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A REVIEW AND EVALUATION OF WEATHER-CROP YIELD MODELS

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Introduction

Concern has been voiced about the increased atmospheric loading of Carbon Dioxide and the longer term climatic change which is expected from the so-called "Greenhouse Effect". One of the anticipated consequences of such future climatic change is that the production environment for major crops in the U.S. grain belt could be adversely impacted with significant negative effects on both the crop production sector and the supply of farm (food) products. This potential impact can only be adequately evaluated, however, if one can (1) project a reasonably reliable scenario for expected climatic change, (2) describe the relationship(s) which exist between crop yields and those climatic variables which are expected to change in the future and (3) develop a plausible scenario for the capabilities of future technologies to modify crop production adversities associated with a more hostile climatic environment. Each of these three tasks is a complex undertaking which can probably only be achieved in degree.

The purpose of this paper is the relatively limited one of reviewing the literature for models which develop specific relationships between climatic variables and crop yields. As a practical matter, however, most past modeling of crop yields has utilized only short-term (intraseasonal) "weather" and not

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long-term "climatic" related variables. In order to fully explain changes in crop yields, these models have also tried to account for the impacts of changing production technologies. As a consequence, our review is mainly of these past weather-technology-crop yield models.

Following a review of recent weather - crop yield modeling efforts we evaluate these models and suggest some conceptual model and data base improvements if we are to adequately project the impacts on crop production of expected future climatic change. Our review and evaluation centers on weather-crop yield models applicable to the central grain belt of the U.S., mainly the Corn Belt and Great Plains production regions.

Longer-Term Climatic Change

The climate varies from year to year and from region to region. Small regional changes, when averaged world-wide, become insignificant. An annual mean fluctuation of 1-2°C on a global basis is a major change for agriculture. (Climate and Food)

An upward trend of approximately 3°F (1.67° C) in mean temperatures occurred in the middle latitudes from the end of the 17th century until 1940. After 1940, average temperatures declined about 1°F (.56° C). The Great Plains of the U.S. were warmer and drier from 1830 to 1930 than now, but fluctuations from year to year were greater than the century's change. At one time, the Rocky Mountains were 20-30% wetter in the summer, and bison herds might have diminished 50-75% even without overhunting as the weather became drier late in the 19th century. (Bryson, 1974)

Some researchers have observed cycles of dry weather. The grain producing areas in both hemispheres experienced dry summers in the 1930's and 1950's. Black and Thompson (1978) tested for nonrandom corn, soybean and wheat yields based on 22-year drought cycles. They concluded that drought cycles do exist, although not every year in a drought cycle exhibits below average yields.

McQuigg maintains that the period 1960-1973 was exceptionally favorable for crop production, and such weather cannot be expected to continue. Drought, defined as an insufficiency of moisture leading to yields 10% below normal, is fairly common. (McQuigg, et al, 1973)

Different areas of the U.S. experience various degrees of dry weather and for different periods of time. The Corn Belt experienced dry weather in the 1930's and 1950's, and precipitation on the eastern seaboard has decreased 15% in the last 100 years. (Thompson, 1975)

It is difficult to assess the impact of human activity on climatic change. Some say the recent 40-year cooling trend may have been caused by man, or, a natural cooling may have been partly offset by a carbon dioxide induced warming trend. We already know that cities alter their internal climate. They are warmer, less windy, less humid, and drier. (Chagnon, 1975)

Man's activity could affect climatic change in a number of ways of which three are as follows: by the accumulation of carbon dioxide in the atmosphere; by smoke particles and dust screening out the sun's energy; and by lead and other particles providing nuclei for precipitation, thus redistributing natural rainfall patterns, with the increased precipitation also resulting in decreased temperatures. In irrigated areas of western states, it is estimated that 10% of the precipitation is that evaporated from irrigated fields. Removal of vegetation decreases humidity and exposes the soil. (Thompson, 1975)

The Greenhouse Effect and Agriculture

Increased atmospheric loadings of carbon dioxide (CO_2) can be expected to affect agricultural production in two ways: (1) the direct effect of CO_2 via enhancement of photosynthesis in plants and (2) the indirect effect of CO_2 via climatic change induced by the "greenhouse" effect. The latter results from reduced reradiation of long wave energy by the earth's surface because of its absorption by CO_2 molecules. The latter effect can be expected to make present production areas into more desirable or more hostile environments. Both effects have implications for agriculture. If adequately severe, those impacts stemming from the greenhouse effect could result in changes in areas of production, the species and varieties produced, production technologies employed, and associated problems.

CO_2 has a direct effect on growing plants. Using a controlled environment study, Rosenberg found that water use efficiency is enhanced by increasing levels of CO_2, within a certain range. Plants can be classified on the basis of their photosynthetic mechanisms; C_3 plants include small grains and legumes, and the C_4 classification contains corn and sorghum. Increasing CO_2 augments photosynthesis, but the effect is relatively more significant in C_3 plants. Photosynthetic activity is increased in C_3 plants; C_4 plants realize a decrease in transpiration. This results in increased water use efficiency in both C_3 and C_4 plants, but for different reasons (Rosenberg, 1981).

Increased levels of CO_2 are beneficial only if plant nutrients are available in sufficient quantities. Therefore, in crop production areas where nutrients are limiting, the benefits of increased CO_2 would be less than under optimal conditions. Also, increased temperatures, an expected indirect effect of increased CO_2, decrease photosynthetic activity if optimum leaf temperatures are exceeded. Photosynthesis is most rapid between 20° and 26° C. (Jolliffe and Tregunna, 1968) Thus detrimental effects of higher temperatures could outweigh the benefits of increased atmospheric CO2. (MacDonald, 1982)

Most scientists agree that increased levels of CO_2 would raise surface temperatures, and likely redistribute rainfall patterns as they are presently known. Exact estimates are not available, as "present models are not sufficiently realistic to provide reliable predictions in the detail desired for assessment of most impacts," but "they can still suggest scales and ranges of temporal and spatial variations that can be incorporated into scenarios of possible climatic change". (National Academy of Sciences, 1983, p. 275) The consensus expectation is a 2 to 3°C increase for a doubling of CO_2. The National Academy of Sciences supports this conclusion, and the generalization that summer soil moisture will decrease in the middle and high latitudes of the northern hemisphere. (1983). Some argue that a smaller increase in temperature is a more likely magnitude. (Idso, 1982) Yield response to higher temperatures depends on the crop, the geographical location, and available soil moisture.

The National Defense University (1980) conducted a study to estimate the effects of global climate change on crop yields between 1976 and 2000. Climatologists were surveyed to get probabilities of future climate scenarios. The model was a "simple, discrete climate response model of apparently broad applicability". (p. 1) They found that a "large warming"[1/] would have a positive effect on Canadian Spring wheat and Soviet winter wheat, a neutral effect on Soviet spring wheat, and a negative effect on U.S. spring wheat. U.S. corn yields would decrease and become more variable.

1/ A large warming is defined as:

+.8°C subtropical latitudes
+1.0°C lower middle latitudes
+1.4°C higher middle latitudes
+3.0°C polar latitudes.

Overall, the report concluded that climate change would have the greatest impact on crop yields in the northern higher middle latitudes, where global temperature changes are amplified. "Small" yield changes are in the majority.[2/] Canadian and Soviet wheat crops would have "large" or "moderate" gains with a large warming (extreme scenario) and an equal loss with a large cooling. All yield changes in U.S. crops would be "small".

Bach (1978), on the other hand, estimated that some areas of the U.S.S.R. would have wheat yields reduced as much as 20% for a 1°C increase in annual mean temperature and a 10% decrease in annual precipitation. In the U.S. grain belt, soybeans, like corn, would benefit from increased, not decreased, precipitation.

Overall, it is difficult to assess the effect of future temperature increases on crop yields, because other factors will change too. A global warming would not be uniform, even for a given latitude. Distance from the ocean and mountains will affect the weather. (Cooper, 1982) Future climates may differ in windiness, cloudiness and frequency of severe weather, all of which influence moisture availability. (Rosenberg, 1982)

Wheat yield response depends heavily on locality. In drier areas, such as Kansas, Oklahoma, South Dakota and North Dakota, yields would decrease with a reduction in rainfall. But in Illinois and Indiana, precipitation is already in excess of optimal levels for wheat production.

