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CROP-CLIMATE MODELS: A REVIEW OF THE STATE OF THE ART

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Although this may seem a paradox, all exact science is dominated by the idea of approximation.

Bertrand Russell

INTRODUCTION

There are two main ways to determine the effects of climate on crops: detailed ecological studies and crop-climate models. Ecological studies involve assessment of the behavior of crops under different climatic norms and prevailing local conditions. Accordingly, the production function for corn, which may be defined as the mathematical function providing the interrelationships between resource inputs and crop yields, will vary from one geographical location to another, depending on: soil types, availability of fertilizer, pesticides and water control, climate and other management techniques. While many of these resource inputs can be controlled, others like climatic variables are beyond man's control. Furthermore, the timing of the resource inputs is an important factor, which significantly affects crop yield. This is because all crops have critical stages, irrespective of the location where they are grown. For example, ecological and physiological studies have identified three stages of growth for sorghum: preboot, bootheading and grainfilling. In terms of yield, lack of soil moisture during the bootheading stage is the most critical stage, followed by grainfilling and preboot. In other words, in terms of timing, water availability during the bootheading stage affects crop yield the most, and thus is an important factor to consider in developing policies and operational practices for yield optimization.

Crop-climate models attempt to relate climatic variables to production data through statistical techniques. Different forms of multiple regression techniques have mainly been utilized so far. This type of model was initially developed to determine at which stages of growth crops were more vulnerable to different forms of climatic inputs (Johnson 1976). A review of many of this type of model can be found in Baier (1973a, 1973b, 1979) and Hillel (1977). In recent years, however, crop-climate models have been developed to analyze the broader issue of estimation of the effects of climatic fluctuations on agricultural production. The present paper reviews some of the more important models developed for this purpose.

CROP-CLIMATE MODELS

Several crop-climate models have been developed in recent years for different types of crops and also for different geographical locations. Among the more notable ones are those developed by Thompson of Iowa State University (1973, 1970, 1969a, 1969b), McQuigg *et al.* for the National Oceanic and Atmospheric Administration (NOAA 1973), Williams of the Department of Agriculture of Canada (1975), and Haigh for the Charles F. Kettering Foundation (1977). The basic approach to all these models has been the "black box" technique, in contrast to models based on the understanding of the different interacting physical processes. The crop-climate models developed thus far are mostly of multiple regression type, and use empirical relationships derived from historical crop yield and climatic data to predict potential future yields from different climatic scenarios.

Thompson Models

The models developed by Thompson are for corn (1969a), wheat (1969b), and soybeans (1970) for certain areas of the United States. Multiple curvilinear analysis was basically used to estimate the influence of climate on the crops considered. For example, for the study on soybeans, Thompson (1970) considered the data available from five states, Illinois, Indiana, Iowa, Missouri, and Ohio, and took account of the following six climatic variables: total precipitation from September to June; July precipitation; August precipitation; June temperature; July temperature; and August temperature.

State-wide averages of monthly mean temperature and monthly mean precipitation were used as climatic variables. It was assumed that climatic variables were related to yield in a curvilinear pattern resembling a parabola, which means that there is an optimum value of the climatic variable in the sense that, at that value, the crop yield is maximized. A linear time trend was included in the regression analysis, and it was further assumed that the yield of soybeans had been increasing at a constant rate, and that the year-to-year fluctuations, i.e., departure from the normal, were due to climate. The dependent or predicted variable was the crop yield, and the independent or predictor variables were the climatic parameters, and technological trend variables. The period analyzed was from 1930 to 1968. Thompson (1970) concluded that, "The record yields of 1961 and 1968 were associated with near normal temperature in June, below normal temperature in July, near normal temperature in August, near normal preseason precipitation, and above normal rainfall in the July to August period."

