frac{E_p}{t^{\frac{1}{2}}} \qquad [10]$$

where

$$E_p = k_s E_{tp} \qquad [11]$$

in which

E = evaporation from the soil

E_p = potential soil evaporation

k_s = a soil factor which depends on the crop and growth stage

t = the time in days since the last soil surface wetting

Equation 10 gives the same type of relation used by Ritchie (1972). It is subject to the constraint that the surface 4 in. (100 mm) of soil cannot be drier than air day. The top 4 in. (100 mm) of soil are dried by evaporation and transpiration to the wilting point and then by evaporation only to air dry.

The values of T_p and E_p are influenced by the kind of crop and stage of growth. Water is assumed to be lost to deep percolation if the sum of SWS and the water applied by irrigation or rain is greater than AW for all root depth increments. This simplification does not account for the possibility of water flow upward into the root zone.

Description of Model

The model was programmed in FORTRAN IV and a simplified flow chart of it is given in Figure 1. The program requires the following input data:

(a) Plant descriptor array

1. regression coefficients for Equation 1 relating soybean development to temperature and daylength
2. constants T_{pth}, λ_6, C, TRA and TRB for Equations 5 and 6.
3. growth period weighting factors for Equation 2
4. coefficients k_c and k_s for estimating the relative effect of crop growth on potential soil evaporation, E_p, and transpiration, T_p, in Equations 9 and 11
5. parameters describing root growth

(b) Soils data

1. initial soil water storage, SWS
2. total allowable water holding capacity of the soil, AW

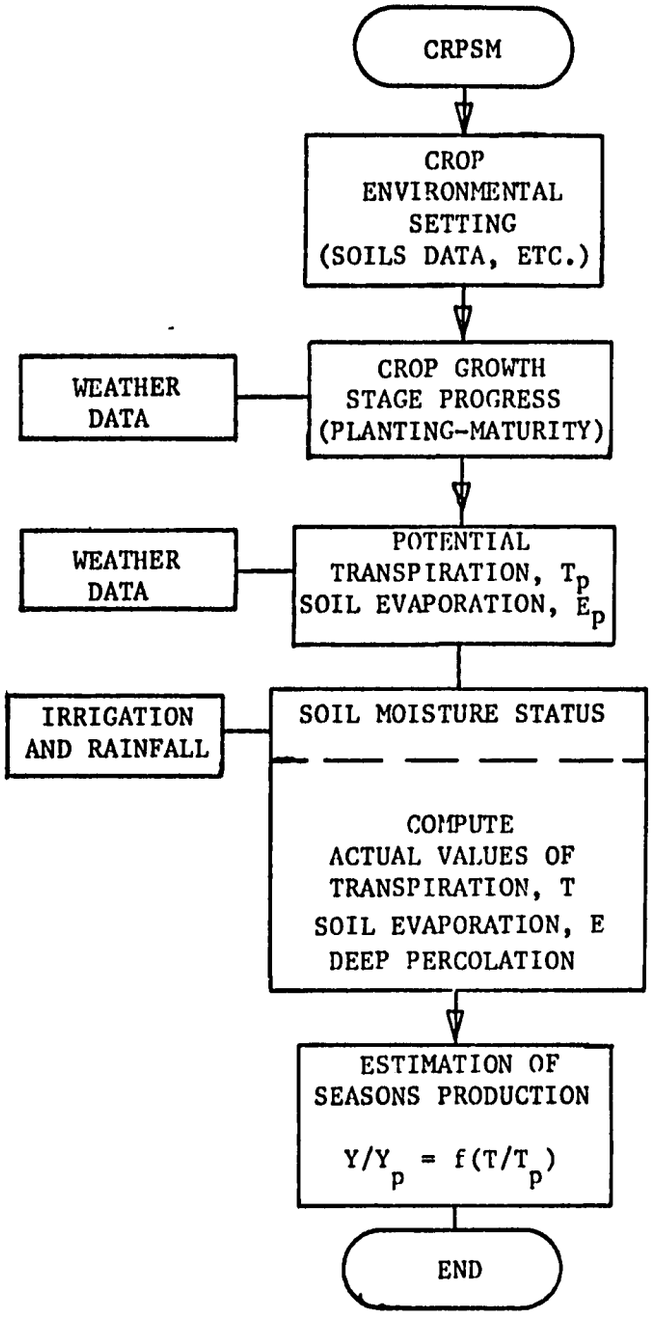

FIGURE 1. FLOW CHART OF WATER AND SOIL MANAGEMENT-CROP GROWTH MODEL (CRPSM).