2/ Yield change magnitudes are defined for the change in expected annual yield compared with the base period (which varies by crop according to the length of available climate records), assuming no change from the level of technology in 1976. They are:

small	0-3% change in yield
moderate	3-6%
large	6-9%

Increased average temperatures would, in general, also be expected to lead to higher maximum temperatures and to a longer growing season. It has been estimated that a 3°C increase in July temperatures would move the 22°C July isotherm (the top of the Corn Belt) from southern to northern Minnesota and Wisconsin. (Benci, et. al., 1975) Corn production would be expected to increase at the expense of crops presently north of the Corn Belt. In the process some relocation costs would also be incurred.

Ramirez and Sakamoto (1975) estimated that wheat could be planted ten days earlier than presently planted if the mean temperature were to increase 2°C. Bach (1975) also found that a 1°C increase would lengthen the entire growing season by ten days. It is possible, though, that such a warming trend could increase the incidence of freezing of crops when planted earlier.

There are other problems associated with higher temperatures. A northward movement of the Corn Belt would place it on less productive soils. Because the northern land is, in general, lighter and shallower, more fertilizer would be required to make it productive. Serious erosion problems could result.

Changes in production patterns will not come without changes in pest problems. Cooper (1982) cites the example of okra, a food that is a weed in southern cotton fields. Its range is limited by cold temperatures, but in laboratory experiments, increased CO_2 reversed the effects of cold damage. If that is the case in open fields, this weed could spread to northern production areas.

Pests are dependent on moisture conditions, temperature, and food quality, all of which are subject to change in a new climate. Species of pests can be expected to change; some may be eliminated, but others will multiply.

In response to all of the possible impacts resulting from climatic change, technology will also change. Irrigation may be required for crop production where it was not previously necessary. In other areas, moisture conserving management practices will be increased and plant breeding, too, will be targeted at adapting crops to these climatic changes. For example, it may be possible to genetically modify plants in order to extend the versatility of tolerance to an expanded range of weather conditions.

Overall, it does appear that future CO_2 induced changes may well be of a magnitude which could significantly alter adversely the climatic environment of the major grain belt of the U.S. It is not our purpose to predict such an occurrence but to evaluate our modeling capability to assess the impact on crop production should significant climatic change occur.

The General Production Function for Crops

To accurately estimate (explain) crop yields, all factors that influence yields should be included in the explanatory model. A general crop yield function for a specific crop can be described in the following way:

$Y = f(A, S, P, W, E, M)$ [3/]

where Y = crop yield

A = crop acreage

S = soil (including both chemical and physical properties)

P = plant factors (including physical and biological properties and environmental response capabilities)

W = weather

3/ Several of the independent variables in this specification become meaningless when averaged over all acres of a specific crop. As a result, for most estimating purposes appropriate geographical disaggregation must be employed.

E = economic environment

M = management (including technology and cultural practices employed)

The economic environment, which includes government programs, market prices and other factors, influences yields by causing some management practices to be more or less profitable. By some estimates, only 65% of available yield-increasing technology is now being used. (Runge and Benci, 1975) This situation occurs either because there has not been enough time or an adequate information flow for adoption of all of the new technology, or because some of the available technology is not economical at the present time. Maximum yields are not synonymous with maximum profits.

The above listed variables are not simply discrete nor are they strictly independent of each other. For example, the economic environment influences the level of crop acreage and a number of management practices. And, as crop acreage changes upward or downward, average soil quality decreases or increases as a consequence of changes in the quality of the marginal acres being cropped.

Biologically, yields are determined by soil fertility, soil type, crop variety, soil moisture, and cropping practices such as row spacing and the incidence and control of weeds, insects, disease, and erosion. Modeling all of these variables would require a very detailed and possibly inaccessible set of data. Because available data are aggregated over many farms, it is difficult to establish exactly when changes in technology occurred, or even what percentage of farms adopted new management practices. As a consequence, most weather-crop yield models have resorted to a "technology trend" to describe changes in management and technology that account for yield variability not related to the weather. Some variables easily fall under technological change. These include increased soil fertility due to additions of nitrogen fertilizer, and genetic improvements in crop varieties. But the total technology system can be complex and difficult to formalize analytically. Soil type is generally considered to remain unchanged over time but does, of course, vary between geographical areas.

The dependent variable of most crop yield weather models, grain yield, is measured in bushels per acre or kilograms per hectare. In the U.S. the former unit of measure is easily and directly comparable over time and the price (value) for major marketable crops is quoted almost exclusively on a per bushel basis.

The independent variables of crop yield-weather models can be separated into two broad categories, environmental and technological. Precipitation, temperature, or a combination of the two in the form of a weather index are the most commonly included environmental variables. These variables are measured either in absolute physical units, or as a deviation from the long-run average. Technology is frequently modeled as a function of time due to the complexity of defining measureable variables for the many cultural and managerial factors that have improved yields. Environmental and technological variables are discussed in the following sections.

Environmental Variables

Precipitation

Precipitation is the fundamental determinant of yields in the U.S. grain belt, water being the most limiting factor in grain production. Because of its importance, rainfall, or precipitation, appears in almost every weather-crop yield model developed.

Precipitation has both a direct and an indirect effect on crop yields. The direct effect is the water required for plant growth. Both inadequate and excessive water can adversely affect this growth process. The indirect effect appears in such forms as runoff and erosion, delayed harvest or planting, and crop abandonment. Runoff and delayed cropping operations are often the result of too much water, while crop abandonment is frequently caused by too little moisture resulting in yields too low to be harvested economically. Most existing models deal only with direct effects of rainfall.

Ceteris paribus, it is desirable to have precipitation variables describe as accurately and precisely as possible the distribution of precipitation throughout the growing season. [4/] Monthly averages are frequently used for models utilizing long series of historical data, even though monthly measurements are not very adequate descriptors of temporal rainfall distribution. An alternative to monthly averages is weekly or daily precipitation. While more precise, such measures are typically not statistically feasible in a time-series regression model due to the loss of degrees of freedom. Weekly or daily rainfall can, however, be used in those models which utilize more precise data including smaller sample plots.

Rainfall has different effects on yields depending on how much moisture is already in the soil. Two approaches have been used to deal with the effect of previous precipitation. One is to measure soil moisture; this approach is generally used with short, detailed data series. The other method is to add a variable for "preseason" precipitation. Such a variable is really a proxy for soil moisture. It is frequently used with historical time series data and often includes rainfall for September through May or June for corn and soybeans, and rainfall for August through March or April for spring wheat.

4/ There are stages of growth that require more moisture than other stages, for example, tasseling is a critical stage in the development of the corn plant that is very sensitive to moisture stress.

Temperature

Most, but not all, weather-crop yield models include temperature variable(s). In addition to minimum and maximum daily or weekly values, averages, deviations from average, and number of days over a specified maximum temperature have been included in model specifications. Most past models, however, have used only monthly average temperatures for the growing season period.

Air temperature is related to evapotranspiration which is the loss of water in the form of vapor from plant and soil surfaces. And, high temperatures are associated with high moisture stress in plants when water is limiting. As a result, some models treat temperatures as a surrogate for evapotranspiration because it is the only related measure readily available. But, temperature is a less than perfect substitute for evapotranspiration.

Weather Indices

Numerous attempts have been made to develop a weather index to use as a "deflator" to remove the effect of weather fluctuations on crop yields. It describes the year to year variation in crop yields due to weather. A value of 100 indicates a year in which environmental factors were neither favorable nor unfavorable; that is, at a given level of technology, weather had a neutral effect on yields. Generally, a trend is fitted to a set of time series data on yield. The influence of weather is then measured by actual yield as a percentage of computed trend yield. Both weather and aridity indices have been used as proxy weather variables in crop yield models.

Stallings (1960) derived a weather index by first removing the trend in yields with a linear regression line for each of seven individual crops in individual locations. The annual local crop specific index was then computed as a ratio of actual yields to computed yields from the linear regressions.

Indices for each crop at each location were weighted together into an index for each particular crop for the U.S. Finally, indices for the seven crops were weighted together into an aggregate index. Later studies, including that of Lawrence Shaw (1965), also derived indices by calculating actual yield as a percentage of trend yield.

R.H. Shaw (1974) developed a moisture-stress index using potential and actual evapotranspiration:

$$1 - \frac{ET}{PET} = \text{stress}$$

where ET = actual evapotranspiration

PET = potential evapotranspiration

This index ranges from 0 to 1. It assumes that the yield reduction is proportional to the percentage reduction in ET below PET. This method does not directly utilize meteorological variables. Various weighting factors were applied to five-day stress index sums during the growing season.

