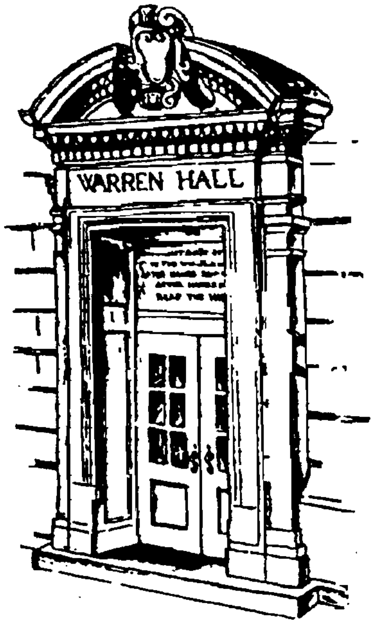
WP 95-16
December 1995



Working Paper

Department of Agricultural, Resource, and Managerial Economics
Cornell University, Ithaca, New York 14853-7801 USA

CLIMATE CHANGE AND GRAIN PRODUCTION IN THE UNITED STATES: COMPARING AGRO-CLIMATIC AND ECONOMIC EFFECTS

Zhuang Li
Timothy D. Mount
Harry M. Kaiser

CLIMATE CHANGE AND GRAIN PRODUCTION IN THE UNITED STATES: COMPARING AGRO-CLIMATIC AND ECONOMIC EFFECTS

Zhuang Li, Timothy D. Mount and Harry M. Kaiser*

Abstract

The analysis is based on an integrated climatic, agronomic and economic model of grain production in the midwestern region of the U.S. The model represents a typical farm and the objective is to select an optimum combination of cultivars for four crops (maize, soybean, wheat and sorghum) conditionally on climate, soil characteristics and the prices of the four crops. The first part of the analysis uses a complete two-way factorial design to estimate the effects of five climatic and agronomic variables and the four prices on yields, total production and net return. With this design, variability can be allocated uniquely to individual explanatory variables. As expected, prices have little effect on yields. For total production and net return, temperature and precipitation are the most important variables, but prices and two-way interactions among the variables are also statistically significant. The ranges of values for temperature and precipitation used in the factorial design are extended in the second part of the analysis. Response surfaces for yields, total production and net return are estimated from these new data. The fitted surfaces are used to evaluate the effects of projections of temperature and precipitation, resulting from global warming, on yields, total production and net return. Two of the three projections imply modest increases in yields, total production and net return and one shows slight declines, particularly for the yield of maize. The differences in these results reflect primarily differences in the projected changes in precipitation because the projected increases of temperature are similar in all scenarios. Furthermore, relatively small reductions in precipitation from the projected values have relatively large adverse effects on grain production.

* Li is an economist at The Cadmus Group Incorporated. Mount and Kaiser are professor and associate professor, respectively, in the Department of Agricultural, Resource, and Managerial Economics, Cornell University. This research was supported by the National Science Foundation, the Economic Research Service of the US Department of Agriculture and the College of Agriculture and Life Sciences, Cornell University.

Climate Change and Grain Production in the United States: Comparing Agro-Climatic and Economic Effects

Zhuang Li, Timothy D. Mount and Harry M. Kaiser

1. Introduction:

Climate places important constraints on agriculture. Research efforts to analyze the influence of weather on crop yields were initiated by crop scientists during the late 1960's (Thompson 1969a, 1969b and 1970). Recent studies by economists have examined the economic impacts of climate change on agriculture at the international level (Kane et al. and Rosenzweig et al.), at the national level (Adams et al. and Mendelsohn et al.), at the regional level (Crosson, Katz and Wingard), and at the farm level (Kaiser et al. 1993 and 1995). Most of these studies simplify the linkages between farmers' decisions and climate.

Research by Kaiser et al. is an exception, which is based on an integrated computer model of a typical midwestern farm (see Li 1995 for a more comprehensive review of these studies). The model includes a stochastic weather generator (Richardson and Wright), the General Purpose Atmospheric Plant Soils Model (GAPS: Buttler and Riha) to predict yields of individual cultivars, and a farm decision model to select cropping patterns. This model (the integrated model thereafter) has been used to study how farmers adapt to climate change at selected sites in the midwestern United sites in the midwestern United States, and on the level of production of four grain crops (maize, soybean, sorghum, and wheat).

A practical limitation of the integrated model is that it is relatively cumbersome to use because the growth of each cultivar is modeled on a daily basis over a growing season. In addition, thirty growing seasons are simulated for a given scenario to provide the information about the mean and variability of yields needed to incorporate uncertainty into decisions about cropping patterns. For this reason, response surfaces for yields, production and net farm return were fitted to provide a more compact representation of the model's results over a range of conditions found in the midwest. Since an orthogonal factorial design was used to specify the simulations used to fit the response surfaces, it is possible to determine the relative importance of individual agro-climatic and economic variables and their interactions in explaining yields, production, and net return.

There are two objectives of the research reported in this paper. The first objective is to determine whether agro-climatic variables, such as rainfall and temperature, are more important than economic variables (the prices of crops) in explaining the variability of production and net return over the ranges of values observed for these variables in the Midwest. The second objective is to extend the estimation of the response surfaces to cover a wider range of temperature and precipitation, and to predict the effects of projected changes in climate developed for the Intergovermental Panel on Climate Change (IPCC) on grain production in the Midwest.

2. Generating Data for the Response Surfaces

A general approach to approximating a complex model is to generate output values for different input configurations, and then to use regression techniques to fit response surfaces (Morgan and Henrion). Methods differ by the procedure used to determine values of the inputs. Three alternative designs are 1) Pseudo Data Technique (Griffin 1877, 1978, and 1982; Hertel et al.), 2) Factorial Designs (Box et al.; Montgomery; Myers), and 3) Latin Hypercube Designs (Iman and Conover; Mckay et al.; Welch et al.). The pseudo data technique is a one-factor-at-a-time design in which one variable is varied incrementally holding all others constant. A complete factorial design, on the other hand, is a design in which all possible combinations of the levels of the inputs are investigated. The Latin hypercube is a sampling procedure in which inputs are selected randomly from a factorial design.

The pseudo data technique gives direct estimates of the marginal effects of each input, but it ignores interactions among inputs (e.g., higher temperature may decrease yields, but coupled with higher precipitation, may increase yields). Factorial designs and Latin hypercube allow for estimates of main effects and interactions. Factorial designs exhibit orthogonality, and, therefore, make it possible to partition the explained variability of the regression among input variables and the interactions, but the number of runs required increases rapidly as the number of factors and factor levels increases. Therefore, a two-level design is often used in applications, even though it is inadequate for estimating the shape of the surface. A Latin hypercube requires fewer observations, but does not automatically preserve orthogonality. It provides better information about surface shapes, but is less suitable for assessing the relative importance among variables. Since the first objective of this research is to assess the relative importance of variables, a two-level factorial design was chosen for the analysis.

The nine input variables used in the analysis include four climate variables (temperature, solar radiation, average precipitation, and precipitation variability), one agronomic variable (soil), and four economic variables (prices of maize, soybean, sorghum, and wheat). For this design, a total of 512 (2^9) observations were generated.[1] The high and low values for the agro-climatic variables were determined from observed ranges of values in the midwestern United States (Table 1) to ensure that the design encompasses typical conditions for this region. The high and low values for the economic variables were specified by increasing and decreasing the average values by the same percentage (± 25%) for the four crop prices. The resulting ranges are approximately 1.5 times the standard deviations observed for prices for the period 1970 to 1990. Due to the orthogonal design, however, these prices have more potential explanatory power than they would in reality when they are positively correlated. The agro-climatic and economic input values were used to simulate the yield of cultivars, production by crop, and net return.