The models for corn (Thompson 1969a) and wheat (Thompson 1969b) were very similar to the one developed for soybeans. For corn, Thompson concluded that, "The highest yields have been associated with near normal summer temperatures and near normal precipitation from September through June. Exceptionally, high yields have been associated with higher than normal July rainfall, with near normal summer temperatures." Similarly, for wheat, it was found that warmer than normal temperatures in early stages of growth and cooler than normal temperatures in the later stages of growth are desirable, but no single climatic variable explained much of the yield variation. However, climatic variables and technology trends accounted for 80-92% of the wheat yield variability in the six states considered.

Haigh Model

More sophisticated models of the characteristics of corn, soybean and wheat production in selected parts of the United States were later developed by Haigh (1977) for the Charles F. Kettering Foundation. The study considered both the total output and the year-to-year variability of that output for corn and soybeans in Illinois and Iowa, winter wheat for Kansas, and spring wheat for North Dakota. The study attempted to answer two basic questions:

(1) What changes, if any, have occurred in the year-to-year variability of crop weather and crop yields and their relationship to each other?

(2) Is the hypothesis that the trend in yields has leveled off in recent years correct?

Haigh attempted to answer these questions by developing structural models to separate the total year-to-year variability of crop yields into weather and management components. Changes in the coefficient of variation of yield (CV_y) were compared with changes in the coefficient of variations of weather (CV_w) over time to analyze yield sensitivity to weather. If the ratio of CV_y/CV_w increased over the period under consideration, it was assumed that there was evidence of an increase in the sensitivity of yields to weather, and vice versa. Four measures of weather were considered: precipitation and temperature; precipitation minus potential evaportranspiration; soil moisture; and growing degree days.

Monthly values of these four parameters were considered for those months regarded most important to crop yields.

Results of the study indicated that:

(1) There is no evidence that technology has reduced the sensitivity of grain yields to weather.

(2) Statistical evidence exists of a leveling off in the rate of increase of corn, soybean and hard winter and spring wheat yields in recent years.

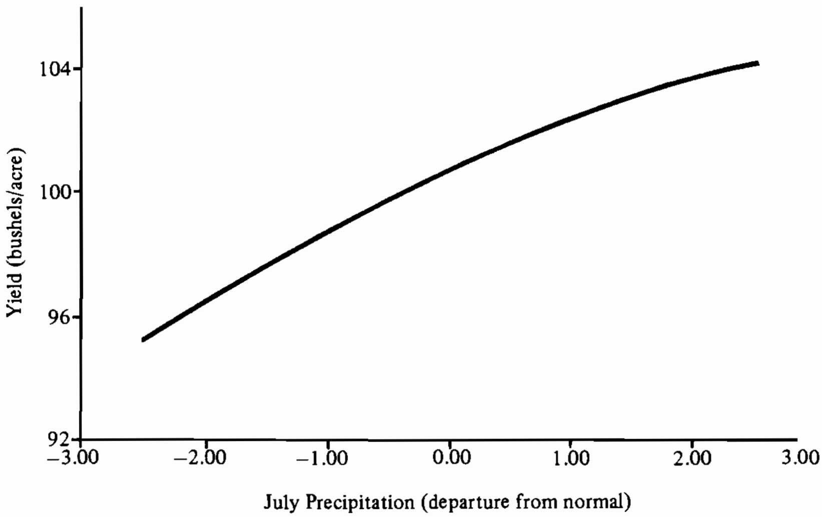
Haigh, however, properly adds a word of caution to such interpretations. For example, with regard to the second conclusion, there is no doubt that year-to-year crop carry-over levels affect government acreage set-aside programs of the United States, and thus the total area of land planted. Hence, when the reserves are high, less area is under cultivation, which means that the farmers take the less productive marginal land out of production. When carry-over stocks are depleted and acreage restrictions are relaxed, as was the case in the early 1970s, these marginal lands are brought back into production. Under these circumstances, it is quite possible that yields in marginal lands are more susceptible to weather, and such use of marginal land in recent years could possibly explain the leveling off in yields that has been observed during such years.

