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Potential Implications of Climate Change for U.S. Agriculture

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Abstract

This report examines potential agronomic and economic effects of several assumed changed-climate scenarios on grain farming in the United States. The analysis is based on a protocol that links climatic, agronomic, and economic models to form an integrated model. Three assumed climate scenarios are investigated for their relative effects on crop yields, cropping patterns, and farm-level profitability. The climate scenarios are simulated for representative farms in Iowa, Illinois, Nebraska, Minnesota, Ohio, Georgia, and North Carolina. The agronomic results indicate that the mild climate scenario has little effect on crop yields and that farmers can effectively adapt to increasing temperatures and precipitation by selecting later maturing varieties. Corn and soybean yields are negatively affected at all sites in the more severe climate-change scenario. Northern States are less severely affected by both climate scenarios in terms of soybean yields. The economic results suggest crop prices are fairly sensitive to the rate and the form of the assumed climate-change scenario. Under the mild climate-change scenario, corn prices (inflation adjusted) increase and wheat prices decrease. Soybean prices increase, but at a lower rate than in the no climate-change case. In the more severe climate-change scenario, soybean and corn prices have the largest increase over time. Net farm revenue is lower under climate change than in the no climate-change case. However, there is little difference in net farm revenue between the mild and the severe climate-change scenarios.

Keywords: Global warming, agricultural cropping patterns and production, regional U.S. impacts, adaptation.

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Introduction

Global general circulation models (GCM's), which are our best tools for predicting future climates, indicate that the earth's surface temperature could rise by an average of 1.5 to 4.5°C (degrees celsius) over the next 50 to 100 years due to increasing concentrations of greenhouse gases in the atmosphere (Intergovernmental Panel on Climate Change, 1990, 1992). These models also predict an increase in average global precipitation, but there is less agreement among GCM's as to the potential distribution of precipitation changes. Any change in climate will have implications for climate-sensitive systems such as forestry, other natural resources, and agriculture.

Regarding agriculture, changes in climatic variables will cause agronomic effects such as changes in crop yields and the moisture content of harvest grain. Climate change will also produce a host of economic effects pertaining to agriculture, including changes in farm profitability, prices, supply, demand, trade, and regional comparative advantage. The agronomic and economic effects of climate change will depend principally on two factors: (1) the magnitudes of changes in climatic variables, and (2) agricultural adaptability to these changes. Our current understanding of the interactions among the physical, biological, and economic forces determining the potential for adaptation is limited. However, to study climate change effects on agriculture adequately, the physical-biological-economic interactions must be explicitly considered.

The purpose of this report is to examine the potential effects of climate change on grain farming for several regions of the United States. The analysis is based on an integrated model that links assumed climate changes with a set of crop yield simulation models and a farm-level economic model. Three climate scenarios are investigated for their relative effects on crop yields, cropping patterns, and farm-level profitability: (1) a baseline no-climate-change scenario, (2) a mildly warmer and wetter climate-change scenario, and (3) a more severe, hotter and drier climate-change scenario. The mild scenario is included to reflect the more optimistic end of the range of current predictions, while the severe scenario is closer to the most pessimistic estimates of climate change. To investigate how various regions might be affected by climate change, the climate scenarios are simulated for representative farms in the states of Iowa, Illinois, Nebraska, Minnesota, Ohio, Georgia, and North Carolina. Characteristics of each location are summarized in table 1. The results of these seven locations are aggregated using a simple model to gain insight on the effects of the climate scenarios on national prices and production.

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Table 1--Location of modeled sites and soil characteristics

Station	Location	Representative soil
Sigourney, Iowa	92.2°W, 41.3°N	Clinton
Urbana, Illinois	88.2°W, 40.1°N	Flanagan
Lincoln, Nebraska	96.0°W, 41.3°N	Sharpsburg
Redwood Falls, Minnesota	95.1°W, 44.5°N	Ves
Greenville, Ohio	84.7°W, 40.1°N	Crosby
Tifton, Georgia	83.4°W, 31.4°N	Tifton
Tarboro, North Carolina	77.5°W, 35.9°N	Norfolk

Previous Research

Several previous studies have examined the potential effects of climate change on U.S. agriculture. Three of these are summarized below.

Adams et al. linked models from atmospheric science, agronomy, and economics to investigate potential agronomic and economic effects of climate change on U.S. agriculture. The results from two general circulation models, Goddard Institute of Space Studies (GISS) and Princeton Geophysical Fluid Dynamics Laboratory-GFDL models), were used to simulate agronomic and economic effects of climate change due to a doubling of atmospheric CO_2. To simulate the agronomic effects on crop yields, crop yield simulation models (SOYGROW, CERES-maize, and CERES-Wheat) were used for various regions. The models were run assuming a direct CO_2 fertilizer effect, with photosynthetic rates for soybeans, wheat, and maize increased by 35, 25, and 10 percent, respectively.[1] The economic effects of climate change were estimated using the predicted yields with a spatial equilibrium model of the United States. The economic (and agronomic) results were highly dependent on the climate scenario. The GISS scenario resulted in a composite price decrease of nearly 20 percent, a production increase of 9 percent for field crops and 6 percent for livestock, and an increase in economic welfare of $10 billion. The GFDL scenario resulted in a composite price increase of 34 percent for field crops and 8 percent for livestock, a production decrease of 20 percent for field crops and 2 percent for livestock, and a loss of economic welfare of over $10 billion. In the case where the CO_2 fertilizer effect was assumed to be zero, the results indicated a loss in economic welfare for both climate-change scenarios.