The data are generated by running the climatic-agronomic-economic models in a sequence. First, the climatic component generates daily values for minimum and maximum temperature, precipitation, and solar radiation. These three outputs plus soil characteristics are inputs into the agronomic component that determines grain yields and moisture content for a set of different cultivars, and field time (i.e., the amount of time permitted by the weather for field operations). These variables in turn become inputs in the economic component, which determines the choice of cultivars, the allocation of acreage among these cultivars, and net return for a given set of crop prices. The yields generated by GAPS represent an ideal maximum for a given soil and set of meteorological conditions. Consequently, yields are scaled down in applications to represent actual experience at a selected site. For this research, different scaling

[1] A single observation required simulating 30 growing seasons for 27 cultivars and took over three hours on a 486 machine. In this study, the term "cultivar" is defined to include information about the planting and harvesting dates as well as the variety of a crop.

factors are specified for the high and low temperatures[2] (see bottom of Table 1) using the values derived by Kaiser et al. (1995) for Lincoln, Nebraska and Redwood Falls, Minnesota. Due to the flexibility provided by the integrated model, both agronomic adaptations (changing cultivars and planting and harvest schedules) and economic adaptations (switching crops) can be considered explicitly.

3. Statistical Properties of the Design Model

The design includes 32 different sets of values for the five agro-climatic variables (2^5) and 16 sets for the four economic variables (2^4). There are ten possible pairwise interactions (C_2^5) among the agro-climatic variables, 6 (C_2^4) among the economic variables, and 20 interactions between the two groups of variables (4×5). In total, the model has 46 variables (an intercept, 9 main effects and 36 pairwise interactions) and 512 observations (32×16). To simplify the way inputs are represented, the low level and the high level for each input are coded to be 1 and -1, respectively. The full model in matrix notation can be written as follows:

$$Y_{512\times1} = X_{512\times46}\beta_{46\times1} + U_{512\times1}$$

where $E(U) = 0$ and $Var(UU') = \sigma^2 I_{512}$. Due to the orthogonal design , the matrix (X'X) is diagonal and equals $512 \times I_{512}$. The OLS estimator is:

$$\hat{\beta} = (X'X)^{-1}X'Y = \frac{X'Y}{512},$$

and the total sum of squares can be partitioned into:

$$Y'Y = \hat{\beta}'X'X\hat{\beta} + \hat{U}'\hat{U} = 512\hat{\beta}'\hat{\beta} + \hat{U}'\hat{U},$$

---

2 Temperature is important because it sets the length of the growing season in the model (specifying a high average temperature corresponds to increasing the temperatures in all months). Clearly there are an infinite number of ways of specifying weather patterns for a growing season. An advantage of using a stochastic weather generator is that weather patterns can be characterized by relatively few parameters.

where $\hat{U} = Y - X\hat{\beta}$. This demonstrates the key feature of using an orthogonal design. Since the matrix (X'X) is diagonal, the explained variability of the regression is uniquely partitioned among the individual regressors. This is not true with observed levels of the variables because they are generally correlated together in some way. Under normality, standard F tests can be used to determine whether sets of effects are zero.

4. Comparing Agro-Climatic and Economic Effects

The final output variables from the integrated model include the scaled yields of individual cultivars, the acreages for cultivars selected, and net return. Net return is part of the objective function in the economic component, and is directly observable in the solution set. Production is computed by multiplying the yield of each cultivar with the corresponding acreage. However, the yield representing a particular crop, or the best yield, depends on which cultivars are selected in the solution of the economic model. When none of the cultivars for a crop are selected, the observation on best yield is missing. To compute missing observations, the average acreages of cultivars in the complete set of solutions are used as weights for calculating the best yield whenever a crop is not selected in the economic component of the model.

The optimal solutions for acreage (and production) by crop include many corner solutions. Most of these occur when one or more crops are not selected, but in a few cases, the entire acreage is allocated to a single crop. The existence of corner solutions implies that the standard Ordinary Least Squares (OLS) estimator of the statistical model is biased. Although appropriate two-tail Tobit models have been developed to analyze these data, an associated problem is that the orthogonal structure of the design is lost (see Li 1995). Consequently, the explained variability of acreage and production by crop can not be assigned uniquely to individual regressors. To circumvent this problem, average production for the four grains is used as an alternative dependent variable. This variable is measured in terms of volume (bushels), weight and calories.

The Best Yield, Average Production and Net Return were analyzed using the model specified in Section 3. The results are shown in Tables 2 and 3. Due to the orthogonal design structure, the total variability for these variables is uniquely allocated among the main effects for agro-climatic and economic variables and the two-way interactions. To simplify the presentation, three groups of two-way interactions are defined. Since the fits of the models for Average Production are relatively poor, three-way interactions were added in Table 3.

The OLS results for Best Yield in Table 2 show that temperature is the dominant variable for soybean, sorghum and wheat. (Soil is also important for wheat.) For maize, however, precipitation and the water-retention capacity of the soil are important. In addition, the interactions among precipitation, soil and temperature are also important for maize. For Best Yield, as expected, the economic variables contribute very little to the fit of the model. This is confirmed by the small computed F statistics for testing that the 6 economic main effects and the associated 26 interactions are all zero (see Table 2).

For Net Return, the main effect for temperature is the largest but, as expected, the effects of the economic variables are more important than they are for Best Yields. Since sorghum is the least sensitive of the four crops to adverse weather conditions, it is typically selected when agro-climate conditions are bad, regardless of price levels. Therefore, Net Return depends strongly on the price of sorghum. The F statistic for testing whether the economic effects and the associated interactions are zero is over 31 compared to a critical value of 1.7 at the 1% level of significance. In this case, the null hypothesis that the economic effects are zero is rejected.

The results for the three measures of Average Production are similar to each other but different from those for Net Return. While temperature is still the most important variable for Average Production, other effects also matter, soil and precipitation among the agro-climatic variables and the price of maize among the economic variables. In addition, agro climatic two-way interactions and three-way interactions contribute to the fit, and in general, interactions are more important than they are in the other models. In spite of including three-way interactions, a larger portion of the variability is unexplained for Average Production than for Net Return (or Best Yields). This may imply that the model's results are more complex in structure for Average Production. Consequently, results can not be explained simply in terms of main effects and second-order interactions. Third-order interactions matter, and higher-order interactions may account for part of the unexplained variability.

While the range of values selected for the input variables is adequate to address the first objective of this paper, scenarios used by other studies on climate change typically involve more extreme temperatures and precipitation. Furthermore, a comparison of results with other studies in a separate paper (Li et al.) shows that it may be important to allow for non-linear responses when evaluating conditions under a warmer climate. For this reason, the analysis was extended to estimate response surfaces over wider ranges of temperature and precipitation for a given soil (The results in this paper imply that the effects of other agro-climatic variables are relatively unimportant.).