Haigh used the models to estimate the percentages of yield variations that could be accounted for by management, weather, or their interactions. For example, for Illinois corn, it was estimated that management accounted for at least 62.1% and at most 82.2% of the variations, whereas weather accounted for at least 11.6% and at most 31.7%. The yield-weather responses, in terms of July precipitation and August temperature, for the Illinois corn are shown in Figure 1. In general, for all the crops considered, yield variations explained by management were roughly two to three times the percentage explained by weather. The results are summarized in Table 1. Haigh points out that a limitation of the analysis was a residual percentage showing, at least statistically, an interaction between management and weather. This interaction term ranged from 10 to 20% of the total yield variation.

Williams Model

Williams (1975) developed crop-climate models to evaluate the potential impacts of adverse climatic trends on the Canadian grain production. He also used a multiple regression approach, which incorporated factors like technological trends, soils, topography, and 12 climatic variables.

His model indicates that if the climate became wetter, substantial reduction in yields may occur, if the seasonal precipitation increased by 25% or more, as shown in Figure 2.



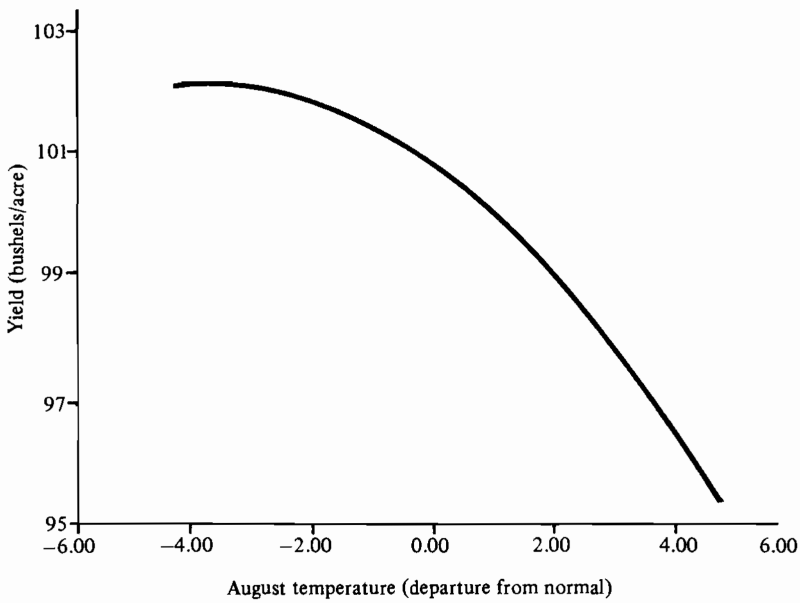


Figure 1 Yield weather response for Illinois corn.

Table 1. Separation of yield variation into management and weather components (Haigh 1977).

Crops	Variation in yield percentage			
	Management		Weather	
	Maximum	Minimum	Maximum	Minimum
Illinois corn	82.2	62.1	31.7	11.6
Iowa corn	78.0	62.4	25.3	9.17
Soybeans	78.2	68.0	15.6	5.4
Kansas winter wheat	77.4	59.7	26.2	8.5
North Dakota spring wheat	67.9	51.2	21.9	5.2