3. potential root depth

(c) Daily weather data

1. maximum and minimum temperatures

2. rainfall

3. solar radiation

4. factors relating daylength to latitude

(d) Optional Management information

1. frequency and amount of irrigation, or date and amount of individual irrigation events

2. desired planting date

3. control data causing the program to increment irrigation amount at given frequencies for the purpose of generating water management production function curves

The program computations proceed on a day-to-day basis using a simple accounting procedure to keep a running account of SWS, T_p, T, E, drainage, irrigation, and rain. The phenologic stages which bracket the growth periods are determined from Equation 1. Values for SYF, LF, $(T/T_p)_4$, and $(T/T_p)_5$ are determined and used in Equation 7 to estimate relative bean yield. The program allows for a reinitialization of the input data with a different amount of water added at the same or different frequency and, if desired, a new planting date. The computations are then repeated for the same set of daily weather data and site conditions.

Calibration of Model

Calibration of the combined soybean phenology-yield model was accomplished using data from the Missouri field tests identified in Table 1 (Johnson, et.al. 1973a, 1973b). Varieties representing each of the three Maturity Groups studied were planted on each of several dates at the three locations listed. Late July planting dates were also

available but were not used because the long season varieties failed to mature. Standard pattern search optimization techniques for fitting models to actual data were used in the process of identifying the parameter values which gave the "best" fit model.

Table 1. Missouri machine harvested soybean yield field data used for calibrating model

Soybean Maturity Group	Location	Year	Planting Date - Yield (Bu/Ac)
II	Spickard	1971	4/23-30, 5/13-29, 6/02-24, 6/23-21
		1972	4/26-38, 5,17-44, 6/04-41, 6/21-50
	Mt. Vernon	1971	4/29-49, 5/11-46, 6/03-39, 6/24-35
	Columbia	1971	4/23-42, 5/13-42, 6/02-44, 6/23-37
III	Spickard	1971	4/23-22, 5/13-21, 6/02-25, 6/23-22
		1972	4/26-42, 5/17-43, 6/02-55, 6/21-45
	Mt. Vernon	1971	4/29-54, 5/11-42, 6/03-37, 6/24-40
	Columbia	1971	4/23-55, 5/13-46, 6/02-43, 6/23-36
IV	Spickard	1971	4/23-19, 5/13-18, 6/02-14, 6/23-22
		1972	4/26-34, 5/17-45, 6/02-51, 6/21-41
	Mt. Vernon	1971	4/29-52, 5/11-48, 6/03-39, 6/24-39
	Columbia	1971	4/23-55, 5/13-45, 6/02-41, 6/23-36

Data from all of the field tests identified in Table 1 were used in the calibration of the model. The "best" fit set of parameters presented in Table 2 was generated. These parameters were then used in Equations 2, 5, and 6 to predict relative yields for each of the field tests. A plot of the model calibration results is shown in Figure 2. The yields predicted by the model closely matched actual field test yields for soil water conditions giving moderate to high yields for May-June planting dates. However, for field trials with extremely early or late planting

Table 2. Calibrated parameter values for Equations 2, 5, and 6 from Missouri soybean field tests

Maturity Group	Parameter Values										Potential Yield
	Equation 2					Equation 5		Equation 6			
	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	T_{pth}	C	TRA*	TRB	Y_p (bu/ac)
II	0	0	0	0.20	0.41	2.25	7.00	0.870	0.5	0.67	73
III	0	0	0	0.10	0.40	3.4	7.00	0.690	0.5	0.66	84
IV	0	0	0	0.10	0.52	1.6	8.53	0.705	0.5	0.65	88

*The value of TRA could not be determined for the field data because the soil moisture was above 50% of available at all times.