Oury (1965) recommended using an aridity index to account for weather. He tested those of Angström and De Martonne in regression equations. These indices are functions of precipitation and temperature, and are calculated for various periods. The indices he tested were fairly simple, but he suggested using the more complex Thornthwaite[5/] index when the required time series data were available. Oury wanted to capture the influence of weather at planting time, during growth, at harvest time, and winter effects (in the case of winter crops).

Shaw (1964) recommended weather indices to avoid problems arising from spatial and temporal aggregation. Because weather indices measure a net effect,

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5/ The Thornthwaite model computes evapotranspiration with reference to the amount of available water remaining in the soil.

timing of precipitation or temperature is not relevant. Also, the problem of geographical aggregation is not as serious, because there is no mismatching of weighting schemes, such as can occur when yield averages and meterological averages are constructed, and no loss of model sensitivity due to averaging out of weather variation over border area (state-level) aggregation. Shaw stressed that weather should be measured relative to the given level of technology because the influence of weather on yield is not independent of technology. The yield averages used to derive the indices were from test plots that the used actual yield effect of weather. Weather indices also allow decreasing returns to meterological variables within a time period and interactions among time periods.

Although several weather indices were developed during the 1960's, interest in their use has faded. They were essentially attempts to determine the efficiency of precipitation and have been largely superceded by the concept of evapotranspiration.

Other Weather-Related Variables

Some of the more recent weather-yield models require more detailed environmental information than temperature and precipitation. Soil moisture, potential and actual evapotranspiration, solar radiation, depth of rooting, water-holding capacity in the root zone, and pressure data have been included. With the exception of pressure data, which is used mainly as a last resort when precipitation data are lacking, these variables add more precision and accuracy to models by depicting smaller geographical areas.

Ravelo and Decker (1978) employed a soil moisture index which is the ratio of actual plant available soil moisture to maximum plant available soil moisture. The index was tested for the upper three layers and the upper six layers of soil. Inches of available stored soil water at planting were used by Runge and Benci (1975), and Leeper (1974) evaluated plant available stored soil moisture on a weekly basis. Bridge (1976) used variations of soil moisture such as daily values of surplus water and the soil moisture deficit summed over the stages of plant growth. Available soil moisture is a more precise measure than preseason precipitation to evaluate plant available water at the beginning of the growing season.

Evapotransporation related measures were discussed briefly in a preceding section and other variables are specific to certain models. Baier (1973) used total sky and solar radiation (cal/cm^2 - day), and Arkin (1980) implemented insolation in his model. Leeper included depth of rooting and available water holding capacity in the root zone.

Technological Variables

Yields of grains in the U.S. Great Plains and Cornbelt have shown an upward trend since the late 1930's. Most of the increase is due to technological progress and favorable weather conditions. Technological improvements include hybrid varieties, fertilizers, cultural practices, herbicides, pesticides, machinery, timing of field operations, changes in row spacing and others.

Time series data often show a linear or quadratic trend in crop yields due to technological advance. Linear trends are frequently used by time series analysts. This is not truly accurate, as it assumes that technology increases yields by a constant amount every year. Adoption of technology is an ongoing process, with different farmers adopting innovations at different times and at different levels. A linear trend assumes no leveling of yields.

Most wheat models show a change in the rate of technological adoption between 1945 and 1955. The LACIE[6/]-CCEA II[7/] model uses an exponential trend with increasing rates of adoption followed by a leveling off of yields. Thompson's corn model has a linear trend from 1930-1960 and a quadratic trend from 1960 on. His soybean model has a linear trend throughout.

Modelers attempting to use quadratic or cubic trends usually find these terms statistically nonsignificant. Quadratic trends assume yields are increasing at an increasing rate, while cubic trends show some leveling off. Cubic trends seem reasonable, as a leveling of yields was expected in the 1970's, but statistically they have not been significant.

Mostek and Walsh (1981) removed trend by expressing each state's yield as a series of fractional departures from the 11-year running mean yield. Instead of using the annual average yield, a given year's yield is subtracted from the average yield of the eleven years around that year, and the deviation from the mean is used in the regression analysis. A problem with using a moving average is that if there is a cyclical weather pattern, then the weather trend becomes part of the technology trend. Also, to use such a method, assumptions must be made about future yields in order to have a moving average for the current year (Thompson, 1966).

Cross-sectional data collected from experimental plots or farms should be adjusted for "farm level" technology. Experimental units typically use high levels of management, often adopting new practices before they are used by the public. Thus models will overpredict yields if they are developed with experimental data. Leeper's model, for example, over-predicted yields for

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6/ Large Area Crop Inventory Experiment - A joint project of the United States Department of Agriculture, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration.

7/ Center for Climatic and Environmental Assessment.

this reason. Also, another study found experimental farm corn yields to be 13% and soybean yields 8.5% above the county average (Swanson and Nyankori, 1977).

The economic environment influences the type of technology that is used. Government programs during the 1950's and 1960's removed land from production. Many farmers took their marginal lands from production and increased the intensity of input use on the acreage which they cropped. This was almost certainly a contributing factor to increasing average yields during this period.

Input and output prices also influence the use of technology. High input prices combined with low commodity prices can cause farmers to cut back on the level of technology. An obvious example of this phenomenon is a reduction in the amount of nitrogen fertilizer applied when its price rises significantly.

In summary, the impacts of technology on crop yields are complex. Yet, any independent effects of technology (those not functionally related to weather variables) must be isolated if the impacts of climate (or weather) on crop yields are to be measured accurately.

Relationships Between Climatic Variables and Yields

Sensitivity to environmental stress depends on the stage of development of the crop. Optimal weather conditions and reactions to stress during different stages of growth, as well as the distribution of crop yields in relation to the weather are discussed in the following section.

The highest yields of grain in the Corn Belt usually occur in summers of lower than normal temperatures, for two reasons. First, higher rainfall is associated with cooler than normal temperatures. Second, cooler weather permits storage of photosynthate. Products of photosynthesis are lost to a greater extent in warmer weather due to higher rates of respiration (Thompson, 1975).

In the Corn Belt, the optimum daily average temperature for corn and soybeans in June, July, and August is about 72°F (22.2°C). The optimum range is not less than 50°F (10°C) at night to not greater than 86°F (30°C) during the day. Temperatures above 90°F (32.2°C) are detrimental to corn and soybeans. Highest corn yields result from normal precipitation for September through June, and above average precipitation in July and August (Thompson, 1975). A cooling trend would benefit corn and soybeans in southern latitudes of the Corn Belt, but could reduce the length of the growing season in northern latitudes.

Development of Corn

The development of corn is influenced by photoperiod and temperature conditions. Moisture stress is most critical to yields during the reproductive stage. Little effect of reduced moisure is evident in the early stages of growth. Plants stressed during the vegetative growth stage can still produce near normal yields if weather conditions are optimal during the reproductive stages even though vegetation is reduced. Yield losses are attributable to a failure of fertilization.

Temperature perturbations reducing corn production include late spring or early fall frosts, consistently low spring temperatures, and unusually high or low temperature departures in summer (Dale, 1983).

Severe early drought can result in stunting and delayed silking. Many plants may fail to silk, and the tassels may be sterile (Leonard and Martin, 1963). Soil moisture conditions during flowering and early grain formation are critical determinants of yield (Salter and Goode, 1967). Tasseling and silking may be delayed by water stress (Claassen, 1970).

Stress during early ear shoot and ovule development influence yield by reducing the total number of kernels and the number of developed kernels. The main effect of stress during ear development is a decrease in the kernel weight (Claassen, 1970). Tasseling, silking, and pollination are most sensitive to stress. Severe stress during the ten days around silking can result in a complete crop failure. In the Corn Belt, rainfall is most important in the first part of August, with temperature being more critical in the second part of August. Most of the crop matures by the end of September (Shaw, 1983).

Thompson's model for Corn Belt states shows corn yields decreasing as temperature increases. A 0.75°C increase, with no change in precipitation, would decrease yields by about 8 percent. However, the influence of temperature is not independent of solar radiation and the evaporative demand of the atmosphere.

Bach (1978) estimated that a 1°C increase in August temperature would reduce corn yields 2 percent. A 2°C temperature increase would reduce yields in most states, although wetter areas like Illinois or Indiana could stand to benefit. Soybeans have a similar response, as higher temperatures in Iowa are beneficial whereas Indiana would benefit from lower temperatures.