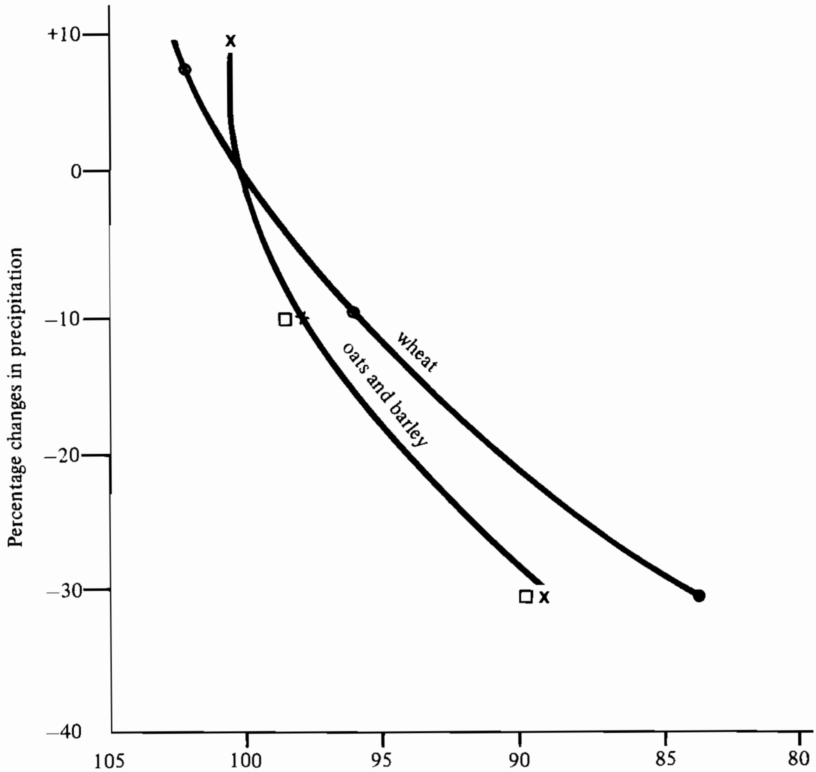


Figure 2 Change in crop yield (%) due to changes in mean precipitation.

Higher precipitation could have adverse effects on spring planting, rates of growth and harvesting. In more humid areas of Canada, where oats and barley plantations tend to dominate, the effects could be more serious. Furthermore, availability of more moisture in mid-summer in the wheat-producing areas could improve yields, thus offsetting early and late season disadvantages.

Williams (1975) also attempted to estimate the probability of crops reaching maturity in an area of some 80 square miles between the Peace and Wapiti Rivers in northwestern Alberta. He found that under "normal" circumstances barley could be grown at 94% of the locations considered. If there is a cooling trend, and the temperature drops by 1 °C (average throughout the growing season), it could be grown at 73%

of the locations. However, with a drop of temperature of 3 °C, it could be grown only at 2% of the 84 points considered. Similarly, under normal circumstances, wheat could be cultivated at half the locations considered. With a 1 °C cooling, it would mature at 15% of the locations, but with a drop of temperature of 3 °C, it would not mature at all. These results are shown graphically in Figure 3. The figure also shows that a 1 °C cooling would reduce the growing season from 9 to 15 days at 5 locations where wheat would mature, and that a 3 °C cooling would reduce the growing season by 39 to 42 days at the two locations where barley would mature. In other words, a cooling trend could significantly alter the present land-use pattern in the Canadian West by making wheat an uneconomic crop. It should, however, be noted that, in all probability, the conditions for wheat cultivation in the southern parts would improve under similar climatic conditions.