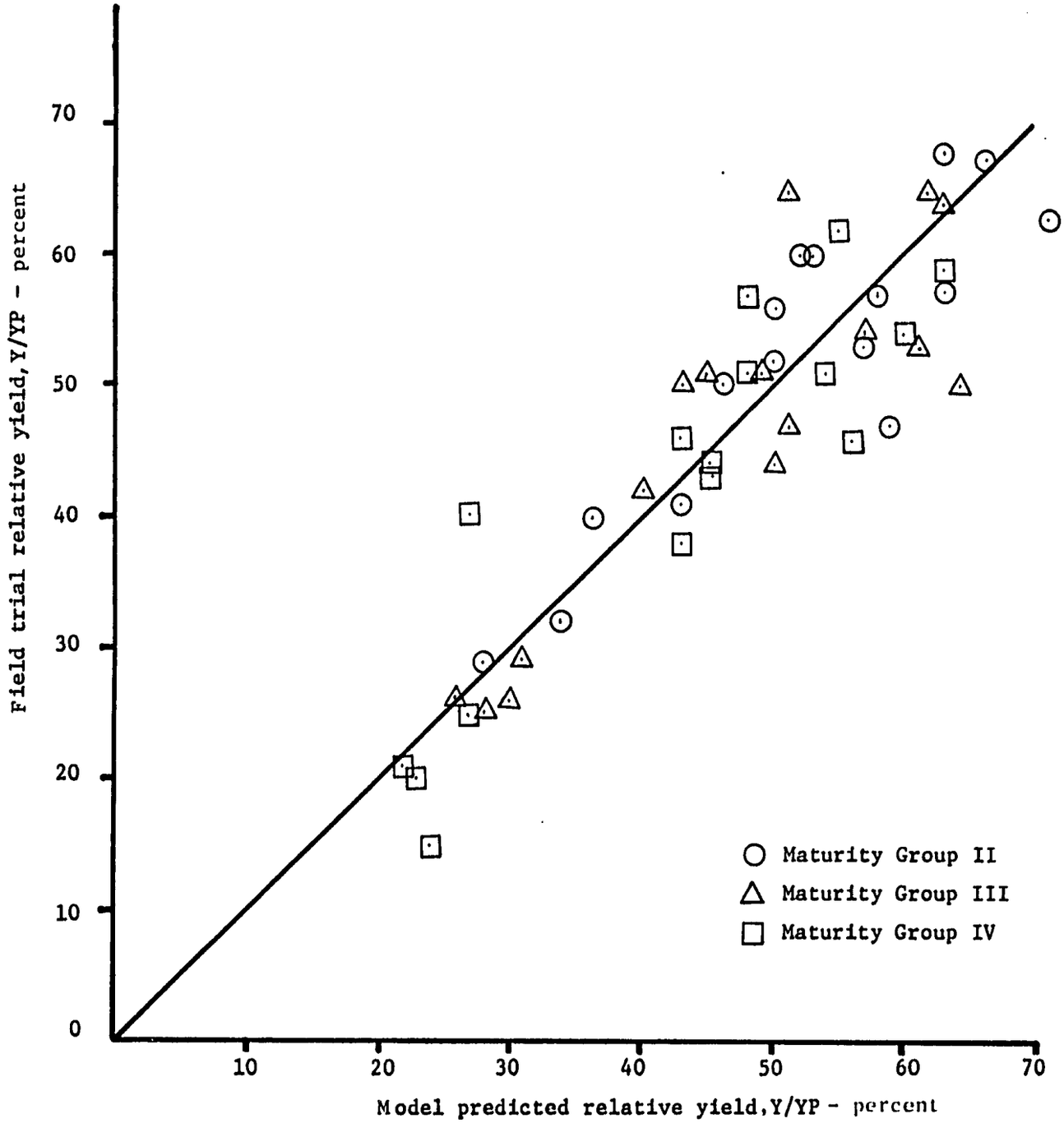

Figure 2. Results of model calibration with Missouri soybean field data, from three sites (Spickard, Columbia, and Mt. Vernon) during the 1971 and 1972 growing seasons.

dates the model over-predicted yield. The average errors were 4.2 percent, 4.9 percent, and 5.0 percent for Maturity Groups II, III, and IV respectively. Inspection of Figure 2 reveals that the model is least capable of matching the Maturity Group III data extremes.