Development of Soybeans

Soybeans are sensitive to drought from flower-seed differentiation until the end of fruiting (Salter and Goode, 1967). Stress during flower formulation results in fewer flowers and fewer pods, and therefore fewer seeds per plant. However, the seeds can be normal size (Sionit, 1977).

Mederski (1983) reported that limiting water during early flowering can decrease yields by up to 3% whereas restricted moisture during flowering to maturity can decrease yields up to 50%. The pod-fill stage is most sensitive to moisture stress. In Illinois, an extra inch of rain in July and August increases yields by .92 and .7 bushels per acre respectively (Bach, 1978).

Ample water before flowering is not as important as after flowering (Mederski, 1983). During vegetative growth, variable responses to soil moisture conditions have been reported (Salter and Goode, 1967).

Germination requires temperatures in the range of 10 to 40°C. Maximum rates occur at 25 to 30°C. Using the SOYMOD I model, Curry and Baker estimated that if the average annual temperature were to fall 2°C, soybean yields could be limited by the fall frosts that would result. Thompson's model suggests that increased precipitation in July and August increased yields. The influence of changing temperature varies from state to state, but in general, increased temperatures were beneficial in June and July but not in August (Curry and Baker, 1975).

Climatic change affects soybean production by its impact on the length of the growing season and the moisture availability. Both factors are affected by temperature. Lower average temperatures can be accompanied by reductions in the length of the growing season, and high temperatures increase water loss by transpiration.

Development of Wheat

There are two patterns of wheat production in the United States. Winter wheat is sown in the fall and harvested in June-July the following summer. Spring wheat is sown in the spring, and is normally harvested several weeks later than winter wheat. Winter wheat is generally not grown where the monthly mean winter temperature is below -6°C. In the U.S. Great Plains, wheat yields increase with normal or above normal precipitation. Wheat grown anywhere in the U.S. is hurt by above normal temperatures.

Wheat yields are highest when the growing season is cool and moist, followed by a warm dry ripening period. The optimal preharvest mean temperature is 16 to 22°C. The optimal temperature for germination is 18°C, with a minimum of 1°C. At high temperatures, germination is irregular. High temperatures are detrimental to yields except for emergence through jointing when above normal temperatures increase yields (Ramirez and Sakamoto, 1975). Most wheat varieties require a frost free season of 100 days or more.

Annual rainfall of 20 to 30 inches is sufficient if most of it falls during the growing season. Even lower amounts can suffice when prior year moisture can be stored by fallowing. Yield differences are more influenced by the frequency of rainfall rather than the mean available soil moisture (Desjardins, 1980).

The greatest reduction in yield is due to stress in the early earing stage. Drought between ear emergence and heading reduces the number of grains produced. Drought at the milk-ripe stage will reduce the weight of the grain. Rapid filling of the grain before the onset of drought is important for drought resistance. Losses from drought during earing are often irreversible (Salter and Goode, 1967).

Even though drought curtails kernel development, it can increase the protein content of the wheat. The shorter the period between formation and ripening of the kernel, the higher the percentage of gluten. The fruiting period is prolonged when the weather is cool and soil moisture is adequate. Under these conditions, more starch is deposited relative to gluten, so the wheat has a lower protein content than wheat produced under moisture stress (Leonard and Martin, 1963).

Michaels (1977) achieved good weather-yield explanatory results for winter wheat by defining 5 phenological periods during which consumptive moisture use, particularly, differed substantially. They were (1) planting and germination, (2) overwintering, (3) vegetative growth, (4) flowering/filling and (5) maturing/harvesting. These phenological periods were approximated by monthly (or multiple month) specifications of calendar time.

Studies illustrate that, on average, 1 inch (2.54 cm) of rainfall during the growing season contributes 2.4 bu./acre to the final yield for the Great Plains states. For a 10% decrease in rainfall (1 to 2 inches less than a normal season), wheat yields could be expected to fall 2.5 to 5 bu./acre. In North and South Dakota, Kansas, Illinois and Indiana, a .5 to 2°C temperature decrease will increase yields, using Thompson's model.

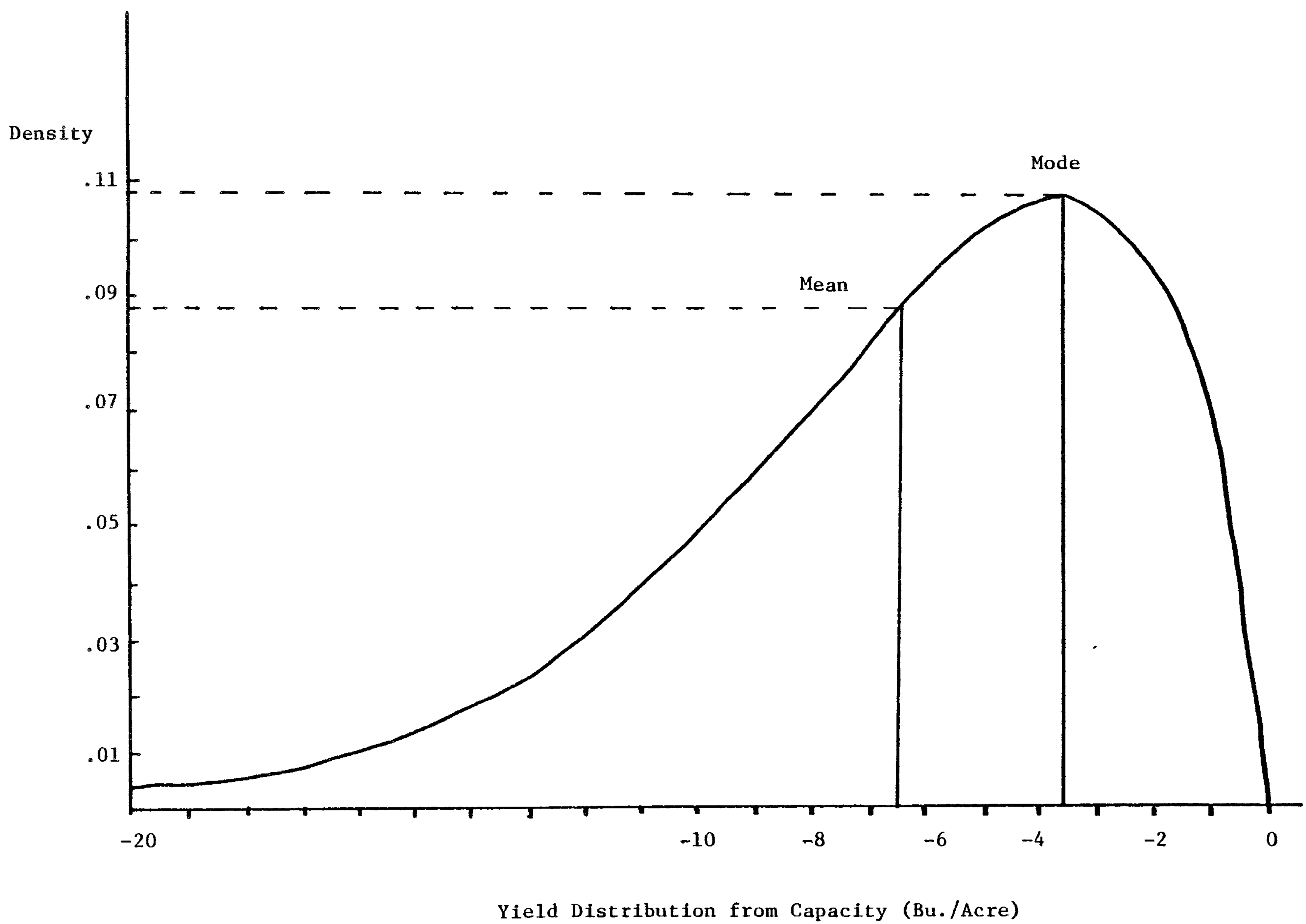
Distribution of Yields and Randomness

An underlying assumption of using mean values in a regression model is that of a "normal" distribution. This is probably not a valid assumption in crop yield models, especially in regard to the influence of weather.