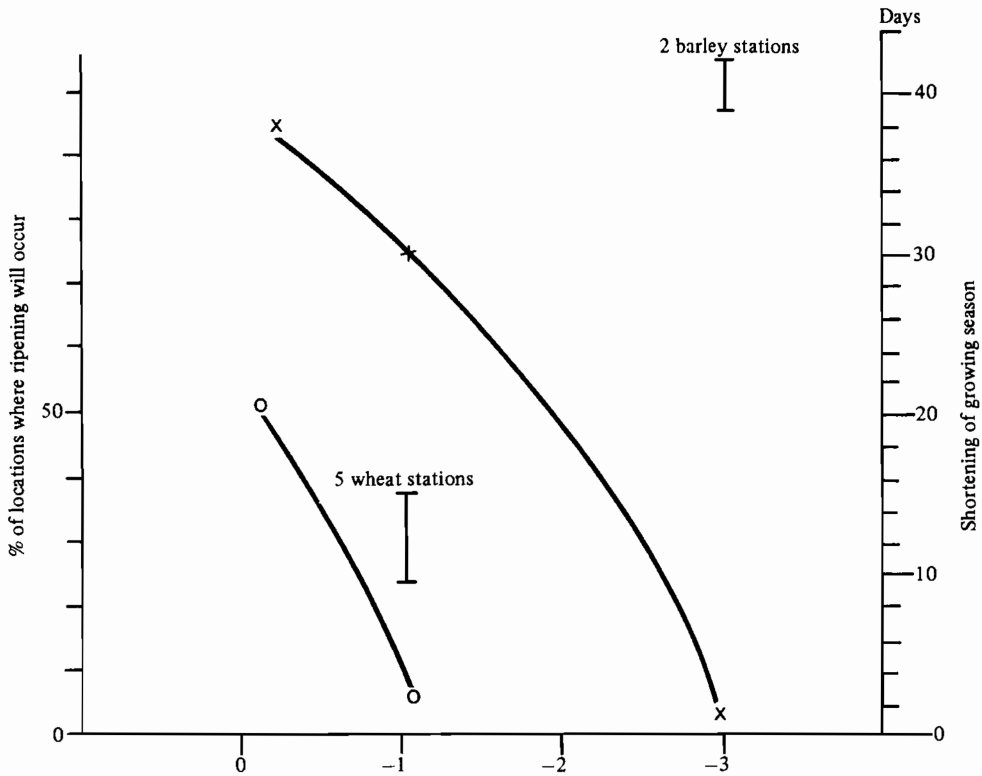


Figure 3 Mean departure from normal crop season temperature (°C):
(a) Percentage of locations at which wheat (o) and barley (x) will ripen in northwest Alberta;
(b) the shortening of the freeze-free season with cooler seasonal temperature.

MAJOR PROBLEMS OF MODELING

While there has been a great deal of interest in crop-climate models in recent years (in addition to the ones mentioned earlier, see also DeWitt 1975, NOAA 1973, Menon and Bowonder 1978, Michaels and Scherer 1977, Thompson 1975, Walther 1977a, 1977b), it is important to note some of the major disadvantages of these types of models. These problems will now be briefly discussed.

First, as mentioned earlier, statistical analyses of multiple regression types basically lead to the development of black-box models, without full understanding of the interrelationships of the different physical processes involved. In other words, it does not necessarily follow that the models developed would have realistic structures (Katz 1977). Thus, spurious correlations and unrealistic structures could present major problems in terms of model validation.

Second, the coefficients of these types of models are statistical estimates, and are not universal constants. These may be subject to several sources of error, most important of which are correlations between climatic predictor variables, and the nonlinear relationships between crop yields and different climatic parameters, both of which will be discussed later.

Third, the square of the multiple correlation coefficient R^2 is often used as an indicator of the quality of the models, and this statistic is assumed to estimate the percentage of the total variability explained by the model. However, R^2 is only an indicator of the statistical significance of the model, and since it is a black box statistic, it does not give any information on the structural accuracy of the model.

Fourth, the relations between crop yields and different climatic variables are seldom linear. Thompson accounts for the nonlinearity by assuming a parabolic relationship. A linear term, departure from normal, and a quadratic term, square of departure from normal, are used as predictor variables for each climatic variable. This necessitates estimation of additional coefficients, and the problem becomes more difficult if the period of data available is short (a real problem for most developing countries), and thus may not constitute a representative sample. This means that the data used may not contain enough extreme climatic fluctuations, and thus it becomes difficult to ascertain if the appropriate functional relations have been used (Katz 1977). For example, there is no quadratic term for May temperature in the wheat model developed by Thompson (1969b), since multiple regression did not generate a realistic coefficient for that term. Furthermore, if the nonlinear relation is represented by using both linear and quadratic terms as independent variables, correlations often arise between linear and quadratic terms, as shown in Table 2 for the Kansas wheat model of Thompson (1969b).

Table 2. Correlations between linear and quadratic terms for Kansas State wheat model (Katz 1977).

Variable		Correlation
Total precipitation,	August-March	0.21
	April	0.68
	May	0.56
	June	0.41
	July	0.63
Average temperature,	April	0.16
	May	-0.03
	June	0.25
	July	0.21

Fifth, in the classical linear regression analysis, a fundamental assumption is that the independent variables are not closely related to each other. This, however, is not correct for meterological variables. For example, mean monthly values of temperature and precipitation, for a given period, often show high negative correlation, which in some cases could be more than 0.40. If an analysis of the climatic data used by Thompson (1969b) for the Kansas wheat model were to be made, it would show increasing correlation with the advance of the growing season, as shown in Table 3.