Rather than relying on the results of a general circulation model, Easterling et al. (June 1993) constructed an "analog" climate from historical data for the 1930's to examine the potential effects of climate change for the MINK (Missouri, Iowa, Nebraska, and Kansas) region. This warmer, drier climate was superimposed onto two technological and economic scenarios, one reflecting current conditions (1984-87) and the other representing technical and economic conditions predicted for the year 2030. The effect of this climate scenario on crop yields was captured using the EPIC model, and the direct effects of CO_2 fertilization, based on laboratory experiments, were incorporated. Under the worst case scenario, where there is no CO_2 fertilization and farm-level adjustments to the new climate, production of corn, sorghum, and soybeans decreased, while dryland wheat production remained the same and irrigated wheat production increased for both the current and 2030 scenarios. About 80 percent of the negative effects from the analog climate was eliminated, assuming farm-level adjustments with current technologies and CO_2 enrichment. For the 2030 scenario, there was actually a small increase in overall production given CO_2 enrichment and farm-level adjustments based on anticipated technologies for 2030.

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[1] The CO_2 fertilizer effect refers to an enhancement in crop yields due to elevated atmospheric CO2, which increases rates of net photosynthesis and reduces stomatal openings, resulting in increased water use efficiency by the plant.

An entirely different approach was taken by Mendelsohn and Nordhaus (June 1994), who examined the effect of climate factors on land productivity as measured by land price. The authors called this a Ricardian approach since it looked at the direct effect of climate and climate change on land values.. The analysis was based on cross-sectional data for almost 3,000 counties in the 48 contiguous States for 1982. Regression analysis was used with land price per acre as the dependent variable and a set of climatic, soils, and socioeconomic independent variables. Marginal analysis was conducted for the effect of temperature and precipitation on land prices. It was found that a 1°F (degrees Fahrenheit) increase in temperature for January, April, July, August, and annually induced U.S. farm values per acre to change by -$89.83, $21.72, -$166.30, $158.36, and -$76.06, respectively, in the United States. An increase in temperature was generally beneficial for agriculture only in the autumn of the year. Similarly, a 1-inch increase in precipitation for January, April, July, August, and annually induced farm values per acre to change by $50.25, $108.51, $4.18, -$56.53, and $26.58 change, respectively. Based on a 5°F increase in temperature, farm values would decrease by $309 per acre and annual gross farm revenue would decrease by $35 per acre. Using the 445.362 million acres of cropland in the United States in 1982, the effect of a 5°F increase in temperature would be to lower farm values in the aggregate by $137.6 billion and farm gross revenue by $15.4 billion. These losses represent 24.7 percent of total farm revenue from crops and 39.4 percent of total farm values in 1982.

The integrated set of climate, crop, and economic models presented in this report represent still another approach for studying the potential agronomic and economic effects of climate change on U.S. agriculture. Our approach differs from the above studies in several ways. First, climate change is modeled here as a gradual, transient phenomenon and is simulated over a 100-year period, 1980-2079. Second, the variability, as well as the averages of temperature and precipitation are assumed to be affected by climate change. Finally, particular attention is given to how local farm management strategies can be used to adapt to climate change.

Modeling Framework

A stochastic weather generator, dynamic crop yield simulation models, a farm-level economic (linear programming) model, and a simple model of the national grain economy are the components of the integrated model. Daily values for minimum and maximum temperature, precipitation, solar radiation, and depth of snowpack for each climate scenario are generated by the stochastic weather generator (Wilks, 1992). A suite of crop yield simulation models for various grains (Riha and Rossiter, 1991; Stockle and Campbell, 1989; Wilkerson, et al., 1983), in turn, use the values of the daily meteorological variables as inputs to compute crop yields, grain moisture contents, and available field time. The output of the crop simulation models is used as input in the farm-level linear programming model to generate optimal crop mix, scheduling of field operations, and the resulting farm profitability. Finally, farm-level results at the various sites are linked through a simple representation of the national grain economy. The output of the integrated model, therefore, shows how crop yields, prices, grain moisture, contents, field time, crop mix, farm profitability, and production are affected by each climate scenario.

Stochastic Weather Generator

The stochastic weather generator is based on a model devised by Richardson (1981) as modified by Wilks (1992) to represent changing climates by Wilks (1992). It consists of a trivariate autoregression representing daily maximum temperature, minimum temperature, and solar radiation, conditional on a chain-dependent stochastic precipitation process. Changes in the parameters of the weather generator governing the daily meteorological variables are imposed consistent with the assumed changes in monthly means and (interannual) variances. The climate scenarios are defined in terms of the changing monthly statistics.