Gallagher (1983) provides empirical evidence of the skewness of crop yields relative to conventional measures of central tendency (mean and mode). He first develops a concept of "capacity" yield which is obtained with "(1) efficient use of technology for controllable inputs and (2) ideal weather." He then estimates the probability distribution for yield disturbances (deviations from capacity yield) which are mainly attributable to environmental factors. The general distribution of his corn yield estimates are shown in figure 1. Two-thirds of the density function is contained between yield deviations from capa-

FIGURE 1.

Source: Gallagher (1983). Figure 6.2, page 96.



city of about -8.2 and -0.9 bushels per acre respectively. Gallagher concludes that (1) the probability function for corn yield disturbances is skewed heavily to the left and (2) the current environment of the Corn Belt is very near optimal for production of corn and soybeans since modal yields fall close to capacity yields.

Huff and Neill (1982) found that large negative deviations in corn yields are more likely to occur than large positive deviations. The same is true for soybeans. Of the five corn belt states studied, year-to-year variation in corn yield is smallest in Ohio, where the variation in July rainfall is least. Year-to-year variation in corn yield is largest in Missouri, where July rainfall displays the greatest variability. Thus, July rainfall is an important variable in explaining the variability in corn yields.

Crop sensitivity to weather may be more strongly related to varying soil types than to climatic differences between districts. In a recent study, Huff and Johnson (1979) found that in northern Illinois, the multiple correlation coefficient between corn yield and July rainfall and temperature and August temperature was approximately .4, as compared to .8 in southern Illinois. In southern Illinois, soils are such that yields depend on frequent rain, more so than the soils of northern Illinois. This implies a stronger yield dependence on weather conditions in southern Illinois.

Day (1965) found field crop distributions to be generally non-normal and non-lognormal, with the degree of skewness depending on the crop and the amount of available nutrients. Mode or median estimates may be preferred to means.

Three Generations of Crop Yield-Weather Models

Weather-crop yield models exist on different scales. They can be described as first, second, or third generation models depending on the complexity of the theory involved and the type and detail of data required.

First generation weather-crop yield models use average values for discrete time periods, such as months or seasons, from historical data for specific geographical areas. The yield equation is in a simple algebraic form. Physiological relationships are implicit, the soil type is a constant, and management and technology are modeled as a static coefficient. Calendar time is used to delineate time periods. First generation yield models are spatially oriented on state or crop reporting district levels (Stuff, et. al., 1979).

Easily accessible data is the main advantage of this type of model. However, its use is ordinarily limited to areas with long historical yield records. First generation models are insensitive due to "averaging out"; that is, losing micro-level variability by using state and monthly data. These models are also restricted by a limited number of parameters, lack of sensitivity to crop calendar changes, and the use of surrogate variables, such as technology trends.

An example of a first generation model is the work of Thompson (1969). His model used 37 years of monthly temperature and precipitation data for the five Corn Belt states. A separate model was developed for each state. Linear and curvilinear technology trends explained non-weather variance.

All other sources of yield variance, like soil type, improved varieties, and increased soil fertility are assumed to be either held constant or captured in the technology trend.

Thompson's model estimates the effect of weather and technology on crop yields. Regression coefficients were developed from historical data series for corn, soybeans, wheat, and grain sorghum in the midwest. Generally, the models explain 80-92% of the variability in yields.

The corn yield model was developed using data from 1930-1967 from Illinois, Indiana, Iowa, Missouri, and Ohio. Twelve weather variables and three technological variables comprise the model. Similar variables were used for the yield models of the other crops.

The weather variables are as follows:

1. Preseason precipitation (September through June)
2. June mean temperature
3. July precipitation
4. July mean temperature
5. August precipitation
6. August mean temperature

7-12 The squares of variables 1-6.

Departures from the "normal" monthly weather variables and the square of the departures from normal were used rather than the original (unadjusted) data. Thompson assumed that the deviations from normal were related to yield in a curvilinear pattern (French, 1982).

Thompson developed technological variables on the agronomic evidence that technology was introduced gradually until 1960 when it was adopted more rapidly. Beginning in 1960, nitrogen fertilizer was applied to corn in increasing amounts. The three technological variables are:

1. A linear time trend which increased by one unit each year from 1930-1960, and became constant after 1960.
2. A linear term which is equal to zero before 1961, one in 1961, and increased by one unit per year.
3. The square of the second term.

The linear trend assumes ever-increasing yields. This model was developed in 1969, when yields had not yet begun to level off. There was not sufficient evidence to model a leveling off of technology.

For grains other than corn, the models are basically the same except for the time points at which the slope of the technology trend changes, and the months used for the weather variables.

Thompson modeled the time trends for wheat in a similar manner to that of corn. The technology variables were a linear term for 1920 to 1945, a linear term for 1945 to 1968, and the square of the 1945 to 1968 term.

It is not clear when wheat yields started increasing due to improvements in technology. There could have been some increase in the 1930's, but the long drought of that period obscured the technological gains. Yields increased rapidly after 1950.

The shape of the technology trend varied somewhat for different states. North Dakota, South Dakota and Kansas were linear after 1945. Oklahoma, Illinois and Indiana were linear from 1920-1945, and curvilinear after 1945. This may be due in part to the use of nitrogen fertilizer in each state. In 1968, the percentage of acres in wheat receiving nitrogen fertilizer varied from 97 percent in Indiana to 23 percent in South Dakota.

The technology trend after 1945 was most closely related to fertilizer, but also to improved, disease-resistant varieties, greater use of summer fallow, and a reduction in acreage, which led to the use of better land, in the 1940's.

As in the case of the corn model, the weather variables entered the wheat model as departures from normal. Preseason precipitation (August-March), April, May and June rainfall and temperature were used. July rainfall and temperature were included only for North and South Dakota.

Second generation yield models are characterized by daily or weekly input data derived from surveys or field experiments. Like first generation models, the yield equation is in simple algebraic form. However, second generation models are more detailed in many aspects. Physiological relationships are recognized, not implicit, and soils are specified by their water-holding capacity and strata factors. Management and technology variables can be either explicitly modeled or specified as constraints. Time integration involves static biological phase weighting (Stuff, et. al., 1979).

A second generation model is capable of estimating yields for any arbitrary unit of area. These models are more accurate and responsive than first generation models due to additional data applied at smaller spatial and temporal scales. The difficulty in using a second generation model arises when trying to locate the necessary data.

A typical second generation model is that of the LACIE project for hard red winter wheat in North Dakota (LeDuc, 1979). Temperature and precipitation variables are used but on a more detailed level than first generation models. Average total weekly precipitation, maximum number of days in which .1, .2, and

1 inch of precipitation fell, average weekly runoff, and soil moisture take the place of precipitation; temperature information is given by average weekly minimum and maximum temperatures, maximum number of days in the week when the temperature is greater than 100°F or 90°F or less than 32°F, and the sum of growing degree days.

The CCEA second generation wheat yield model is a more detailed model than the first generation CCEA model. The yield equation of this multiple regression model can be described as:

$$Y_j = \alpha + YR + T_j + \sum_{i=1}^{n} W_{ij}$$

where the W_{ij}'s are weather variables, Y_j = yield for the jth crop district, n is the number of weather terms, YR = year - 1950, and T_j is a trend variable of the form:

$$T_j = 28 * A_{1j} * \exp\left\{ \{-.001 * A_{2j} * \left[(\text{year} - 1920) - (50 * A_{3j})\right]\}^2 \right\}$$

This allows for an exponential rate of increase in the mid-1950's and a slowdown in the rate of change in the 1970's. A_1, A_2 and A_3 were determined from a nonlinear programming algorithm. The final variables were selected using step wise regression procedures.

Although this model provides an improved estimate for two of the three years of the project as compared to the first generation CCEA model, it is operationally more difficult to use and a greater amount of precise data is required.

Third generation models are more detailed than first and second generation models. The data are obtained from controlled or designed experiments. Daily or hourly values of environmental variables are required. The yield equation can be anything from a simple algebraic representation to an extended series of differential equations. Instead of modeling a region or a field, the level of detail is that of individual plants. Physiological relationships, soils, and management and technology are explicitly modeled. Time integration is biological and dynamic (Stuff, et. al., 1979).

An advantage of using third generation models is the increased precision achieved as compared to geographically large-scale models. This is because third generation models better describe plant growth and development processes, are created from detailed weather and crop information, and are not likely to mix input variables of different scales (size of geographical area) (Strand, 1981). The disadvantages of third generation models are the high costs of model development, the inadequacy of existing data bases and the extremely small spatial representation.