In our opinion the closeness of fit between the model and field data is excellent, especially considering simplified assumptions used. We believe this is the most successful attempt to date of matching a crop-growth-yield model to such a large array of field data. Our model is based on practical physical realities of plant growth processes. Therefor, it is considerably more useful and powerful than a regression equation. The calibrated parameters which match a given set of field data contain, in a condensed form, the significant transferable information which can be extracted from that field data. This condensed and transferable information is much better adapted to subsequent use in management studies than the original data or the results of any "black box" type of data analysis. The computer programmed model provides a valuable technique for transferring the knowledge of crop production technology obtained at one research location to any other site. All that is required to estimate production at the new site is the appropriate weather, soils, and management data.

Application of the Computer Programmed Model

Applying the calibrated model as a management tool is demonstrated by using historical data from Mt. Vernon, Missouri for five years (1968-1972) and predicting what the effect of planting date would have had on soybean yield. The predicted results are plotted in Figures 3, 4, and 5 for Maturity Groups II, III, and IV respectively. These plots show

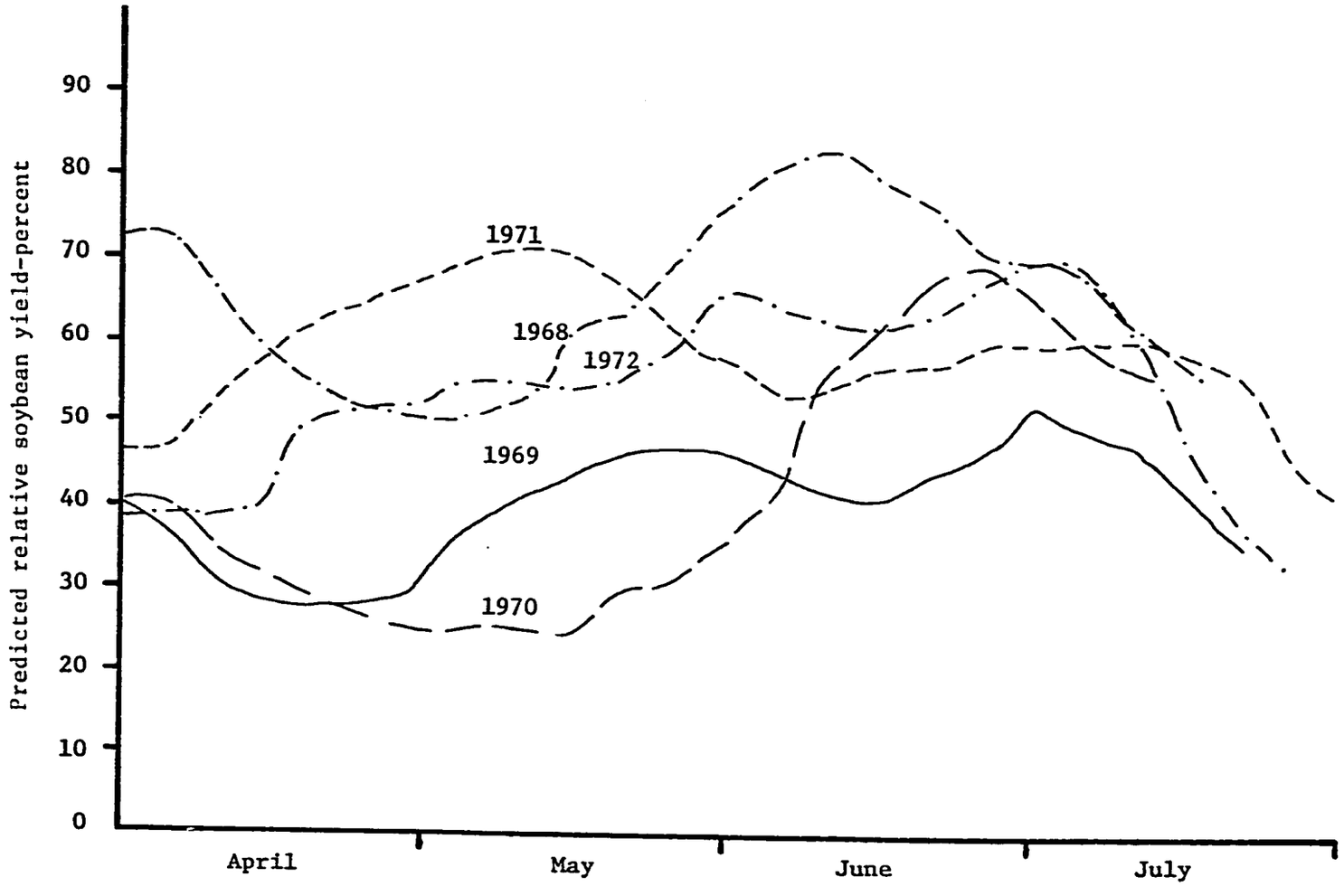

Figure 3. Model predicted relative soybean yield (maturity group II) versus planting date at Mt. Vernon, Missouri, 1968-1972.

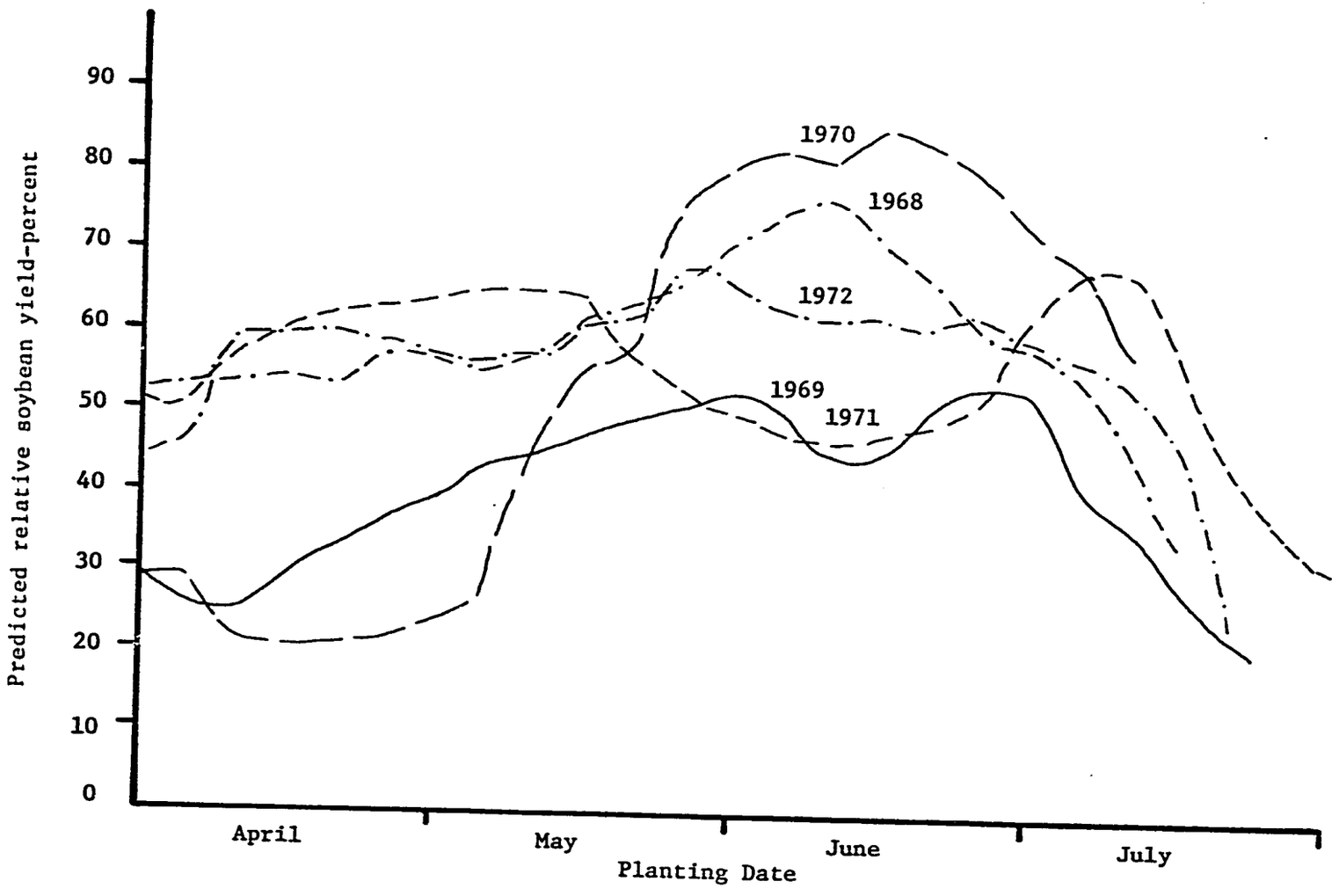

Figure 4. Model predicted relative soybean yield (maturity group III) versus planting date at Mt. Vernon, Missouri, 1968-1972.