Table 3. Correlations between monthly total precipitation and monthly mean temperature for Kansas State wheat model 1920-1968 (Katz 1977).

Month	Correlation
April	-0.14
May	-0.28
June	-0.69
July	-0.73

In addition, high correlations often exist between the values of average temperature and precipitation for months adjacent to each other. These, in certain instances, could exceed 0.30. These two correlations, in combination, could introduce severe multicollinearity in the analysis, so much so that they could often be higher than the correlation between meteorological variables and crop yields. Such a situation will naturally introduce major errors in the analysis to the extent that even the signs of the coefficients could be erroneous (Snee 1973).

Last but not least is the difficulty of separating increases in yields due to different components, i.e., management, technology, and climate. It is generally agreed that the most important factors in increasing crop yields during the last 40 years or so have been technology, increases in the use of pesticides and fertilizers, improved genetic quality of seeds, investment in machinery and better water control. The problem, so far as crop-climate models are concerned, is to separate to what extent yields have increased due to changes in technology, management, and climate. At the present state of the art, it is not possible to separate such components of yield completely and realistically (Haigh 1977). Furthermore, technology is neither given nor can it be expected to remain constant over time. Neither can it be assumed that the actual production techniques used in the field are necessarily equivalent to the present state of the art. From past and present experiences, it can be assumed that even in cases where investment required is minimal, certain farmers will adopt the technological changes relatively quickly, while others will take a much longer time. Hence, any technological change in such analyses will appear empirically over a period of time. The technological trend, of course, can be represented in such models by segmented linear trends, but the actual process of location of the points of change is not an easy task. In addition, the average farmer may not have much influence on the price of his crops or climate, but he often does adjust resource use compared with relative prices or anticipated weather. In other words, farmers are changing the pattern of resource use in agricultural production, due both to technological changes and changes in the relative prices of the crops. Separation of these components, especially within a modeling context, is a very difficult task. An example would be useful to illustrate this point. If crop prices remain as they are at present, but energy costs increase significantly in the future, it is likely that current energy-intensive farming practices will change because of economic reasons. It is quite possible that farmers may decide to use less fertilizer and/or pesticide, which will obviously have a major impact on the recent observed patterns of yield increase.

Finally, some comments on the Haigh model are necessary, since it is the only model that is based on a ridge regression technique, designed for multicollinear data for stabilizing estimates of coefficients. The standard errors obtained in this case are somewhat larger, when compared with results from many of the other models. For example, for North Dakota spring wheat, it was just over 14% of the current yield levels, rather a high figure. This, as Haigh himself points out, is to be expected because ridge regression leads to a larger standard error if $k > 0$. On the other hand, if $k = 0$, it should be realized that the ridge regression coincides with the ordinary least squares solution.

Institute of Ecology Model

The scenarios for this study were selected to represent the extremes in weather-influenced yields (Institute of Ecology 1976). The example chosen included when agricultural production was:

(1) severely reduced by stress, 1933-1936;

(2) moderately reduced by stress, 1953-1955;

(3) very high because of favorable weather, 1961-1963;

(4) up and down because of unusual variability in weather from one year to the next, 1971-1975.

The Thompson models for corn, wheat, and soybeans were used to identify the weather-years for these scenarios. The study considered ecosystems producing corn, wheat, sorghum, and soybeans in the United States and wheat in Canada.

Of the following three major variables in food production, the first two were kept constant to demonstrate the influence of the third:

(1) area cultivated, planted and harvested;

(2) use of agricultural technology, including varietal selection, chemical application, and mechanization;

(3) weather during the planting, growing, and harvesting season.

In other words, the scenarios used were developed on the basis that the total crop area cultivated remained constant at the 1975 level, and so did the 1973 technology for agricultural production.