5. Specifying Temperature and Precipitation under Climate Change

Three IPCC (Inter-governmental Panel for Climate Change) climate scenarios are illustrated in Figure 1. The values at point BP are treated as the Base, representing the current climate for the Midwest.[3] The three IPCC scenarios are based on GCM (General Circulation Model) simulations assuming that greenhouse gases will double by 2050 (Greco, Moss, Viner, and Jenne).[4] Predicted values of temperature and precipitation for given longitude and latitude are available over the InterNet for the Geophysical Fluid Dynamics Laboratory Model (GF), the Max Planck Institute Model (MP) and the UK Hadley Center Model (UK). The values for temperature and precipitation used to generate data for the analysis in Section 3 (Table 1) reflect relatively small differences compared to Figure 1.[5] Data were generated for Best Yield, Average Production, and Net Return at each of the 25 grid points in Figure 1.[6] For these runs, other agro-climatic variables (except for soil) were held at the average level. Two separate data sets were produced, one for each type of soil.

The three projections of higher temperatures in Figure 1 are similar to each other, with the UK model giving the largest increase. The projected changes in

[3] The values at Point BP are determined by averaging the values for temperature and precipitation observed in Redwood Falls, MN and Lincoln, NB (a temperature of 16.44°C and precipitation of 71.71 mm).

[4] The GCM predictions of the "current" decade are inconsistent with the Base values (16.44 ^{0}C and 71.71 mm per month) used in this study. Furthermore, the variability among different GCM results is larger than the variability through time within each GCM. Coarse grid resolution is always a problem with GCM's, and probably accounts for the differences in predictions. For this research, the GCM results are normalized so that the predicted temperature and precipitation for the "current" decade are equal to the Base values.

[5] The origin in Figure 1 corresponds to the mean of the original design (all variables set to zero). The "high" temperature in Table 1 is one grid point up from the origin in Figure 1, and the "low" precipitation in Table 1 is two grid points to the right of the origin in Figure 1. In the original design, temperature and precipitation both ranged from -1 to +1, and in the new grid, temperature ranges from 0 to +4 and precipitation from 0 to -2.

[6] Due to its tolerance to heat and drought, sorghum dominated production throughout the grid when the prices were set at the average values, making the analysis uninteresting. Therefore, a modified set of prices was specified to ensure a realistic mix of crops at the Base point.

precipitation are all relatively small.[7] For this reason, another more extreme scenario is defined (Worst Case; WC) in which the climate gets substantially drier as well as warmer. The results for this latter scenario are much more ominous than they are for the other three scenarios.

6. Response Surfaces for Climate Change

The 25 observations for the grid in Figure 1 were used to fit a response surface for Best Yields, Average Production and Net Return in terms of temperature and precipitation using a third-order polynomial model.[8] The fitted polynomials were then used to generate 3-dimensional surfaces (Figure 2). The vertical axes in Figure 2 measure the percentage differences from the value at the Base. (The range is from -100% to +50% for all plots.) Since the surfaces for both types of soil exhibit similar behavior, only those for the good soil (Ves) are presented.[9]

The 3-dimensional plots reveal that the yield of maize is sensitive to both temperature and precipitation. The yield increases initially with temperature but then decreases. The maximum yield is 38% above the Base. The adverse effects of less precipitation are initially small but become more severe as it gets drier. For example,

---

7 The direction of the axis for precipitation in Figure 1 is reversed from the implied direction in Table 1. The reason for this is that the convention used in Figure 1 (moving to the right implies less precipitation) makes it easier to interpret the three-dimensional surfaces shown in Figure 2.

8 If t and p denote temperature and precipitation, the third-order polynomial model is $y_t = \beta_0 + \beta_1 t + \beta_2 p + \beta_3 tp + \beta_4 t^2 + \beta_5 p^2 + \beta_6 t^2 p + \beta_7 tp^2 + \beta_8 t^3 + \beta_9 p^3$. The fit of the model is quite good for the four Best Yield and for Net Return (more than 95%) and satisfactory for Average Production (80% for the bad soil and 89% for the good soil). For all 25 observations, the scaling factors for high temperature (see Table 1) were used. Efforts to merge the 25 new observations with the 512 original observations were unsuccessful (the null hypothesis of identical models was rejected using a standard F test). This result was attributed to the effects of using two sets of scaling factors in the original design.

9 To provide additional information about the role of agronomic adaptation to climate change, one set of runs was conducted with all cultivars as possible choices, while another included only the dominant cultivar for each crop at the Base for all grid points. However, as the climate becomes warmer and drier, the cropping patterns quickly switch to one cultivar of sorghum, and the differences between the two sets of runs are small. Therefore, only the results for multiple cultivars are presented.

as precipitation decreases by 40 mm from the left axis in Figure 1 (highest precipitation), the decrease in yield is 30%. However, as it drops by an additional 20 mm, the yield decreases by another 40%.

The yield of soybean is sensitive to temperature, but relatively insensitive to precipitation. Like maize, the yield initially goes up and then goes down as temperature increases. Unlike maize, however, the yield of soybean is relatively insensitive to changes of precipitation. In fact, the maximum yield (21% above the Base) occurs under drier conditions than the Base. As expected, the minimum yield (17% below the Base) happens under the hottest and driest conditions.[10]

Sorghum is relatively insensitive to temperature and precipitation. The yield is quite stable within the entire grid, and ranges from 3% above the Base to 12% below it. Wheat, like maize, is sensitive to precipitation, especially under the driest conditions. The yield does not vary much when precipitation is more than 30 mm below the base, but decreases drastically below that level. Wheat is, however, less sensitive to temperature than maize.

The patterns of Average Production and Net Return are more complex because it reflects the interactions between agro-climatic and economic forces. Variability in production can be caused by either changes in yield (agro-climatic effect) or cropping pattern (economic effect). To understand this behavior, it is helpful to divide the surface plots into three sections by precipitation: normal precipitation (20 mm above the Base to 10 mm below the Base), low precipitation (10 mm to 30 mm below the Base), and drought (30 mm below the Base or less). Under normal precipitation, production consists of mostly maize, and Average Production is similar to that of maize. Under low precipitation, production is a mixture of wheat and sorghum. Since wheat and sorghum have lower yield than maize, Average Production decreases. Under drought, Average Production decreases further because of the adverse effects of

[10] These differences appear to be small in Figure 2 because the vertical scale is the same as it is for maize.

increased dryness on wheat. However, it then increases due to a crop-shift from wheat to sorghum, which has higher yields than wheat.

Net Return is primarily determined by the yield of maize for the normal precipitation region. Like maize, the peak level (45% above the Base) happens at around +1.5 °C and +25 mm. However, as the yield of maize declines with drier conditions, the cropping pattern changes, first to wheat and then to sorghum. This change, motivated by profit maximization, generates a higher Net Return than continuing with the same crop. This is evident by comparing the relatively gradual decline in the Net Return compared to the steeper decline for Best Yield of maize.

7. A Comparison with Other Studies

A common implication of other studies of global warming is that overall agricultural productivity will decrease in middle-latitude countries (such as the United States) and increase in higher-latitude countries (such as Canada and Russia) under the climate warming induced by a doubling of greenhouse gases. For example, according to Kane et al., a 3.71 °C increase in the median temperature in the summer months will reduce average yields in the United States for maize, soybean, and winter wheat by 23.8%, 34.6%, and 16.0%, respectively.