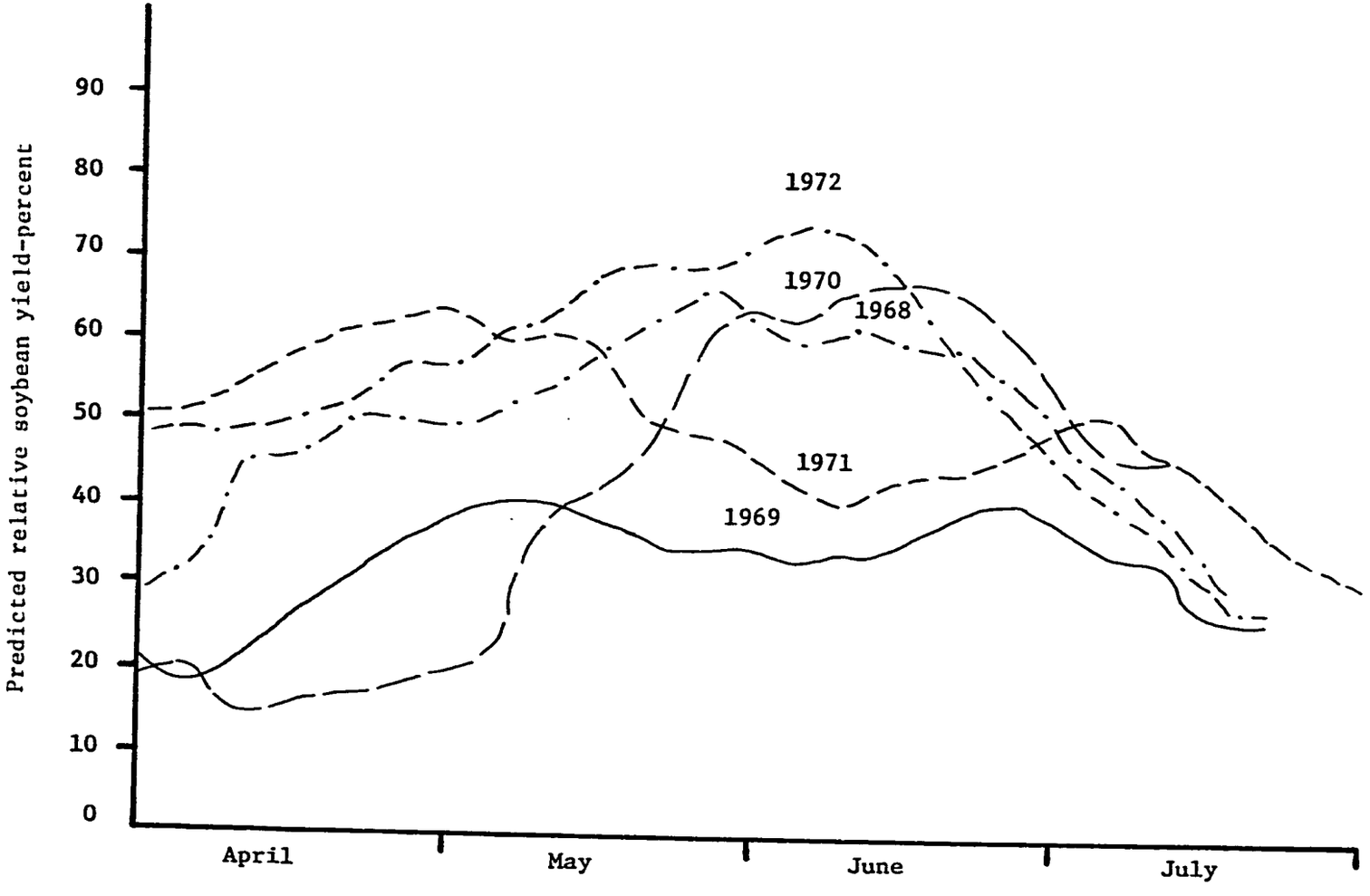

Figure 5. Model predicted relative soybean yield (maturity group IV) versus planting date at Mt. Vernon, Missouri, 1968-1972.