On the basis of such analyses, the scenario yields for US corn were estimated; these are shown in Figure 4. It clearly indicates the gap between climatically favorable and adverse years, and also emphasizes the year-to-year variability in yields. The annual corn production in the United States for the scenario years, on the basis of yield figures, is shown in Figure 5. It indicates that except for one scenario year, 1936, the domestic annual consumption level of 1975-1976 in the United States can be easily met. Similar

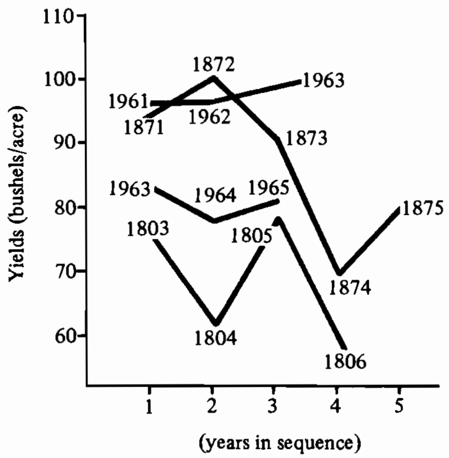


Figure 4 Scenario yields for US corn.

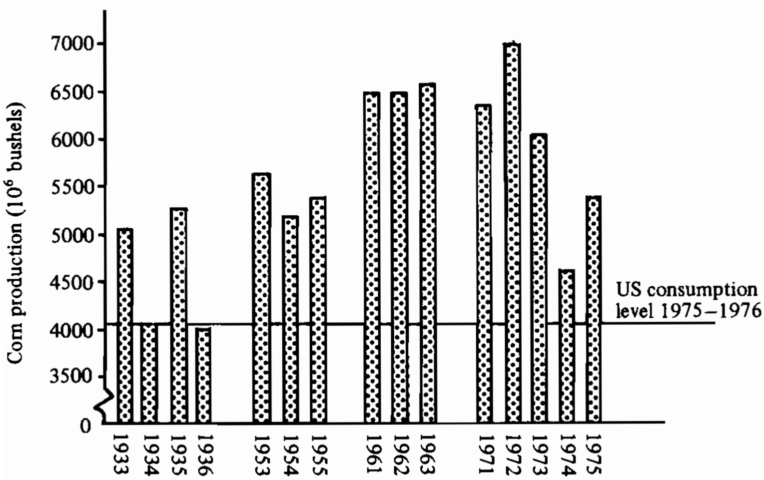


Figure 5 Scenario production of US corn.

production figures for other crops in the United States for scenario years were obtained for wheat, sorghum, and soybeans. An interesting conclusion was that sorghum production is most influenced by climatic fluctuations, followed by corn and wheat. Soybean production seems to be the least affected as shown in Figure 6. If wheat production scenarios for the US and Canada were compared, it can be concluded that, "Although there is some tendency for good conditions in one part of the region (of Canada, where wheat production is concentrated in an area of 24 million acres) to compensate for poor conditions in another, this is much less effective in reducing the variability of annual yields than is the case in the much more extensive and climatically heterogeneous US wheat region of 169 million acreas." However, if only the US spring wheat crop is considered, the situations in Canada and the US are not very dissimilar.

The study also considered annual fluctuations in crop yields in both absolute and relative terms. Absolute deviations were expressed in yields per unit area or in total weight or volume of the departure from the expected norm, whereas relative yields were defined as a percentage of the mean or norm. The study concluded that so far as major North American grain crops are concerned, the absolute variability has increased, but the relative variability has decreased during the period considered. These variabilities were indicated by the standard deviation and coefficient of variability for each decadal period (Institute of Ecology 1976). The year-to-year relative variability seems to have been reduced between 30 to 40% during the period 1935 to 1975. It was, however, not possible to separate the causes of such a development: whether it was the good climate of recent years or technological developments that provided a buffer. The two are of course interrelated, and with the data available, the two factors could not be effectively separated.

The scenario model building by the Institute of Ecology is an interesting development since it did not assume any climatic change, rather the emphasis was on what would happen to the production of certain crops if certain climatic variations, observed in three to five year periods since 1933, were to reoccur. It did not attempt to prepare the best or worst case scenarios.