At the national level, Rosensweig et al. and Adams et al., estimated the yield effects of climate change for different regions of United States through simulations of crop models. In another study, Kaiser et al. (1993) examined farmers' adaptability under three scenarios of climate change for a southern Minnesota farm using the same basic model as the one used for this research. The different specifications for climate change in these three studies are summarized in Table 4. The levels of temperature and precipitation are well within the ranges of the grid in Figure 1 except for the increase of precipitation specified in Rosensweig I. The estimated response surfaces described in Section 6 can be used to predict Best Yields, Net Return, and Average Production using the changes of temperature and precipitation specified in the three studies. In all cases, the initial levels of temperature and precipitation are set at point BP. Consequently, the predicted changes of the dependent variables are defined consistently and represent the effects of climate change in the specified scenarios using the same model (response surface) and the same initial conditions. (When comparing the original studies, the predicted changes are derived from different models for a variety of different locations in the Midwest.) Given the non-linear shapes of the response surfaces, it is important to note that differences in the predicted effects of a scenario between the response surface and the original study may be caused by differences in the initial conditions as well as by differences in the characteristics of the models.

The results are consistent with those of Kaiser et al. (1993) for the yield of soybean (Table 5). The discrepancy for the yield of sorghum is due to updating the version of the sorghum model used in GAPS. However, the predictions for the yield of maize appear to be anomalous because one would expect that the effects of a warmer climate would be less serious in a cooler region (i.e. Minnesota) compared to the Average Midwest. The explanation relates to the specifications made about the length of the growing season. In this study, a longer growing season is specified and this in turn implies that a wider array of late maturing cultivars of maize can be grown successfully. The predicted increases in Net Return are small in all scenarios compared to Kaiser et al. In this study, however, prices are held constant, and in Kaiser et al.'s study a supply response is incorporated. In general, the rankings of the variables for the three scenarios are consistent in the two studies.

The results from this study are quite different from with those in Adams et al.'s and Rosensweig et al.'s studies (Table 6 and Table 7). A fundamental difference is the way that yield responds to precipitation in a warmer climate. In Adams et al., yield is much lower under Scenario II (warmer and drier) than under Scenario I (warmer and wetter). The implication is that yield is very sensitive to moisture levels under a warmer climate. In contrast, the results of this study show that yields (except for maize) are relatively insensitive to precipitation differences over the range observed in the midwest. Furthermore, the difference in precipitation used by Adams et al. is quite small compared to the observed range for the Midwest (compare Table 1 and Table 4). This type of sensitivity of yields to precipitation would be exhibited by the response surfaces for maize and wheat if the initial conditions at the Base BP were much drier (see Figure 2).

There appears to be no simple explanation for the differences between this study and Rosensweig et al. (Table 7) . Yields decrease in Rosensweig et al. in all scenarios, even when precipitation increases (Scenarios I and III). In contrast, the yield of maize increases in this study in Scenarios I and III and decreases in Scenario II. The yield of soybean increases in all three scenarios, and the yield of wheat increases in Scenario I and decreases in the other two scenarios.

The basic features of the results in Rosensweig et al. are that higher temperatures generally have adverse effects on yields and the effects of precipitation are relatively modest. The opposite is the case in Adams et al. In this study (and Li et al.), a modest increase in temperature is generally beneficial unless it is associated with a substantial decrease in precipitation, and in this latter situation, the increased sensitivity of yields to precipitation would be compatible with Adams et al. but not with Rosensweig et al.

8. Predictions Based on the IPCC Scenarios

Using the four different scenarios of climate change described in Figure 1, the overall effects on Best Yield, Average Production and Net Return are summarized in Table 8. For GF, the yield of maize increases for the next eighty years. The increase is large for the first thirty years but levels off from that point onward. Initially the rise in temperature and small decrease in precipitation are beneficial for maize, but as temperature continues to increase, these beneficial effects diminish. The UK scenario is beneficial for maize during the first decade due to increases in temperature. However, as temperature increases further and precipitation falls, the yield starts to decrease. It increases again after 2030 when precipitation begins to rise. For MP, the yield is unaffected for the first ten years, probably because the positive effects of higher temperature are offset by the negative effects of lower precipitation. However, it goes down after 2000 as rainfall continues to decrease. Under WC, the yield of maize goes down substantially after 2010 and is reduced by 50% by 2040.

The yield of soybean increases throughout the eight decades under both the GF and MP climate change scenarios. The increases are large initially and get smaller toward the end. Under the UK scenario, soybean yield increases even more in the first three decades, but then decreases. This is not surprising, since the temperature increase for UK is much larger than it is for GF or MP. Under the WC scenario, soybean yields increase for the first three decades, but decrease thereafter. The reduction from the Base is over 15% by 2060.

Sorghum yields for the GF and MP scenarios show little change over the entire eight decades. The increases in temperature implied in the two models are too small to have a large impact on sorghum. In addition, sorghum yields at the end of the simulation period for the GF and MP scenarios are similar, even though the precipitation levels are different. This is due to sorghum being relatively insensitive to precipitation. The yield for the UK scenario shows a larger decrease than the yield for the GF and MP scenarios due to the relatively large increase in temperature for UK, and for the same reason, the final yield for WC shows an even larger decrease than it does for UK.

The predicted effects on the yield of wheat are similar and relatively small for all three GCM's. In these cases, the yield first increases and then decreases. While the maximum yield is observed in 2020 for GF and MP, it comes sooner for UK. In contrast, yield decreases substantially under WC because of the reduced precipitation.

The composition of production at the Base is 80% maize, 5% soybean and 15% wheat. As temperature increases and precipitation remains stable in GF, the growing conditions become more and more favorable for maize, causing the cropping pattern to shift even more towards maize. Since maize is more productive than wheat, the shift translates into increased Average Production for GF (25% above the Base by 2060 in Figure 3).

The increase in temperature in UK, which benefits maize initially, causes the cropping pattern to shift toward maize. However, the negative effects of decreased precipitation soon become more important, and then production falls. As precipitation decreases further, more acreage is allocated to wheat. As a result, Average Production falls. However, when precipitation in UK starts to increase, maize becomes the dominant crop again, and Average Production for UK goes back up to over 15% above the Base in 2060 (see Figure 3).

MP predicts the lowest precipitation among the three IPCC scenarios. The drier climate implied by MP has two different negative effects on production over time. First, it causes the yields of maize and wheat to decrease. Second, more land is diverted from maize to wheat. As a consequence, Average Production under the MP scenario in 2060 is almost 15% below the Base (see Figure 3).

Average Production under WC decreases for the first six decades but increases in the last decade. While the same pattern is also predicted by UK, the underlying reasons are quite different. Since WC is the warmest and driest scenario, the switch from maize to wheat occurs quickly, causing large initial reductions of Average Production. In the last decade, a switch to sorghum results in increased Average Production.

While the direction of changes in Average Production are different, depending on the scenario used, Net Return is shown in Figure 3 to be less sensitive to climate change than Average Production for the three IPCC scenarios. Under these scenarios, Net Return generally remains above the Base due to crop switching. Average Production is influenced by the negative yield effects of a drier climate, as well as switching land from maize to wheat. For Net Return, switching from maize to wheat, a higher priced crop, provides a cushion for Net Return that compensates for the lower yield of maize under drier conditions. However, the effect of WC is catastrophic. Under extremely dry conditions, sorghum becomes the dominant crop. This keeps Average Production up, because sorghum has high yields, but decreases Net Return because sorghum has a much lower price.