This model is used to simulate daily values for minimum and maximum temperature, precipitation, and solar radiation over a 100-year period (1980-2079) for three climate scenarios. The first climate scenario (Scenario 1) is a baseline reflecting no change in climate, generated using parameters fit to observed climate data at the stations listed in table 1. In climate Scenario 2, which corresponds in temperature to the relatively mild time-dependent "Scenario B" of Hansen et al. (1988), average global temperature increases by 2.5°C by the year 2060 (predicted time of equivalent doubling of CO_2), with half of the warming occurring between 2030 and 2060. Average precipitation for Scenario 2 is assumed to increase linearly over time at a rate sufficient to increase average precipitation by 10 percent at each location in 2060. Scenario 3, which corresponds to the more severe "Scenario A" of Hansen et al. (1988), includes an increase in average global temperature of 4.2°C by 2060, again with half of the warming occurring between 2030 and 2060. Under this scenario, average precipitation is assumed to decrease linearly so that it is 20 percent drier by 2060. The assumed global and annual temperature changes are distributed spatially and intra-annually using results from Santer et al. (1990), as described in Wilks (1992).

The simulation results are organized into 10-year decadal time slices, with the meteorological parameters pertaining to the middle year of the decade. For example, a number of arbitrarily many years representative of the climate of the 1990's can be generated using parameter values appropriate to 1995. In order to obtain distributions of the agronomic and economic states of nature, 40 years of synthetic weather data are generated for each decade at each site.

One advantage of using a stochastic weather generator is that changes in variability of temperature and precipitation can also be imposed. For both climate Scenarios 2 and 3, the imposed changes in variability for temperature and precipitation are based on the time-dependent changes in average values. Specifically, the standard deviations of average monthly temperature are decreased linearly in proportion to increases in average monthly temperatures. This assumption is based on the results from several GCM simulations of how temperature variability may change (Rind et al., 1989; Wilson and Mitchell, 1987). In addition, the diurnal temperature range (maximum minus minimum daily temperature) is decreased consistent with observational (Karl et al., 1993) and modeling (Rind et al., 1989) studies. The variance of average monthly precipitation is assumed to increase in the wetter Scenario 2 and decrease in the drier Scenario 3 as a function of the mean changes, according to the power law relationship of Waggoner (1989).

Crop Yield Simulation Models

The daily values of meteorological variables from the stochastic weather generator for each climate scenario were used by dynamic soil-crop-atmospheric simulation models to generate annual crop yields for corn (maize), soybeans, and winter wheat, as well as grain moisture contents and field time availability for each, over the 100-year period. At all sites, continuous monocultures of each crop were simulated. Where appropriate, multiple-cropping systems (winter wheat-soybeans and maize-soybeans) were also simulated. In contrast to most crop simulation studies, the simulation for each cropping system (monoculture or multiple crop) was performed over a continuous 11-year cycle, with output from all but the first year of the simulation used as input for the economic model. This allows crop water used by the previous crop to affect field time availability and soil water available to the current crop.

The crop simulation models used in this report were developed independently by different groups of researchers. Teams of researchers familiar with a specific crop are usually the developers of crop models. We used distinctly different crop yield models rather than a generic model for all crops in order to make maximum use of the knowledge available for the crops investigated. This means that crop models for different species are not necessarily similar in that they reflect the research agendas that have been pursued for each particular crop. In the case of corn, the model used in this report was initially developed by Stockle and Campbell (1989), with a yield simulation added later by Riha and Rossiter (1991). The wheat model used in this report was also developed by Stockle and Campbell (1989) for spring wheat, and was modified to simulate winter wheat by adding a winter survival component. The soybean model is based on SOYGROW developed by Wilkerson et al. (1983).

Simulating the effect of soil on crop growth, yield, and field time availability requires information on soils representative of the region. For each site, a soil series was selected to represent the major type of soil used for crop production in the major land resource area (Austin, 1972) in which the site is located (see table 1). The necessary information for the simulation model for each soil series is obtained from the EPIC soil data base.

In addition to simulating yields, grain moisture contents at harvest and field time availability were also simulated, since this information is required by the farm-level economic model. The field time variable is computed as daily hours available for performing field operations and is limited by excessive soil moisture. Grain moisture is reduced as time between crop maturity and harvest increases, with the rate of reduction being a function of pre-harvest weather.

A major objective of this study was to simulate possible strategies for adapting to changing climatic and consequent economic conditions. Simulation of farm management adaptation was included in several ways. First, as mentioned previously, all three crops and both multiple cropping systems were simulated for every location over the 100-year period, regardless of the extent they are presently adopted. The economic framework then chose from among these, and could alter current crop mix. Second, for every crop in the cropping system at each site, three crop varieties (cultivars) were simulated. These crop varieties represent early-, mid-, and latematuring types. In general, later maturing varieties have a greater yield potential then early and mid varieties. However, later maturing varieties can be more vulnerable to yield reduction due to frost and drought, and may be more likely to have higher grain moisture at harvest than early- and mid-maturing varieties. Third, crop yields and grain moisture contents were simulated for several combinations of planting and harvesting dates.