Third generation models are developed on a highly technical level of plant physiology. SORGF, a grain sorghum growth-simulation model, is a third generation model that forecasts crop status during the growing season (Arkin, et al, 1976). The variables, including daily values of insolation, rainfall, and minimum and maximum air temperature were collected from ten fields in central Texas for one growing season. This is a dynamic growth model on a plot-size scale.

SORGF was used by Arkin to forecast crop status within the growing season. The probability that a certain yield might occur, the most likely occurring yield, the greatest and smallest occurring yield, the probability that yield may be greater or less than a particular value, the average yield expected over many years, (50 years of simulated weather data were used in this study) and the expected year-to-year variability in yields over many years can be determined from the results of the simulation.

This model used data collected during the season as feedback to increase precision of the yield forecast. Feedback doesn't eliminate errors, but it does increase the accuracy of predicted parameter values. Information required for feedback includes leaf number, weight, and area, stalk and head weight, and the date of emergence.

Because the objective of this research is to evaluate weather-crop yield models for the purpose of assessing impacts of long-term climatic changes, third generation models are probably not appropriate. First and second generation models are specified at a level of detail more reasonable for this type of analysis. These models use weather data which are more highly correlated with measurable changes in climate than is true for third generation models.

Evaluation of Models

The following section is a general evaluation of crop yield-weather models. Criteria for selecting models are discussed, as well as frequently encountered problems. Desirable features necessary for estimating impacts on crop production associated with climate changes are discussed. A table summarizing characteristics of specific models is presented in the appendix.

A good model should meet several criteria. First, the model should reflect the relationships expected from agronomic theory. We should have reason to believe that a cause and effect relationship exists between crop yields and weather events. The modeled relationship should result in parameters of the correct sign and of reasonable magnitudes.

Second, the model should be statistically sound. It is desirable to find a model relatively free of statistical problems. Selected variables should be statistically significant, and the model should have good predictive capabilities.

Third, the model should be economically feasible, both in the amount and kind of required data, and in the cost of development and estimation. Precise, detailed models are often prohibitively expensive to develop and use.

If expected relationships from agronomic theory are present, the model has "appropriate structure" (LeDuc, 1979). We would expect an increase in rainfall to increase yields up to a point, after which more precipitation would be detrimental. This type of situation indicates a non-linear response function of yields to rainfall. In general, most models are in accord with agronomic theory. Thompson's model shows yield increasing with increased precipitation at appropriate times. Good representations of non-linear response functions are more difficult to model.

Outliers in the data can influence the model when they are not representative of the true relationship. Episodic weather events such as flooding, untimely frost, or hail are probably the chief sources of outliers in the data. Models that overestimate yields in 1970 and 1974 do so because of the corn blight and delayed planting, followed by a dry summer and an early frost respectively. Some crop yield-weather modelers dealt with episodic weather phenomena by throwing out the bad data.

The marginal value of precipitation is difficult to capture in most models. For low levels of precipitation, water is scarce and additional precipitation increases yields at an increasing rate. At higher levels, additional precipitation increases yields at a decreasing rate and eventually decreases yields (Shaw, 1964). Multiple linear regression models assume that each additional inch of precipitation has the same effect on yield as the first inch (Thompson, 1963).

Even if a model corresponds to agronomic theory, it must be evaluated for its statistical validity. Specifically, crop yield-weather models must deal with multi-collinearity, overaggregation of data, proxy variables and problems in defining and modelling technology. Crop yield-weather models may encounter the statistical problem of multicollinearity. Multicollinearity indicates that the variables are correlated with each other, possibly even more than with the dependent variable. This condition can exist if individual variables share a common time trend. Excessive multicollinearity results in large standard errors for estimated coefficients and, consequently, unreliable estimates.

Independent variables in crop yield-weather models may be correlated spatially or temporally. Katz (1979) found the following correlations between total monthly precipitation and mean temperature:

Month	Correlation [8/]
April	-0.14
May	-0.28
June	-0.69
July	-0.73

8/ Kansas State values, 1930-1980.

The correlations between precipitation and temperature in June and July are fairly high.

Starr and Kostrow (1978) maintain that the correlation is "quite weak" between climatic variables. The strongest correlation in their study was -0.613, between August precipitation and temperature. They also found a weak tendency for temperature anomalies to persist from one period to another.

Thompson observed that higher rainfall is associated with cooler than normal temperatures. However, higher evapotranspiration rates and plant moisture stress are associated with warmer weather. The influence of temperature is intercorrelated with insolation and evaporative demand of the atmosphere. As a result, the temperature-precipitation interaction caused Thompson's regression equation to overestimate yields in poor weather years and underestimate them in good weather years.

Most of the variability in crop yields is attributable to weather and technological influences. However, technology is ambiguously defined and very difficult to measure. Despite the difficulty in dealing with technological variables, they are major determinants of yield variability and cannot be overlooked. McQuigg (1975) estimates that 70 to 80 percent of the variability in crop yields is due to technological factors. Few of the methods suggested to deal with technological factors have been successful. Most modelers, including Thompson, Steyaert, and Huff and Neill, have used a time trend or proxy variables. This approach assumes that the residual variance is due to weather. Other methods such as lagged research and development expenditures and acres in hybrids have had only limited success.

One of the problems with using proxy variables is that they pick up the effect of all variables left out of the equation. This means that if the weather variable also had a linear trend, it will be captured by the time trend rather than the weather component. For example, a cooling trend which has occurred over the last forty years may be a source of error when using time trend to explain technological change. Actual measures of definable factors are preferable to proxy variables, but the specification of technological variables is not easily accomplished. Another problem is uncertainty in the rate of technological adoption. After most technological discoveries, the change is not immediate. Few producers use state-of-the-art techniques. What they choose to adopt and when they adopt it depends on economic circumstances. Also, capital equipment is frequently not changed until the old capital reaches obsolence, rather than at the time of discovery of new technology. Thus, technological change appears empirically only after a period of time (Haigh, 1977). Even so, whether a linear, a quadratic or some alternative trend best represents technology is uncertain.

Nelson and Dale (1978) felt technology could be modeled more accurately without a time trend. They evaluated a Thompson model, a "modified" Thompson model, Leeper's model, and a model by Dale and Hodges. The modified Thompson model used the same twelve weather variables as the full Thompson model, but only one variable, the average application of nitrogen on corn land in Indiana, defined technology. The full Thompson model uses time as a surrogate technology variable. Nelson and Dale found the other three models to be superior to the full Thompson model. They concluded that "models in which some function of year is used to consider technology may provide inaccurate estimates of the effect on crop yields caused by changes in weather or technology".

In addition, weather and technological variables interact. Shaw (1964) observed that in 1930, a two-inch (5.08 cm) deficiency of rain decreased yields 25 percent while in 1960, a two-inch deficiency of rain decreased yields 10 percent. He concluded that an interaction between technology and weather may exist. Part of this interaction is due to field practice decisions that are based on the weather. Haigh (1977) estimated that 20 percent of the variability in corn yields was attributable to the interaction of weather and technology. Many models neglect this point.

As in all models, data manipulation and aggregation are important considerations in crop yield-weather models. Regression models describe the variability of the dependent variable due to the change in the independent variables. When data is averaged over space or over time, some of the variability is lost, making the model insensitive to changes in the variables. State and monthly averages are commonly used, especially in first-generation models, and this aggregation of data appears to be excessive and thus adversely affect the model's performance. For example, many of the crop yield-weather models use data from USDA crop reporting districts. Usually, a weighted average of the districts is used for the state-level model. This may not be a good representation when the weather varies among districts. One district could have surplus rain while another is dry. The average is "normal" precipitation for the state yet this doesn't accurately describe the geographical distribution of rainfall. Furthermore, crop yields and meteorological factors are not monotonic; that is, crop yields do not always increase as the amount of a meteorological factor increases. (Shaw, 1964)

Aggregation of data over time poses similar problems to those encountered in spatial aggregation. While it is convenient to use monthly variables (calendar time), the development of a crop is better described by phenological or biometerological time. They do not always coincide. Monthly data implicity assumes that particular phenological stages occur at the same time each year (Strommen, 1979). However, most plant responses are not linear (Haun, 1982). Most models using time series data are in calendar time; small-scale plot models are usually based on phenological stages. Even so, not all models that use biomeoterological time work well. Feyerherm's model performed well, within one bushel per acre of USDA estimates, but Ravelo and Decker's model based on biometerological time was not as successful in predictive ability.