An important conclusion of this analysis is that decreased precipitation poses a much bigger problem than increased temperature. For the three IPCC scenarios, Net Return only falls below the Base (2020 to 2040 for UK, and 2040 to 2060 for MP) in the driest periods. In fact, the analysis shows that a moderate increase in temperature is generally beneficial (as in GF), as long as it is not accompanied by decreases in precipitation (as in MP). Nevertheless, the modest changes in precipitation predicted by the three IPCC scenarios may hide the real danger. A relatively small additional decrease in precipitation has major adverse effects. Even with sorghum as the dominant crop in WC, Average Production in 2060 is only two-thirds of the level at the Base, and Net Return is reduced by almost one half.

Conclusion:

This paper describes the performance of an integrated climatic-agronomic and economic model of grain production in the Midwest, which has been used extensively to study the effects of gradual global warming on the production and yields of maize, soybean, sorghum and wheat (e.g. Kaiser et al. 1993 and 1995). The model contains considerable detail about the growth of individual cultivars under specified climate conditions, and about the choice of an appropriate cropping pattern to meet economic and management criteria.

The first part of the analysis uses an experimental design approach to generate data for evaluating the relative contributions of climatic, agronomic and economic variables to explaining the variability of the outputs (e.g. yields and net return). Given the orthogonal design, total variability can be partitioned uniquely among the individual regressors. For yields, as expected, economic variables are not important. Temperature is the dominant variable for the yields of soybean, sorghum and wheat. Soil and precipitation are both important for the yield of maize. For net return and average production, temperature is the most important variable, but economic variables and interactions also contribute. For production, the price of maize is the most important economic variable because the yield of maize is generally high compared to the yields of other crops. For net return, the price of sorghum is the dominant economic variable because sorghum is the only crop that can tolerate the most adverse climatic conditions.

The second part of the analysis extended the ranges of temperature and precipitation considered (holding other variables constant) and fitted response surfaces for yields, average production and net return. These results show that the yields of maize and to a lesser extent wheat are adversely effected by lower precipitation. The yields of soybean and sorghum are relatively insensitive to precipitation over the range specified. With high precipitation, maize dominates the cropping pattern. Under drier conditions, wheat substitutes for maize, and finally, under the driest conditions, sorghum is the dominant crop. Increasing temperature generally increases yields initially and then decreases yields. This phenomenon is also exhibited by average production and net return, and for these variables, lowering precipitation has much larger adverse effects than increasing temperature.

A comparison of the predicted effects of specified changes in climate was made with the studies by Kaiser et al., Adams et al. and Rosensweig et al. Since the models are essentially the same, the results from this study can be reconciled with the results of Kaiser et al. In contrast, the results in this study differ from the results of Adams et al. and Rosensweig et al. In this study, yields are much less sensitive to lower precipitation than they are in Adams et al., and yields are less adversely affected by higher temperatures than they are in Rosensweig, et al.

The effects of three IPCC scenarios for climate are evaluated together with an extremely dry and hot scenario. Two of the three IPCC scenarios show generally positive effects on grain production (+25% and +16%), and in particular, on the yield of maize (+17% and +12%). The other IPCC scenario shows moderate negative effects on production (-14%) due to a lower yield of maize (-5%). In contrast, the Worst Case shows a 34% reduction in production (and an 88% reduction in the yield of maize). The main reason for these different results is the assumption made about precipitation. The relatively positive conclusion for the IPCC scenarios are conditional on the assumption that higher temperatures are not associated with lower precipitation. In particular, the non-linearity of the response surfaces for the yields of maize and wheat is important. If the climate conditions are extended beyond the range observed in the Midwest, results are very sensitive to the assumptions about precipitation. Under dry conditions, relatively small changes in precipitation have substantial effects on the yields of maize and wheat, and therefore, on grain production compared to the corresponding effects under current conditions. Although there is general agreement among different climate models about temperature increases, even the direction of change of precipitation for a specific location is uncertain. This uncertainty about changes of precipitation presents a major limitation in our ability to understand the potential effects of climate change on grain production.

References

Adams, R.M., C. Rosensweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen, Jr. "Global Climate Change and US Agriculture." *Nature* 345(6272):219-24, 1990.

Box, G.E.P., W.G. Hunter, and J.S. Hunter. *Statistics for Experimenters*, John Wiley & Sons, 1978.

Brink, L., and B. McCarl. "The Tradeoff Between Expected Return and Risk Among Cornbelt Farmers." *Amer. J. of Agr. Econ.* 60:259-63, 1978.

Butler, I.W., and S.J. Riha. "GAPS: A General Purpose Simulation Model of the Soil-Plant-Atmosphere System." *Version 1.1 User's Manual*, Department of Agronomy, Cornell University, 1989.

Crosson, P., L. Katz, and J. Wingard. "The MINK Project, Report IIA, Agricultural Production and Resource Use in the MINK Region without and with Climate Change." TRO52C, DOE/RI/01830T-H7, Department of Energy Carbon Dioxide Program: Washington DC, 1991.

Doane's Facts and Figures for Farmers, Doane Agricultural Service Inc., St. Louis MO, 1972.

Griffin, J.M. "Long-run Production Modeling with Pseudo-Data: Electric Power Generation." *Bell Journal of Economics* 8:112-27, 1977.

Griffin, J.M. "Joint Production Technology: The Case of Petrochemicals." *Econometrica*, 46: 379-96, 1978 .

Griffin, J.M. "Pseudo Data Estimation with Alternative Functional Forms." *Advances in Applied Microeconomics* Vol. II, JAI Press, 1982.

Hazell, P.B.R. "A Linear Alternative to Quadratic and Semivariance Programming for Farm Planning Under Uncertainty." *Amer. J. of Agri. Econ.* 53:153-62, 1971.

Hertel, T.W., and P.V. Preckel. "Approximating Linear Programs with Piecewise Linear Summary Functions: Pseudo Data with an Infinite Sample." *Staff Report*, Department of Agricultural Economics, Purdue University, No. 86-7, 1986.

Iman, R.L., and W.J. Conover. "Small-Sample Sensitivity Analysis Techniques for Computer Models." *Communications in Statistics-Theory and Methods* A9, 1749-1874, 1980.

Kaiser, H.M., S. Riha, D. Wilks, D.G. and R. Sampath. "Potential Implications of Climate Change for U.S. Agriculture." Economic Research Service Report. USDA, forthcoming 1995.

Kaiser, H.M., S. Riha, D. Wilks, D.G. Rossiter and R. Raman. "A Farm-level Analysis of the Economic and Agronomic Impacts of Gradual Climate Change." *Amer. J. of Agr. Econ.* 75:387-98, 1993.

Kane, S., J. Reilly, and J. Tobey. "Climate Change: Economic Implications for World Agriculture." *AER-No. 647*, US Department of Agriculture, Economic Research Service, Washington DC, 21 pp., 1991.

Katz, R.W. "Assessing the Impact of Climatic Change on Food Production." *Climate Change* 1:1, 1977.

Katz, R.W. "Probabilistic Models." Probability, Statistics, and Decision Making in the Atmospheric Sciences. A.H. Murphy and R.W. Katz, eds. Boulder, CO: Westview Press, 261-88, 1985.

Li, Z. "Climate Change and US Agriculture: An Integrated Assessment of Grain Production." *Unpublished Ph.D. Dissertation*, Cornell University, 1995.

Li, Z., T.D. Mount, H.M. Kaiser, S.J. Riha, D.S. Wilks and R. Sampath."Modeling the Effects of Climate Change on Grain Production in the US: An Experimental Design Approach." Department of Agricultural Economics, Cornell University, Working Paper 95-5, 1995.