Actual farm yields are generally lower than simulated yields since the simulations represent potential yields under ideal management conditions. Consequently, the yield results from the crop models are adjusted to represent actual farm-level yields. This adjustment is done for each crop by multiplying individual simulated grain yields by the ratio of the actual average yield in the 1980's to the average simulated yield for the 1980's at each location.

While increased concentrations of CO_2 in the atmosphere should have some enhancing effect on crop yields, this so called "CO_2 fertilizer effect" is not considered in this report for several reasons. First, there is uncertainty among scientists about the magnitude of this enhancement. While the effects of elevated carbon dioxide in controlled greenhouse experiments are well documented, there are uncertainties over the magnitude of the CO_2 fertilizer effect under actual farm conditions in which nutrients and other resources are limited. Second, there is evidence that other effects, such as ozone depletion and companion pollutants created from fossil fuel combustion accompanying the CO_2 increases, will negatively affect yields (Wolfe and Erickson, 1993). Hence, if the CO_2 fertilizer effect is to be considered, so also should these other effects. Third, there are potentially important feedbacks between the direct effects of CO_2 and the interaction of plants with the environment that complicate the representation of these direct effects (e.g., McNaughton and Jarvis, 1991). Finally, as Wolfe and Erickson (1993) point out, current models do not account for the interactions between plant-physiological effects of CO_2 and other environmental factors. For example, there may be no benefit, or even a negative effect, from increased atmospheric CO_2 at low temperatures (less than 15°C). They also note that many researchers have found that photosynthetic stimulation from high CO_2 may not continue with prolonged exposure. The focus of this report is on isolating the role of adaptation in response to climate change. Incorporating the CO_2 fertilizer effect into the analysis detracts from this focus.

Farm-Level Economic Model

The farm-level economic component is a linear programming model that simulates the annual farm-level decisionmaking process, including crop mix and field operation scheduling decisions. It is assumed that the farmer makes these decisions facing three sources of risk affecting net farm revenue: yield levels, crop prices, and grain-drying costs (due to uncertain grain moisture). The risk associated with yields and grain-drying costs were incorporated into the economic model by running the stochastic weather generator and crop yield simulation models multiple times for each decision period, to generate distributions of yield and grain moisture contents. These distributions are referred to as "states of nature." It is assumed that the farmer makes plans having only probabilistic knowledge of which of these simulated yield and drying cost states of nature will occur. The procedures for generating the crop price states of nature are discussed in the next section.

Given the random yield, drying costs, and price states of nature, expected net revenue per acre for each activity (crop, variety, and planting-harvest date combination) was then calculated as follows:

$$E(C_{ijk}) = [\sum_{t=1}^{n} YC_{ijkt}\, PC_t - VCC_t] / n, \text{ where:}$$

$E(C_{ijk})$ is expected net revenue per acre for crop C, variety i, planting period j, and harvest period k; YC_{ijkt} is the yield (bushels per acre) of crop C, variety i, planting period j, harvest period k, and state of nature t; PC_t is the price (dollars per bushel) of crop C, state of nature t; VCC_t are the variable costs for crop C, state of nature t, and n is the number of states of nature. Note that for each crop, variable costs were assumed to be the same across varieties and planting and harvest combinations; however, variable costs vary across states of nature since drying costs may differ. Data for the economic model that did not come from the crop simulation model include variable costs, technical coefficients, and grain prices. Variable cost data for all crops for each location came from Davenport (1988) and are equal to total cash expenses. Technical parameters that give the amount of labor required to produce an acre of each crop are based on the firm enterprise data systems coefficients for 1982 (U.S. Department of Agriculture, 1979-82). Grain price data are from selected issues of Agricultural Prices.

Net revenue risk due to uncertain yields, grain drying costs, and prices is represented by a MOTAD (Minimization of Total Absolute Deviations) framework (Hazell, 1971). It is assumed that the farmer maximizes expected net revenue, but discounts by subtracting a risk term to reflect an aversion to instability in net farm revenue. The risk term is equal to a linear approximation of the standard deviation (total absolute deviations) of expected net revenue, multiplied by a risk aversion coefficient (a coefficient of zero implies the decisionmaker does not care about risk, while any positive coefficients mean that the farmer dislikes risk). Discounted net farm revenue (hereafter referred to simply as net revenue) was maximized subject to a set of resource constraints including acreage and labor availability. The risk aversion coefficient was set equal to 1, which is in the range that Brink and McCarl (1978) found representative for Corn Belt farmers. A MOTAD linear programming model was formulated for the representative farm in each of the seven States of the study. While crop yields, drying costs, other variable costs, technical parameters, and resource endowments are specific to each location, crop prices were derived at the national level and are the same for each farm.