predicted relative soybean yield varies considerably for different years and planting dates. With some exceptions the better planting dates are from mid-May through the end of June. This trend is illustrated more clearly in Figure 6 which shows the five year average relative yields for each of the three Maturity Groups. Soybeans planted later than mid-July show a marked decrease in yields and may not mature before inclement fall weather. The longer season Maturity Group IV varieties tend to benefit most from earlier planting dates. These predicted trends are in accord with general experience in Missouri.

The present form of the program is also useful for scheduling irrigation to maximize soybean yield for any given planting date. Irrigation during growth periods 2 and 3 may contribute to lodging and thus actually decrease yields. Table 3 gives a summary of predicted Maturity Group II soybean yields for a series of one-inch supplemental irrigation

Table 3. Predicted influence of incremental one-inch applications of irrigation water on soybean yield at Mt. Vernon, Missouri, using 1969 weather data

Planting Date	Cumulative Irrigation Water Applied (inches)	Dates of one-inch Irrigation Applications (in order of selection)	Relative Yield (percent)
April 17	0	None	30
	1	July 31	41
	2	July 31	50
	3	July 31	58
	4	July 25	62
May 17	0	None	45
	1	Aug 15	52
	2	Aug 15	68
	3	July 25	76
June 16	0	None	42
	1	Aug 9	62
	2	Aug 24	76
	3	Aug 9	85
	4	Aug 9	91