Maddala, G.S., and R.B. Roberts. "Statistical Cost Analysis Revisited: Comment." *Quarterly Journal of Economics* 96:177-82, 1981.

Maddala, G.S., and R.B. Roberts. "Alternative Functional Forms and Errors of Pseudo Data Estimation." *Review of Economics and Statistics* 62:323-27, 1980.

McKay, M.D., W.J. Conover, and R.J. Beckman. "A comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output From a Computer Code." *Technometrics* 21:239-245, 1979.

Mendelsohn, R., W.D. Nordhaus, and D. Shaw. "The Impact of Climate on Agricultural: A Ricardian Approach." *Cowles Foundation Discussion Paper* No. 1010, 1992.

"Minnesota Agricultural Statistics 1985." St. Paul MN, Crop and Livestock Reporting Service.

Moen, T.N., H.M. Kaiser, and S.J. Riha. "Regional Yield Estimation using a Crop Simulation Model: Concepts, Methods and Validation." *Agricultural Systems* 46:79-92, 1994.

Montgomery, D.C. *Design and Analysis of Experiments*, 2nd Ed. John Wiley and Sons, 1984.

Myers, R.H.. *Response Surface Methodology*, Allen and Bacon, Inc., 1971.

Nebraska Agricultural Statistics 1986, Lincoln, Nebraska Crop and Livestock Reporting Services.

Richardson, C.W., and D.A. Wright. "WGEN: A Model for Generating Daily Weather Variables." *ARS-8*, United States Department of Agriculture, Agricultural Research Service, August 1984.

Richardson, C.W. "Stochastic Simulation of Daily Precipitation, Temperature, and Solar Radiation." *Water Resources Research* 17:182-90, 1981.

Rosensweig, C., M. Parry, G. Fisher, and K. Frohberg. *Climate Change and World Food Supply*. Environmental Change Unit, Oxford University, 1993.

Thompson, L. "Weather and Technology in the Production of Wheat in the US." *Journal of Soil and Water Conservation*, 24:1969.

Thompson, L. "Weather and Technology Effects on Corn Production." *Agronomy Journal*, 61: May 1969.

Thompson, L. "Weather and Technology in the Production of Soybean in the Central US." *Agronomy Journal* 62, March 1970.

Watt, B.K., and A.L. Merrill. *Handbook of the Nutritional Contents of Food*, Agriculture Handbook (USDA), New York: Dover Publications, 8:1975.

Welch, W.J., R.J. Buck, J. Sacks, H.P. Wynn, T.J. Mitchell, and M.D. Morris. "Screening, Predicting, and Computer Experiments." *Technometrics* 34:15-25, 1982.

Table 1. Values for Input Variables and Scaling Factors

Input Variables	High	Low
Temperature (Celsius)	17.69	13.79
Soil Type	Ves	Dickman
Precipitation variability[1]	Large	Small
Precipitation (mm per month)	133.99	60.84
Solar ($MJ / m^2 \times day$)	19.28	18.00
Price of maize ($/bushel)	3.01	1.81
Price of soybean ($/bushel)	7.68	4.61
Price of sorghum ($/bushel)	4.86	2.92
Price of wheat ($/bushel)	4.18	2.51

Scaling Factors[2]	High	Low
Yield of Maize	92/186	120/184
Yield of Soybean	30/52	36.1/48
Yield of Sorghum	100/122	60.2/108
Yield of Wheat	55/83	35/86.2

[1] Defined jointly by p_{01}, the probability of a wet day following a dry day, and p_{11}, the probability of a wet day following a wet day. The values of p_{01} and p_{11} are 0.22 and 0.48 for the large variability, and 0.20 and 0.36 for the small variability. The two probabilities for the large variability always imply a larger variance of precipitation than those for the small variability for any given average level of precipitation.

[2] High corresponds to the high temperature (Lincoln, NE) and Low to the low temperature (Redwood Falls, MN). Each scaling factor corresponds to a ratio of yields in bushels per acre.

Table 2. Analysis-of-Variance for Best Yield and Net Return
(Allocation of Variability around the Mean in Percent)

	Maize	Soybean	Sorghum	Wheat	Return
Main Effects					
Temperature	2.02	71.47	94.45	67.59	53.98
Soil	37.61	0.06	0.02	14.47	0.67
Precipitation variability	0.28	0.16	0.08	0.06	0.19
Precipitation	33.87	0.07	0.00	5.08	0.54
Solar	4.31	1.73	3.37	0.14	0.93
Price of maize	0.02	0.04	0.00	0.04	1.02
Price of soybean	0.00	0.42	0.01	0.00	0.03
Price of sorghum	0.00	0.01	0.00	0.01	21.71
Price of wheat	0.00	0.07	0.01	0.00	0.14
Two-Way Interactions					
Agro-climatic (10)	12.72	0.78	0.32	4.35	3.35
Economic (6)	0.23	1.90	0.08	0.36	0.34
Cross (20)	0.33	0.39	0.01	0.06	10.73
Unexplained	8.61	22.92	1.65	7.85	6.36
Total	100.00	100.00	100.00	100.00	100.00
F statistic[3]	1.31	1.44	1.00	0.96	31.24

[3] Test statistics are obtained under the null hypothesis that prices have zero impact. The critical F-values at 5% and at 1% significance level are 1.46 and 1.70, respectively.

Table 3. Analysis-of-Variance for Average Production
(Allocation of Variability around the Mean in Percent)

	Volume	Weight	Calories
Main Effects			
Temperature	26.33	25.98	26.33
Soil	7.57	7.82	7.57
Precipitation variability	0.08	0.07	0.08
Precipitation	3.70	3.76	3.70
Solar	1.61	1.54	1.61
Price of maize	3.44	3.41	3.44
Price of soybean	0.60	0.56	0.60
Price of sorghum	0.86	0.73	0.86
Price of wheat	0.57	0.66	0.57
Two-Way Interactions			
Agro-climatic (10)	17.06	17.47	17.96
Economic (6)	1.22	1.22	1.14
Cross (20)	6.91	6.95	7.10
Three-way interactions (84)	8.13	8.06	7.94
Unexplained	21.93	21.76	22.93
Total	100.00	100.00	100.00

Table 4. Scenarios Used in Three Other Studies
(Changes from the Current Climate)

Studies		Temperature (°C)	Precipitation (mm)
Scenarios			
Kaiser	I	+2.50	+7.30
	II	+2.50	-7.30
	III	+5.00	-14.60
Adams	I	+4.32	+7.20
	II	+5.09	-2.40
Rosensweig	I (GISS)	+3.7	+35.86
	II (GF)	+3.8	-25.10
	III (UK)	+4.8	+8.61

GISS is Goddard Institute for Space Sciences;
GF and UK defined in Figure 1.

Table 5. A Comparison with Kaiser et al
(Percentage Change from the Base)

Studies	Kaiser et al.			This Study		
Regions	Minnesota			Average Midwest		
Scenarios	I	II	III	I	II	III
Yield						
Maize	0	-4	-11	22	8	-3
Soybean	14	16	12	15	17	16
Sorghum	15	16	7	0	0	-6
Wheat	N/A	N/A	N/A	0	4	-1
Production	N/A	N/A	N/A	35	6	-12
Return	139	173	173	29	12	-3

N/A - values not reported.