Finally, monthly averages can be misleading. There could be 25 days of no rain followed by five days of torrential downpours, with a monthly average that is "normal" (Shaw, 1964). Weekly averages may be more representative but smaller increments of time also have disadvantages, as degrees of freedom are limited. Even though averages indicate whether the growing season had been cool or warm, rainy or dry, they do not quantify episodic weather events. That is, averages cannot capture the effect of a late spring or early fall frost, both of which can significantly reduce yields.

Most crop yield-weather models do not include soil type as a variable. This limits their applicability to the geographic region where the data originates. Soil type varies by region and within regions, so the same climatic conditions in different areas will result in different yields. Most models assume soil type as constant.

Even if a model meets all of the listed criteria, it may not be feasible to develop. Development of models that use a large amount of detailed data may be limited by both cost and availability of information.

The most limiting factor of existing second generation models is data base inadequacy. These models require large amounts of detailed data, such as varietal yield components, weekly or daily precipitation, daily minimum and maximum temperatures and evapotranspiration, usually for each stage of development.

First generation models don't need detailed data, but they do need a long sequence of historical data. Yield, temperature and precipitation data are required. Most areas of the U.S. would have no problem obtaining this information, but the predictive capability of first generation models is generally inferior to that of the second generation.

All models should be verified. First, we can ask quite simply, do the coefficients make sense? They should have the sign and magnitude expected by agronomic theory. Second, they should be tested with independent data. One way is to use all but 2 to 3 years of the data to develop the model, and then use the remaining data to test the model's performance.

Finally, none of the models examined dealt with multi-year climatic variables except for limited preseason moisture variables. Increasingly, more attention has been given to making accurate yield predictions by updating information within the season. Predictions made close to harvest should be more accurate as more information comes available. But, these types of prediction do not address the issue of long term climatic change.

Conclusions

A consensus appears to have developed relative to the likely global impacts of expected "greenhouse" induced effects on climate. For the major U.S. Grain Belt the probable consequences are reduced rainfall and increased mean temperatures during the crop growing season. Given the generally favorable current climatic conditions of this region for grain production, the expected climate changes appear likely, *ceteris paribus*, to have negative net impacts on the yields of the major crops of the region, corn, soybeans and wheat. But, currently available climate-crop yield models are either (1) so global and so general in their specification or (2) so limiting in their inclusion of functional (and long term) climatic variables, so as to defy a comprehensive statistical evaluation of their predictive accuracy. Any reliable estimates of future impacts of climate change on crop yields, even abstracting from possibly different future technology interactions, will require a more comprehensive climate-crop yield modeling effort which:

1) models separately each of the major economic crops,
2) utilizes key components of second generation crop yield-weather models to specify climate-yield relationships which include both
    a) phenological time and
    b) weather variables which include extreme (maximum and minimum) temperatures and additional information on the distribution of precipitation within the phenological time periods analyzed,
3) provides for an effective explanation of inter-year climatic influences, particularly those incurred by the cumulative effects of multi-year reductions in precipitation,

4) permits independent estimation of models for substate-level production regions and subsequent aggregation and,

5) provides for specification of technology-yield relationships more complex than those of simple linear time trend.

Though the above set of modeling requirements are substantial, they are by no means prohibitive. Major resource commitments are now being made to model crop yields on an intra-seasonal basis in order to project short term commodity supplies. Only some of these resources need to be diverted to longer term modeling in order to upgrade substantially the quality of climatic change-crop yield modeling efforts. If substantial climatic changes do occur in the future, technology developments (such as new crop varieties, new soil moisture conservation techniques, etc.) will be induced to counteract the new climatic adversities. These technological changes and their impacts on crop yields will need to be tracked over time in order to evaluate their effects. But, again we should be able to learn from the past. Counteracting the effects of any major reductions in precipitation (soil moisture) may well be the most challenging technological issue of them all.

Appendix Table 1

Summary and Evaluation of Weather - Crop Yield Models

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Stallings (1960)	Weather index	Weather measured as a residual of linear technology trend; index = actual yield computed yield	Trend removed with linear regression line	Weather effects are computed as a residual and not estimated directly	Not Applicable: Measures ex post effect of weather	7 crops weighted into index for entire U S 0003 R^2 < 6811 (Corn, Oats, Barley, Wheat, Soybeans, Cotton, Tobacco)	High level of aggregation May not be applicable to subaggregate areas for most models, weather trend could be included with technology trend
Oury (1965)	Aridity Index	Angstrom's Index Index = $\frac{\text{Precipitation}}{1.7^{T}}$ Where T = temperature (°C) But other indices can be used	None	Angstrom index in accord with van't Hoff's law of physics	Not Applicable	Applicable to any crop in an area	Data easily accessible, eliminates incorrelation of temperature and precipitation Does not allow for soil-weather interaction
Palmer (1958)	Moisture Index	Monthly precipitation, mean monthly temperature, available soil moisture at the start of the month	None	Combines temperature and precipitation as predictor variables	Not applicable	Western 1/3 of Kansas and Central Iowa	Universal, as normal temperature and precipitation produce an index of zero in all seasons & all climates Better suited for climatological analysis than for operational use Results unrealistic when applied to areas with different climates

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Thompson (1969) Corn	First Generation	Precipitation, Sept - June; mean temperature June, July & August; July & August total precipitation; The squares of the above six variables	Linear trend, one unit per year, 1930-1960, linear trend, one unit per year, 1961-1969, The square of the second term	Assumes technology was introduced gradually from 1930-1960 and more rapidly after 1960's; no levelling of yields	R^2 = 94	Corn - Illinois, Iowa, Indiana, Missouri, Ohio Models are state-level	Overestimates in poor years Underestimates in good years Not sensitive to episodic events Weather variables modeled as departures
Thompson (1969) Wheat	First Generation	Total precipitation August - March, April, May, June rainfall, April, May June average temperature July rainfall and temperature for North and South Dakota only	Two linear time trends, 1920-1945 and 1945-1968	Same as Thompson corn model	Variables accounted for 80-92% of yield variability	Wheat-Illinois, Indiana, Kansas, Oklahoma, North Dakota, South Dakota	Same as Thompson corn model
Thompson (1970) Soybeans	First Generation	Total precipitation September-June, July, and August, June, July, and August temperature	Linear time trend, increased one unit per year, 1930-1968	Assumes no levelling of technology Increased August temperatures decreases yields, precipitation beneficial to yields	R^2 not reported	Soybeans: Illinois, Indiana, Iowa, Missouri, and Ohio	Same as Thompson corn model
Williams & Robertson (1965)	Regression Model	Conserved soil moisture and monthly total precipitation, which are aggregated into other variables	None, because "cultural practices did not change sufficiently 1952 to 1963 to significantly affect yield"	Satisfactory, but reasonableness of signs on yield-weather variable coefficients varies by district	Coefficient of determination Alberta 88, Saskatchewan 87 Manitoba 66	Wheat - Canada	"Bad" data thrown out (rust, disease, frost damage) Temperature data not included

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATIO
Shaw (1977)	Moisture StressIndex	Evapotranspiration (potential & actual)	Used Thompson's technology trend relationship	In accord with agronomic expectations, Increasing the stress index decreases yield Increasing the time trend increases yield	R^2 not reported	Corn - Iowa	1970 and 1974 yields were overestimated These were atypical years because of disease and drouth
Leeper (1974)	Ordinary Least Squares Regression Analysis	Average weekly maximum temperature, total weekly precipitation, plant available stored soil moisture at planting, and the field tasseling date	none	Model uses sums of cross-products of precipitation and temperature which are not easily evaluated relative to structure	Average R^2 of 4 districts = 58	Corn - Illinois	Developed from experimental plots with intensive management Does not predict average yields accurately Tested by Klugh; worked well for Illinois, Indiana and Iowa, not well for Missouri Tested by Keener with multiple regression Found accurate estimates for three of four states May not have worked well because a better description of soil moistur is needed; regression models are inherently specific to area where developed; and much marginal land goes in & out of production in Missouri, therefore mana ment practices are changing