A Simple Model of National Grain Price Determination

Grain price states of nature are generated using regression equations that specify price as a function of national crop yields and other factors affecting price. To estimate these price equations, U.S. annual data from 1965 through 1991 were used. For each crop, price--deflated by the Consumer Price Index (CPI)--was specified as a function of annual average national yield, Government support price for the crop, per capita disposable income deflated by the CPI, price in the previous year, and an intercept dummy variable equal to 1 for 1973-75 and zero otherwise.

The intercept dummy variable was included since 1973-75 represented a period of unprecedented high crop prices due to an increase in U.S. exports to the Soviet Union. The three fitted equations used to generate the crop price states of nature are presented in table 2.

To generate the grain price states of nature, values for the exogenous variables (deflated per capita disposable income and Government support prices) need to be specified for the period 1990-2079. To reflect recent trends in declining support prices and a movement toward a market-oriented policy, it is assumed that support prices for each crop are reduced by 1 percent per year for 1990-2079. The intercept dummy variable, DUM_{7375}, was set to zero for the entire 100-year period. The forecast for deflated per capita disposable income uses the following regression equation:

$$INC/CPI = \underset{(2.86)}{4647.06} + \underset{(4.87)}{1.005}\,(INC/CPI)_{t-1} - \underset{(-2.06)}{.415}\,(INC/CPI)_{t-2} + \underset{(2.51)}{85.175}\,T \qquad R^2=.97$$

where T is a time trend equal to 1 for 1965, 2 for 1966, and so on. The grain price states of nature are generated by substituting the specified values of all exogenous variables, as well as the weighted-average yield values from the seven States into the crop price equations. The average yield values for the seven States are weighted by each State's share of production for the 1980's; therefore, corn yields in major corn-producing States (such as Iowa) influence the simulated national average yield more than less important corn States, such as Georgia. Based on data from 1965-91, the weighted-average yield from these seven States is very close to the national yield for all three crops considered in this report. Since there are 40 yield states of nature simulated for each decade, there are also 40 price states of nature generated per decade.

To summarize the methodology, for each climate scenario, the simulation began with the generation of daily weather values for the 100-year period (1980-2079), using the stochastic weather generator. The daily values of the weather variables for each year were used by the crop simulation models to generate annual crop yields for various plant-harvest dates, grain moisture contents, and field time. The agronomic results were tabulated on a decade-by-decade basis, resulting in 10 sets of results for each scenario. Crop price states of nature were generated by using the yield states of nature along with the specified values of the exogenous variables in the estimated price equations. For each decade, a total of 40 states of nature were generated for crop yields, drying costs, and grain prices for the linear programming model. It is assumed that the farmer makes crop mix and field operation scheduling decisions based on the expected net revenue and total absolute deviations from expected net revenue resulting from these 40 states of nature. To economize on the number of simulations required, the economic model was solved once per decade based on the 40 states of nature that are reflective of the decade. Since the economic model is an annual model, the results can be interpreted as a representative year in the decade. All costs, technical parameters, and resource endowments in the linear programming model were held at their average 1980 values for the entire simulation period. However, variety selection, crop yields, grain moisture contents, grain drying costs, and crop prices were varied by

Table 2--Estimated crop price equations

Variable	Soybean price	Corn price	Wheat price
Constant	0.409	-8281	-2509
	(0.07)	(-1.44)	(-026)
Average U.S. yield	-1.340	-0739	-0547
	(-2.74)	(-2.68)	(-1.10)
Per capita income	0.482	1.232	0.514
	(0.77)	(1.91)	(0.48)
Support price	0.179	0.625	0.621
	(0.53)	(3.23)	(1.98)
$Price_t$-1	0.614	0.300	0.123
$Dummy_{1973-75}$	0.118	0.369	0.544
	(0.67)	(3.17)	(3.99)
Adjusted R^2	0.73	0.85	0.79
Regression standard error	0.18	0.14	0.18
F-statistic	14.69	29.56	20.31

Figures in parentheses are t-values.

decade and by climate scenario based on the results of the crop simulation model.

Agronomic Effects

Table 3 shows regional average crop yields for 1980 and the percentage change from 1980 for 2030 and 2070 under the two climate-change scenarios.[2] The national average yield is equal to the average of yields for the seven States, and is weighted by each State's percentage of the seven States' combined production in 1980.

Recall that Scenario 2 is the relatively mild case where global temperature increases by 2.5°C and precipitation increases by 10 percent by 2060. Scenario 2 has little negative effect on crop yields for all sites during the first 70 years of the simulation. This is not unexpected given that precipitation is increasing and the increases in temperature are moderate. Increasing temperature can result in a shortened growing season and therefore reduced crop growth potential. However, this is offset over this period by replacing current varieties with later maturing varieties. In areas where winter wheat yields are affected by cold winter weather and snowpack (e.g., Nebraska), there is a positive effect of Scenario 2 on yields. In the last two decades of the simulation, a slight decrease in corn yields occurs at most locations, resulting in a 9-percent decrease in the national yields relative to 1980 levels.