Table 6. A Comparison with Adams et al
(Percentage Change from the Base)

Studies	Adams et al. (mid-point values)						This Study	
Regions	Upper midwest		Central midwest		Lower midwest		Average Midwest	
Scenarios	I	II	I	II	I	II	I	II
Yield								
Maize	45	-15	15	-15	-15	-5	19	12
Soybean	45	5	25	-5	25	-5	15	14
Sorghum	N/A	N/A	N/A	N/A	N/A	N/A	-5	-6
Wheat	5	-25	5	-25	-5	-25	-3	-2
Production	N/A	N/A	N/A	N/A	N/A	N/A	32	14
Return	N/A	N/A	N/A	N/A	N/A	N/A	26	13

N/A - values not reported;
Upper midwest: Minnesota, Wisconsin, Michigan;
Central midwest: Iowa, Illinois, Indiana, Ohio, and Missouri;
Lower midwest: Kentucky.

Table 7. A Comparison with Rosensweig et al
(Percentage Change from the Base)

Studies	Rosensweig et al.						This Study		
Regions	Iowa			Nebraska			Average Midwest		
Scenarios	I	II	III	I	II	III	I	II	III
Yield									
Maize	-21	-27	-42	-22	-17	-57	18	-22	-19
Soybean	-7	-26	-76	-12	-18	-31	24	19	14
Sorghum	N/A	N/A	N/A	N/A	N/A	N/A	-2	-2	-6
Wheat	-4	-12	-15	-18	-36	-33	11	-3	-4
Production	N/A	N/A	N/A	N/A	N/A	N/A	3	-31	33
Return	N/A	N/A	N/A	N/A	N/A	N/A	28	-15	25

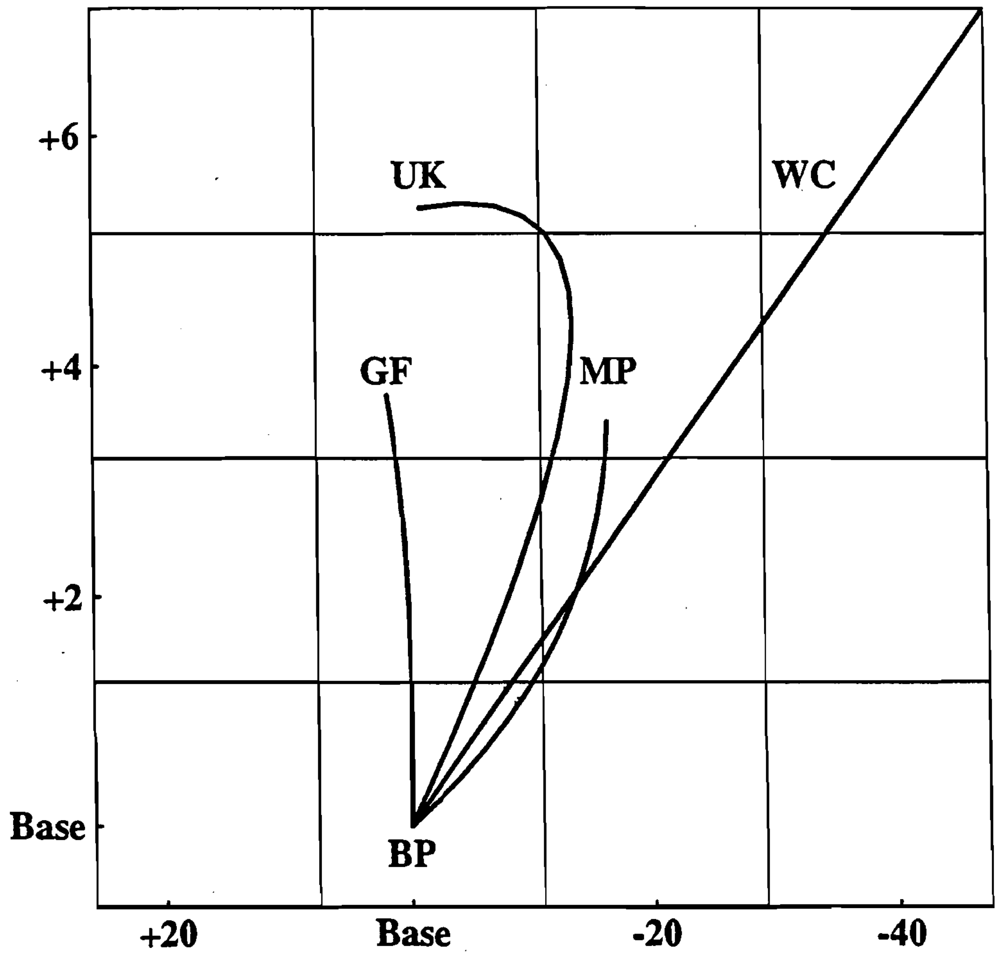
N/A - values not reported.

Table 8. Predictions for 2060 under Different Climate Scenarios: [a/]
(Percentage Change from 1990)

	GF	UK	MP	WC
	Multi-cultivars			
Best Yield				
Maize	17.27	12.08	-4.61	-88.50
Soybean	16.88	12.45	19.17	-16.13
Sorghum	-2.55	-7.12	-1.53	-12.04
Wheat	-0.18	-3.12	2.39	-54.94
Average Production	25.05	16.12	-14.10	-34.25
Net Return	22.30	13.91	-1.87	-46.59

[a/] The four scenarios are defined in Figure 1.

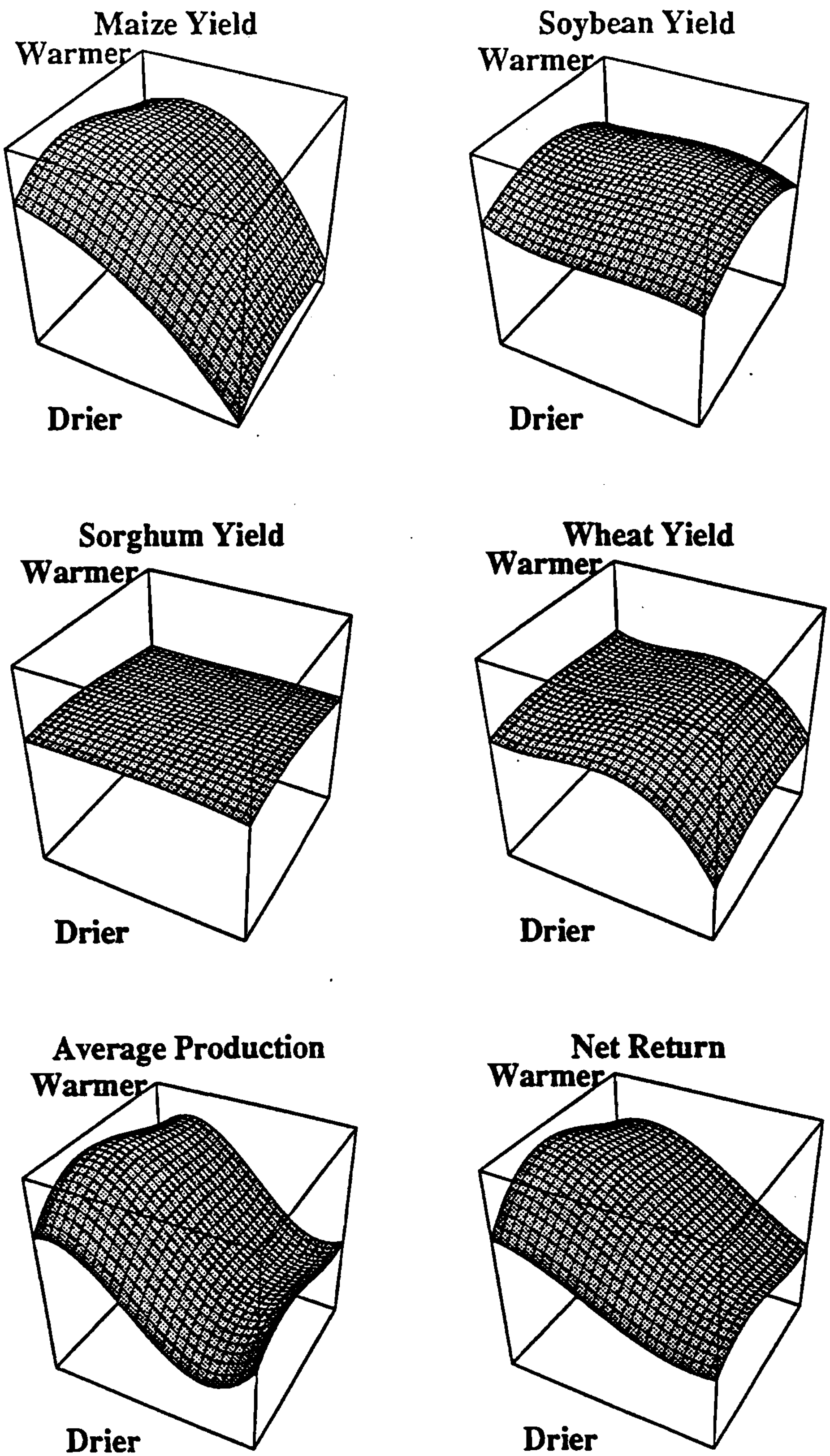
Warmer (Degrees Celsius)