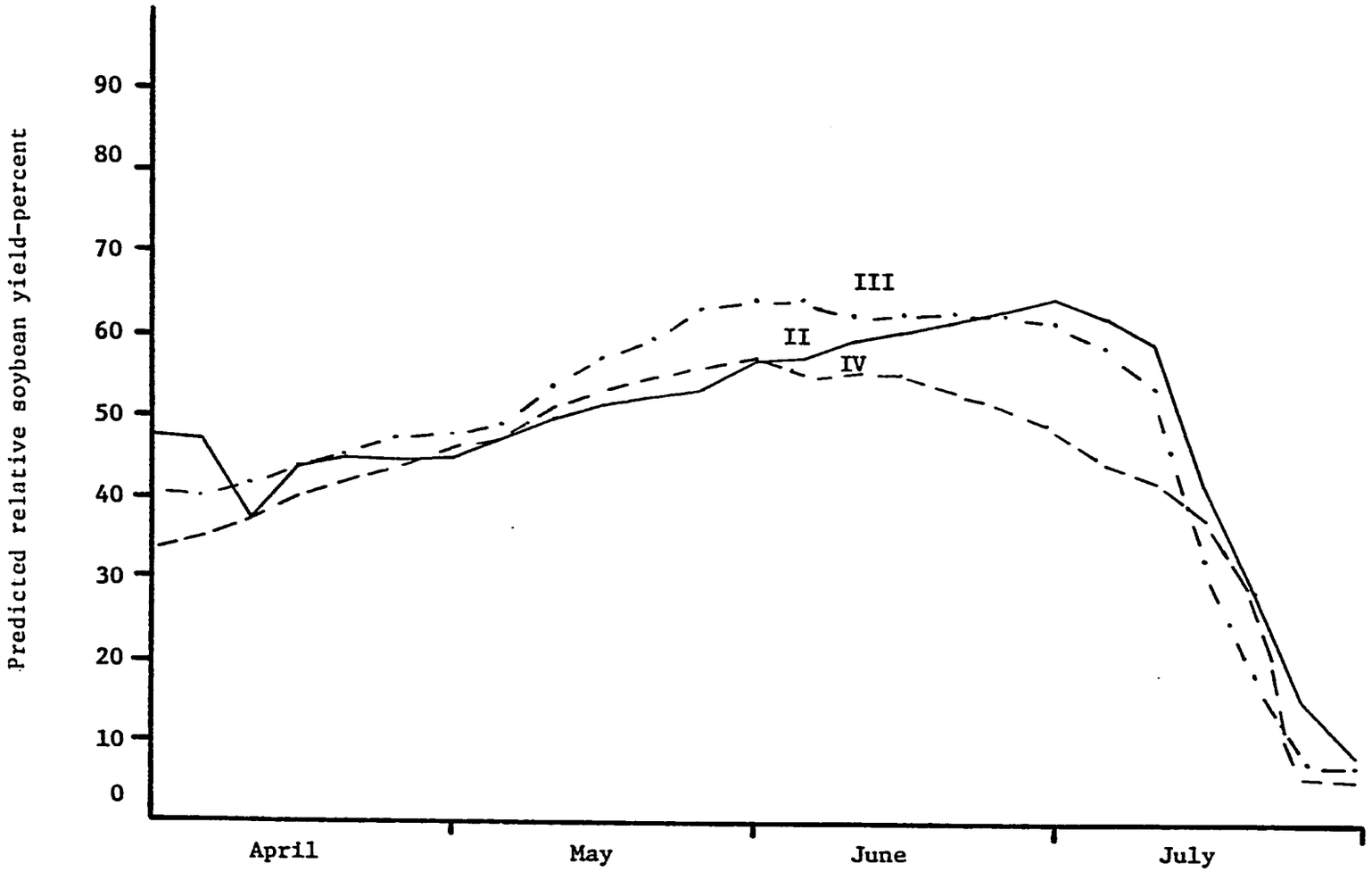

Figure 6. Five-year average model predicted yield versus planting date for maturity groups II, III, IV, at Mt. Vernon, Missouri.

applications. This is for three different planting dates at Mt. Vernon, Missouri using 1969 weather data. The strategy used in the program is to add irrigation water at the "best" time for each planting date until only marginal predicted yield increases were obtained from an additional water increments.

From Table 3 it is possible to estimate what the value of applying supplemental irrigation water would have been for different planting dates in 1969. For example: with the Maturity Group II potential soybean yield of 73 bushels per acre, the timely application of 4 inches of water to a crop planted on June 16, 1969 would have resulted in an additional yield of 73 (91-42)/100 = 36 bushels per acre. This high predicted yield increase resulted because 1969 had little rainfall during the critical (4th and 5th) soybean growth periods. At $4.90 per bushel the additional 36 bushels would be worth $176 per acre. Thus, the increased yield from only 4 inches of applied water in a single year such as 1969 may be sufficient to justify a supplemental irrigation system.

Conclusions

The simplified model which we have developed predicts soybean yields which are in close agreement with field research data. Our model only includes the effects of temperature and daylength on the development of the soybean plant. To estimated bean production we only used the effect of soil moisture on plant transpiration. The effects of severe moisture stress and solar radiation on phenologic timing are not included and additional research is needed before we can adequately define these and other factors.

The computer programmed model can be used to make long term analyses using historical weather records from various sites to develop planting date-potential yield probability tables. These tables will give "best" planting dates and supplement irrigation requirements to assure desired yield level. Thus, the program can be used to transfer results of field trials from a limited number of sites and years to any site where historical weather data and soils information is available.

This predictive technique can be perfected into a valuable tool for selecting soybean varieties with promising production possibilities at specific sites throughout the world. Such a technique, while not eliminating on-site field research, would provide a basis for designing field demonstration plots. The program can also be used for evaluating irrigation strategies by weekly updating with the new weather data.

BY developing and applying our crop yield model strategy wer hope to accomplish the following:

1. Greatly reduce the amount of field research needed to determine the interactions between preferred soil moisture conditions and planting dates at various localities.

2. Improve the transferability of field research results by better analysis and utilization of specific site environmental data (weather, soils, etc.).

3. Provide a basis for focusing field research efforts to obtain transferable information which should greatly reduce the quantity of tests required and improve both the efficiency and speed of crop-water-soil management information transfer.

A complete crop yield model would contain the collected results in an organized and retrievable form of many field experiments with each variety from various sites. The computer programmed model would be ready for application

to the problems of predicting expected crop yield for given varieties as influenced by weather, soils, water and fertility management and other environmental factors.

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