The bottom portion of table 2 displays the regional and national yield patterns for Scenario 3, where global temperature increases by 4.2°C and precipitation decreases by 20 percent by 2060. In this scenario, the decline in national corn yields begins sooner and is more than twice as severe as in Scenario 2. The decrease in corn yields occurs in all regions and is due to higher temperatures, which shorten the length of time for growth of a particular variety. In addition, the decrease in precipitation in this scenario causes yield reductions due to drought stress. By 2070, national average corn yields have decreased by 21 percent compared with 1980 levels. This scenario has less of a negative effect on national soybean yields through most of the simulation. However, by the last decade of this period, national average soybean yields decline by 14 percent. Winter wheat yields are affected the least under severe climate change. In this case, national average yields fall by 9 percent in 2030, but remain at these levels for the duration of the simulation.

There are several regional patterns of climate change effects on crop yields for the two scenarios. With respect to corn yields, Georgia suffers the largest negative yield effect under the mild climate-change scenario, and experiences the second largest negative effect under the severe scenario. However, the effect of both scenarios on corn yields in North Carolina is actually less

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[2] The yield averages for each decade are wighted averages over the possible planting-harvest dates (which are specific to each location). The weights are derived by the linear programming results and are equal to the optimal proportion of how much of each crop is planted and harvested for each combination of planting-harvest dates. For example, if for a particular decade and location 75 percent of soybeans are planted in period 2 and harvested in period 5, and 25 percent of soybeans are planted in period 3 and harvested in period 6, then average soybean yield for that decade would equal 0.75 times the average soybean yield for planting period 2 and harvest period 5, plus 0.25 times the average soybean yield for planting period 3 and harvest period 6.

Table 3--Average U.S. crop yields under no climate change in 1980 and the two climate-change scenarios for selected decades

	Average yield 1980			Percentage yields					
				1980-2030			1980-2070		
	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
	Bu. per acre			*-------Percent-------*					
Mild climate change scenario:									
Iowa	124	50	38	-4	11	1	-13	10	-3
Illinois	174	49	76	1	5	-20	-10	5	-28
Minnesota	109	41	58	5	15	-11	-7	51	19
Nebraska	97	40	53	6	4	20	0	2	27
Ohio	118	53	56	1	8	2	-9	14	4
North Carolina	83	33	49	-2	0	6	-8	6	11
Georgia	83	39	45	3	-1	3	-15	-18	6
Average	129	47	58	1	9	-3	-9	13	8
Severe climate change scenario:									
Iowa	124	50	38	-11	11	-1	-24	-23	-4
Illinois	174	49	76	-4	5	-28	-20	-20	-25
Minnesota	109	41	58	-6	16	-9	-38	24	-11
Nebraska	97	40	53	-3	5	3	-5	-23	-1
Ohio	118	53	56	-2	13	-4	-15	-4	0
North Carolina	83	33	49	-4	-2	7	-16	-47	10
Georgia	83	39	45	-15	-5	-3	-32	-65	-1
Average	129	47	58	-6	10	-9	-21	-14	9

than the national average. There is more of a regional pattern of climate-change effects on soybean yields. In the mild climate-change case, the only negative yield effects occur in the two Southern States, while all five Northern States experience positive yield effects. Under severe climate change, the negative effects on soybean yields in the two Southern States are two-to-three times as severe as those occurring in the northern states. The effects of the two climate-change scenarios on wheat yields tend to be more positive in the South than in the Northern States, but there are some exceptions to this generalization. The percentage change in wheat yields in North Carolina due to both climate-change scenarios is more positive than the national average. On the other hand, while wheat yields in Georgia fare better than the national average in Scenario 3, the yield benefits of Scenario 2 for Georgia are lower than the national average.