Drier -> (mm of Precipitation)

BP - Base Point (16.44°C, 71.71mm)
GF - Geophysical Fluid Dynamics Laboratory
MP - Max Plank Institute
UK - United Kingdom Hadley Center
WC - Worst Case

Figure 1. Alternative Scenarios for Temperature and Precipitation



(The vertical scales are all +50% to -100% from the Base levels, and the horizontal axes correspond to the grid in Figure 2.)

Figure 2. Estimated Response Surfaces

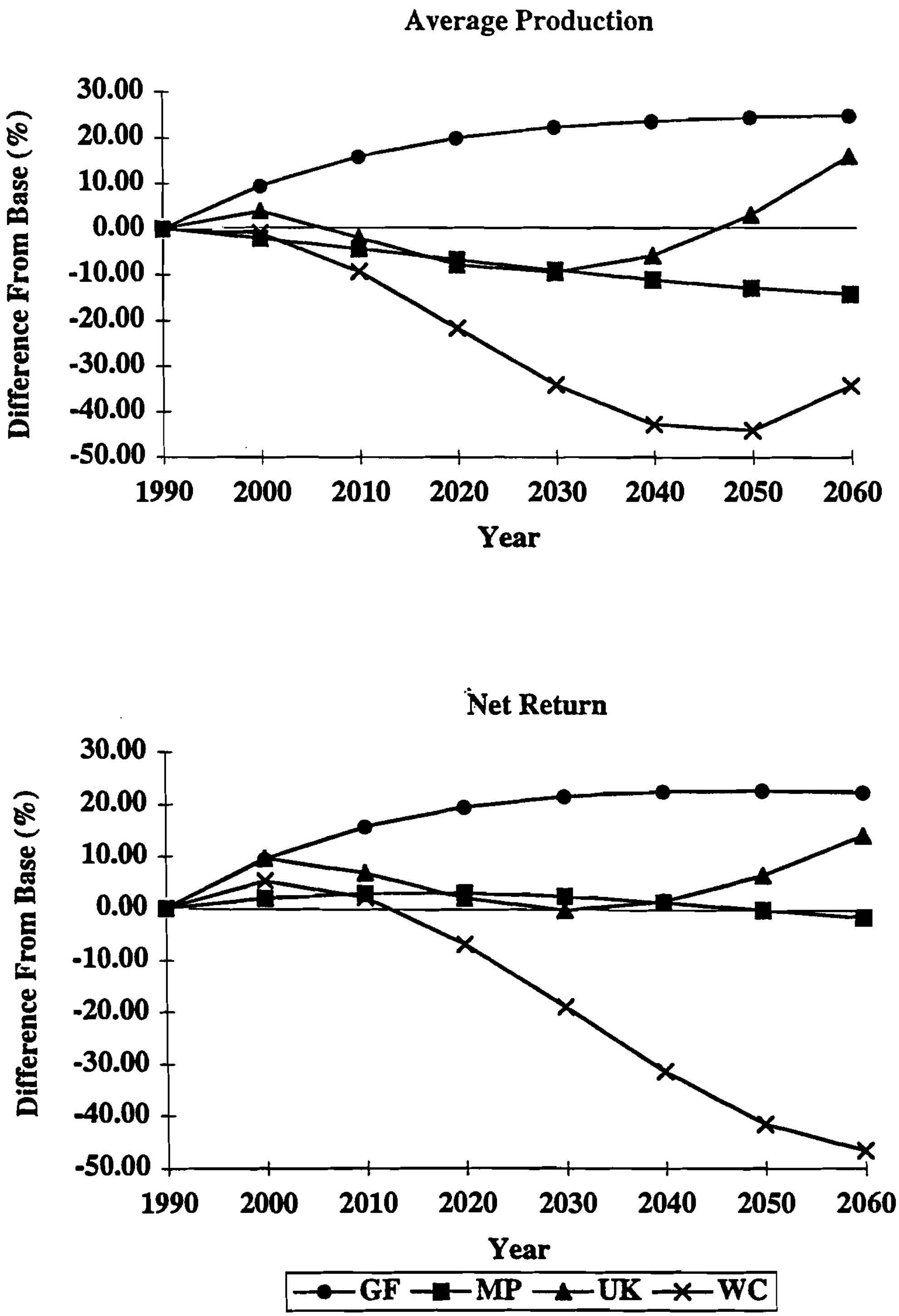


Figure 3. Average Production and Net Return under Alternative Climatic Scenarios

OTHER A.R.M.E. WORKING PAPERS

No. 95-06	Estimating the Organizational Costs of Managing the Farm	Loren W. Tauer
No. 95-07	Global Hunger: The Methodologies Underlying the Myth	Thomas T. Poleman
No. 95-08	On the Option Value of Old-Growth Timber: The Case of the Headwaters Forest	Jon M. Conrad
No. 95-09	Global Warming: When to Bite the Bullet	Jon M. Conrad
No. 95-10	Recent Trends in Food Availability and Nutritional Well-Being	Thomas T. Poleman
No. 95-11	Time Preference, Abatement Costs, and International Climate	Neha Khanna Duane Chapman
No. 95-12	Inequality and the Politics of Redistribution and Public Good Investments	Jo Swinnen Harry de Gorter
No. 95-13	The Kuznets Versus the Marx Pattern in Modern Economic Growth: A Perspective from the Japanese Experience	Yujiro Hayami and Junichi Ogasahara
No. 95-14	A New Algorithm for Computing Compensated Income from Ordinary Demand Functions	Jesus Dumagan Timothy Mount
No. 95-15	Endogenous Commodity Policies and the Social Benefits from Public Research Expenditures	Jo Swinnen Harry de Gorter