CONCLUSION

The crop-climate models discussed herein are still in the early phases of development. They already provide some interesting insights on the effects of climatic variables on crop production. However, further developments, both in terms of modeling sophistication and our understanding of the interrelationships between the different processes involved, are essential before their potential can be fully realized, and the models can actually be used in decision-making and planning processes.

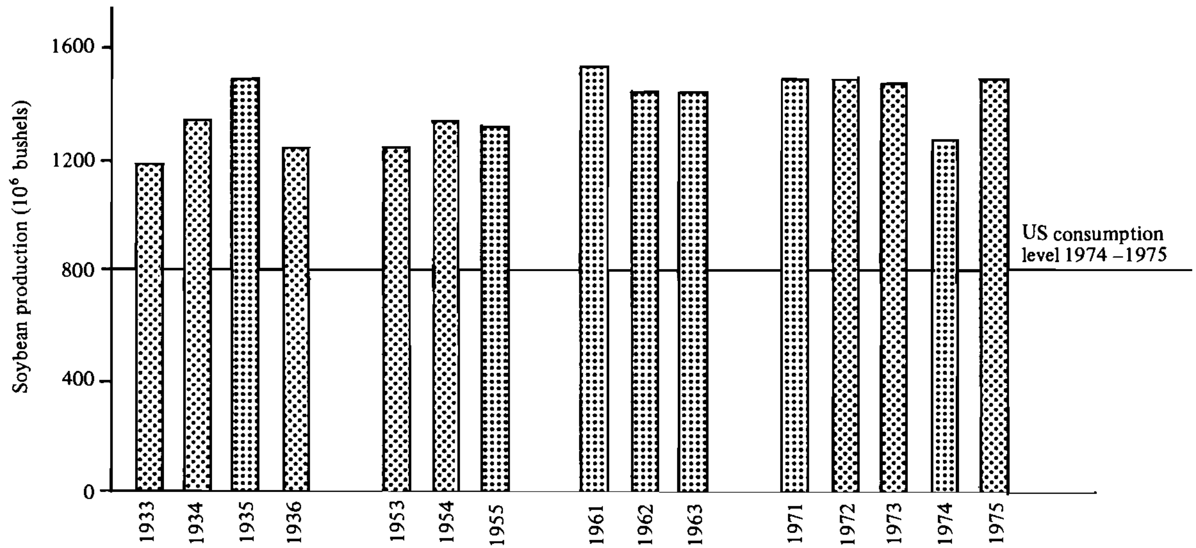


Figure 6 Scenario production for soybeans.

One of the main difficulties of estimating the net effects of climatic variables on crop yields is the desirability of having precise information on the actual timing of the occurrence of different meteorological conditions at specific locations. Generalized climatological statements, while interesting, are at present not very useful for planning and operational purposes. This can be illustrated by a study that was carried out by the South Dakota University (1973) on the effect of an additional inch of precipitation on the yields of wheat during the growing season due to weather modification. Analyses of data from experiment stations around the state indicated that yields of wheat in experimental plots, where all known technology is used, would increase by 5.3 bushels per acre. Similar data from commercial farms indicated that the additional water availability would increase yields by only 1.8 bushels per acre.

Similar analyses for corn indicated that, if the precipitation was distributed throughout the growing season, the commercial yield would increase by only 1.0 bushel per acre. However, if this additional source of water could be somehow concentrated between the one month period of 15th July and 15th August, the predicted increase was 12 bushels per acre, a 1200% increase over the previous condition. Similarly, if the additional water availability was extended over a two-month period, between 15th June and 15th August, the predicted increase was 12 bushels per acre. These facts indicate that generalized statements of climatic fluctuations are not very useful for agricultural production purposes. It could also be concluded that relatively little is known about the net effects of changing climates on crop production and water resource planning. From a modeling viewpoint, it seems that the next development should be consideration of much shorter time periods than a season. This should provide better information and understanding than has hitherto been possible.

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