Economic Effects

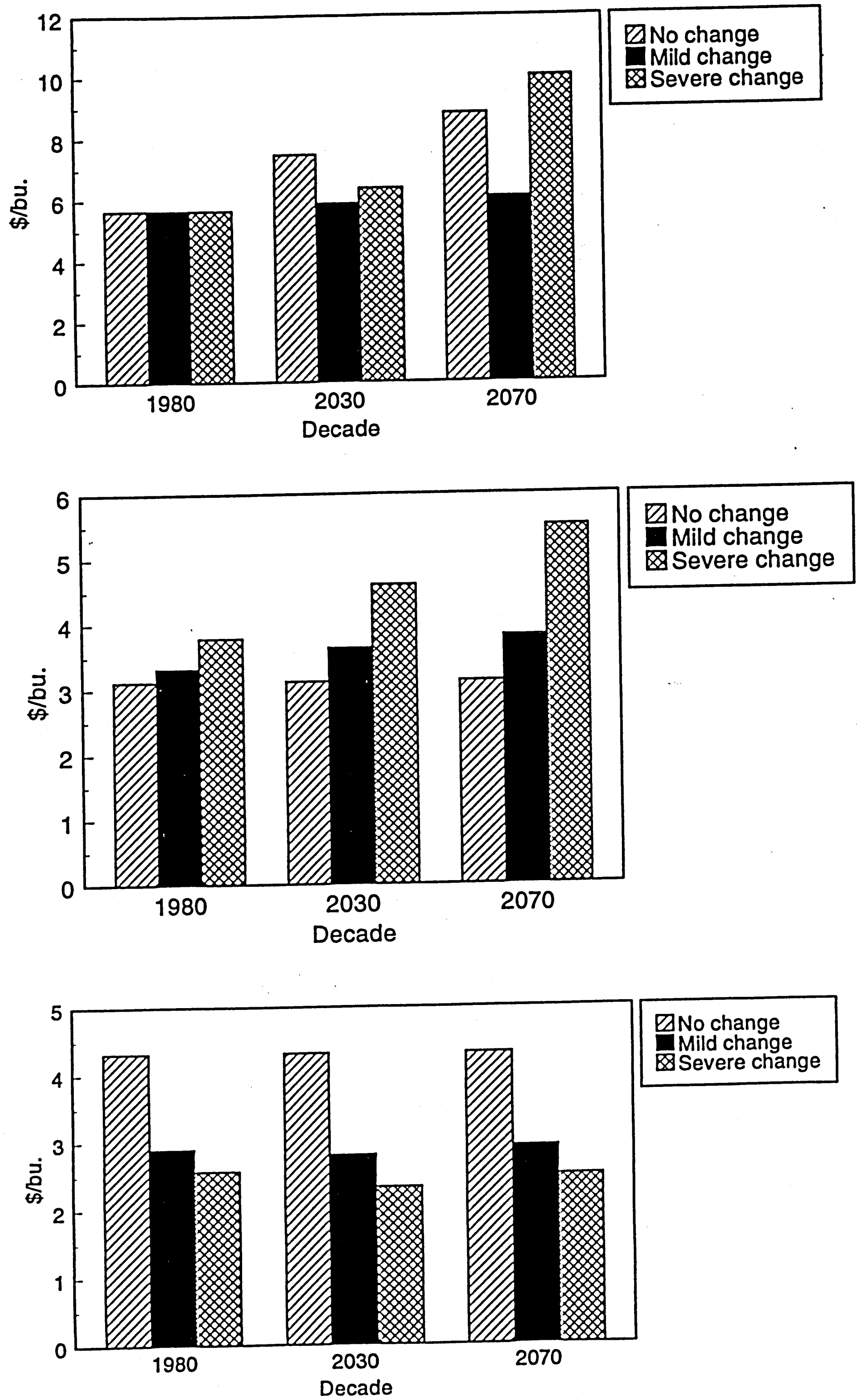
Effect on Crop Prices

Figure 1 presents national average crop prices by decade for 1980, 2030, and 2070 for each climate scenario. It is clear from this figure that national crop yields play a major role in determining price levels over time for most crops. In the case of no climate change, where grain yields from 1990-2070 are the same as 1980 yields, average soybean prices (all prices are in 1980 dollars) rise from the $5.64 per bushel average in the 1980's to $8.79 per bushel in the 2070's. Corn prices also rise, increasing from $3.72 per bushel in the 1980's to $3.78 per bushel for the decade of 2070. Even though support prices are declining over time, soybean and corn prices increase because of the projected increase in real income. Average wheat prices decline from $4.32 per bushel for the 1980's to $2.57 per bushel for the 2070's. The decrease in wheat prices is mainly attributable to the assumption that support prices will decline by 1 percent per year over the period 1990-2070. This scenario provides a reference, or baseline to compare with the climate-change scenarios in terms of their effect on crop prices.

Under Scenario 2, the increase in soybean prices is significantly less than in Scenario 1 due to the result that national average soybean yields are increasing in this scenario. In this case, soybean prices increase from an average of $5.64 per bushel for the 1980's to $6.06 per bushel for the 2070's. On the other hand, because average U.S. corn yields decline in this scenario, corn prices increase more than in the baseline. Corn prices increase from an average of $3.12 per bushel in the 1980's to an average of $4.60 per bushel in the 2070's. Since there is little difference in wheat yields between this scenario and the baseline, average wheat prices are comparable.

The effect of Scenario 3 on soybean, corn, and wheat prices is similar in direction to Scenario 2 price effects, but the magnitude of change is different. National average soybean prices are comparable between Scenarios 2 and 3 until 2060, and are lower than those in Scenario 1 up to 2060. However, national average soybean prices soar in the 2070 decade under Scenario 3, reflecting the abrupt decline in national average soybean yields after 2060. For the entire 100-year period, the average soybean price increases from $5.64 per bushel for the 1980's to $10.02 per bushel for the 2070's. Corn prices are higher under Scenario 3 than under Scenarios 1 and 2. The 43-percent increase in corn prices from

Figure 1.
Real prices for soybean, corn and wheat crops for selected decades



1980-2070 is due to a larger decline in average U.S. corn yields under Scenario 3 relative to the other scenarios. Average wheat prices for Scenario 3 are comparable with Scenarios 1 and 2, decreasing by 42 percent from 1980-2070.