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
McQuigg (1973)	First Generation	Same as Thompson	Same as Thompson	Same as Thompson	Wheat R^2 .82-.90 depending on state	Wheat, corn, soybeans. Same states as Thompson	Same as Thompson's model, updated with more recent data
Haun (1982)	Second Generation	Growth index, modeled from daily maximum temperature, precipitation, age from emergence, variety, year, location, estimated soil moisture, latitude, beginning date, running 15-day sum of maximum temperature, running 15-day sum of % estimated soil moisture, sum of % estimated soil moisture from beginning date to prediction; squares, cubes and cross products of above variables	Average amount of Nitrogen applied (kg/ha)	Difficult to assess, many cross products used	$.758 \leq R^2 \leq .816$	Corn - Illinois, Iowa, Minnesota	First developed a growth index, which was used in the subsequent analysis of growth-yield relationships. Model developed from 1950-73 data, 1974-77 used for test
Runge & Benci (1975)	Ordinary Least Squares Regression Model (Same as Leeper)	Total weekly precipitation, mean maximum daily temperature for a given week, available stored soil moisture at planting	Used ratio of USDA estimated production to predicted state production, to prevent overestimation of yields from experimental plot data	Model uses sums of cross-products of precipitation and temperature	Not reported	Corn-Illinois, Indiana, Missouri, Eastern Kansas, Eastern Nebraska	Technology conversion factor appeared to be low

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Perrin & Heady (1975)	Regression model combining cross-sectional & time series data	Monthly Palmer moisture indices	Application of Nitrogen fertilizer, % acres planted to hybrids	Satisfactory, Unexpected coefficient signs could be result of multicollinearity or by fitting response function to non-homogeneous area of cropping practices	Illinois Corn R^2 = 86 Iowa Corn R^2 = 83 Kansas Wheat R^2 = 61 Nebraska Wheat R^2 = 55 North Dakota Wheat R^2 = 70	Corn - Illinois & Iowa Wheat - Kansas, Nebraska, North Dakota	Yield increase of 5-6 bu/acre unexplained May need more precise specification of technological factors
LACIE-CCEA I (Center for Climatic and Environmental Assessment).	First Generation	Monthly climatic variables; inclusion dependent on level of significance	Thompson - type trend	Inclined variables chosen on basis of sign being agronomically expected, & coefficient being statistically significant	Statistics not reported, large yield discrepancies in 1971 and 1974 Sakamoto 81-9 R^2, varies by state	Wheat in various crop districts Models are state-level	Neglects episodic events, need improved long-term weather forecasts before this model can improve estimates "Bootstrap" test years prior to prediction year are used to develop model coefficients
LACIE-CCEA II	Second Generation	Average weekly total precipitation, maximum number of days in which more than 1, more than .2, and more than 0 1 inches of rain fell, average weekly maximum and minimum temperature; maximum number of days when the maximum temperature exceeded 100°F or 90°F, and the minimum temperature was	Allows for exponential rate of increase in mid-1950's and slowdown in rate of change in the 1970's	Precipitation beneficial from emergence to heading, high temperatures detrimental from jointing to turning, runoff harmful	R^2 = 88	Hard red wheat in North Dakota	Improved estimates for 1974 to 1976 Used bio-meteorological time scale Quality of phenological data from 1950-1956 is poor "Bootstrap" test used independent test years (1974-1976)

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
LACIE-CCEA II Continued	Second Generation	less than $32^{o}F$; sum of growing degree days; average weekly surface moisture; average weekly subsurface moisture, average weekly runoff					
LACIE-Feyerherm	Second Generation	Potential & actual evapotranspiration; soil moisture stress term; subsoil moisture stress term, precipitation; excess precipitation, daily minimum and maximum temperature; average daily maximum temperature	Varietal yielding ability component, proportion of wheat fallowed, irrigated, and continuously cropped, elemental nitrogen applied for each cropping practice	Signs and magnitudes of coefficients are agronomically acceptable	Within 1 bushel of USDA estimates in years of lowest yields Underestimates USDA yields by 3-4 bushels per acre in years of highest yield	Winter & Spring Wheat: U S Great Plains	Underestimates high yields; does not detect losses from episodic events Uses biometeorological time scale
Starr & Kostrow (1978)	Multiple Regression Analysis of Yield Against Coefficients of eigenvectors of climate anomaly sequences	Eigenvectors of climate anomaly sequences, using monthly mean temperature and precipitation for preplanting and April through August.	Piecewise linear technology trend	Difficult to determine meaning of eigenvalue coefficients	R^2 = 65 1974 underpredicted by 807	Spring Wheat; North Dakota, South Dakota, Minnesota and Montana	Shifts in planting time not adequately represented Model developed from 1932 - 1971 data, 1972-1975 saved for independent test

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Steyaert, DeLuc & Mc Quigg (1978)	Principal Components Analysis	Eigenvectors of Pressure Data	Piecewise linear technology trend	Difficult to determine meaning of eigenvalue coefficient	Canada and U S explained 88% of variance USSR explained 96% of variance	Winter & Spring Wheat U S , Canada, and USSR.	Pressure is spatially continuous, avoids problems associated with precipitation and temperature
Arkin, Maas & Richardson (1980)	Third Generation	Insolation, rainfall, and minimum and maximum temperatures for each day of the growing season (simulated data)	None	Based on actual plant process	Root mean-square-error is reduced between predicted and observed values of head weight when feedback is used at half-bloom	Grain sorghum in central Texas	Uses feedback during the growing season to improve precision of the model used to forecast date of physiological maturity and head dry weight at that date. Predicted yields compared with actual in the field
Swanson & Nyankori (1979)	Regression Analysis Using Historical Data	Total precipitation, September through April, May, June, July and August, May, June July, and August temperature	Linear time trend	Questionable, model shows yield decreasing when August precipitation increases	Corn R^2 = .831 Soybeans R^2 = .703	Corn & Soybeans in Illinois	Lin and Seaver, reviewers of this study, claim regression yield functions don't make sense, i e , one equation shows yield increased 53 times from 1950 to 1976, another equation shows yields are 1/10 of the 1950 value Some yield functions not statistically significant

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Ravelo & Decker (1981)	Iterative Regression on a Bio-meterological time scale	Daily precipitation, maximum & minimum air temperature, potential & actual evapotranspiration, soil moisture index	None	Difficult to evaluate	Coefficent of determination 35 for independent test of model	Soybeans - Illinois, Indiana, Kansas, Missouri	May need technology trend 20 Station years from 10 locations for 1957-1976 were selected at random for the independent test Estimated yields using prediction model were compared with actual yields
Mostek & Walsh (1981)	Analysis using cross-correlations and multilinear regressions	Eigenvectors of monthly temperature and precipitation.	Trend removed by expressing each state's yield as a fractional departure from the 11-year running mean state yield	Difficult to assess meteorological interpretation of eigenvectors Correlations precipitation and temperatures variables are reasonable	30-35% of yield variance explained by weather during individual months 60-70% explained for entire growing season	Corn - 40 states	Assumption of linearity in crop-weather relationships not strictly valid.
Pope & Heady (1982)	Three stage least squares regression model	Departure from normal (long-run average 1950-1980) September-June total precipitation; July and August rainfall, June, July & August temperature	Time function plus nitrogen used per corn acre	Coefficients have appropriate signs; Weather variables are modeled as quadratic and linear functions, reflecting non-linear response of yield to weather	Illinois R^2 = 989 Indiana R^2 = 986 Iowa R^2 = 990 Missouri R^2 = 985 Ohio R^2 = 989	Corn, corn silage, oats, soybeans, wheat and alfalfa hay for Illinois, Indiana, Iowa, Missouri, Ohio.	Uses systems of equations; models are state-level.

Table 1 Continued

MODEL	CLASSIFICATION	SPECIFICATION OF WEATHER VARIABLES	SPECIFICATION OF TECHNOLOGICAL VARIABLES	STRUCTURAL VALIDITY	CAPABILITY FOR YIELD PREDICTION	COMMODITY COVERAGE	PRELIMINARY EVALUATION
Huff & Neill (1982)	Multiple Regression Analysis and Probability Estimates Resulting from Weather-Induced Variations in Yield	June, July and August mean temperature and rainfall totals, a preseason rainfall total, and the year of observation	Quadratic trend	Appropriate variables, signs and magnitudes not reported. Expected a cubic technology trend, as it assumes a levelling of yields, but quadratic function fit best	Percent of variance explained by weather and technology variables ranges from 84% to 94%	Corn and soybeans Iowa, Illinois, Indiana, Missouri, Ohio	Model developed from 1931- 1969 data, 1970-1975 used to test validity of the model

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