Based on the estimated grain price equations, it is clear that soybeans are the most price-responsive to changes in national average crop yields due to climate change. For example, for a 1-percent decrease (increase) in national average soybean yields, there is a 1.34-percent increase (decrease) in the price of soybeans, assuming all other factors affecting price (e.g., income, support prices, etc.) are held constant. On the other hand, the estimated price responsiveness of wheat is very low. In this case, a 1-percent decrease (increase) in national average wheat yields results in only a 0.55-percent increase (decrease) in the price of wheat, holding all other price determinants constant. The price-estimated responsiveness of corn is between that of soybeans and wheat. A 1-percent decrease (increase) in national average corn yields results in a 0.74-percent increase (decrease) in corn prices.

Effect on Net Farm Revenue

The economic (linear programming) model was solved for each location using the national price states of nature with the local-level yield and grain-drying cost states of nature predicted by the crop simulation models. The linear programming model is calibrated for each State in order to obtain the approximate crop mix observed in the 1980's. This is accomplished by adjusting prices and yields for the crops so that the linear programming model simulates cropping patterns for the 1980's that correspond to observed cropping patterns for the 1980's. All adjustments for prices and yields made for the 1980's (e.g., increase modeled soybean yields by 1.5 percent) are carried over to the remaining decades of the simulation. Also, an inter-temporal constraint on crop mix is included, which restricts shifts in crop acreage to be 10 percent or less between each decade, e.g., the limit on a change in corn acreage between each decade is +/-10 percent.

Table 4 presents the percentage change in regional net farm revenue from 1980 for selected decades under the three climate scenarios.[3] If there is no change in climate, modeled net farm revenue will increase over time for all seven States. The representative farm in Ohio leads the way, while the lowest level of growth in net revenue occurs in Nebraska. The increase in net revenue is due to farmers switching crops in response to increasing prices and the relative profitability of each crop. In all States, the relative share of corn acreage declines, while soybean acreage increases over the 100-year period. For example, in Iowa, the relative split between corn and soybean acreage goes from 54 percent corn and 46 percent soybeans in 1980 to 24 percent corn and 76 perent soybeans in 2070. This is due to the result that soybean prices are rising more than corn prices in Scenario 1.

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[3]Recall that net farm revenue here is discounted by a risk term represented by a linear approximation of the standard deviation of net revenue.

Under the mild climate change (Scenario 2), net farm revenue will also increase over time for all seven States. However, toward the end of the century, farmers at most sites are clearly in a worse economic condition under this climate-change scenario relative to no change in climate. This result holds for all States considered in the study with the exception of Nebraska. Net farm revenue for the representative farm in Nebraska is marginally higher in Scenario 2 than in Scenario 1. This result is due to Nebraska corn and wheat yields being the most favorably affected by this climate change scenario relative to the other regions. The mild climate-change scenario generally has a greater negative effect on net farm revenue in the two Southern States than in the Northern States. For example, the increase in net revenue from 1980-2070 for Georgia and North Carolina under Scenario 2 is 56 and 66 percent, respectively, of the increases in the no climate-change case. For the five Northern States, the increase in net revenue from 1980-2070 under Scenario 2 averages 83 percent of their increases in Scenario 1.

Under the severe climate-change scenario, net farm revenue in all but two States will still increase over 1980 levels (table 4). By 2070, net revenue in Georgia and Illinois, however, decrease by 43 percent and 30 percent, respectively, from 1980 levels. Hence, the Georgia and Illinois representative farms are in a worse economic condition than present conditions under the severe climate-change scenario. On the other hand, net revenue under the severe climate-change scenario is higher than in the mild climate-change scenario for three States (North Carolina, Ohio, and Minnesota). This is due to the fact that crop yields tend to be lower in Scenario 3, but this is more than offset by higher prices in Scenario 3 relative to Scenario 2. Yet, these locations still have lower farm profitability relative to the no-climate-change scenario.

Effect on Cropping Patterns and Production

For all locations, farmers altered both crop mix and varieties in response to climate change. Table 5 shows the percentage change in optimal crop mix from 1980 for selected decades under the three climate scenarios. Multiple cropping is not an optimal system in any location or climate scenario.

Under no climate change, there is a clear pattern for all regions to devote less acreage to corn and wheat and more acreage to soybeans. The profitability of soybeans is increasing over time relative to corn and wheat. This is due primarily to the real price of soybeans increasing significantly more than the prices of the two other crops under this scenario. The largest regional shift in soybean acreage under this scenario occurs in Nebraska, where soybean acreage increases 133 percent from 1980-2070.

In the case of mild climate change, there is not a strong pattern toward growing more soybeans and less corn and wheat as was the case for no climate change. In fact, by 2070, only three States (Illinois, Ohio, and North Carolina) devote less acreage to corn than in 1980. The four other States do increase corn acreage over the 100-year simulation. At the same time, soybean acreage also increases under the mild climate-change scenario for four of the seven locations. However, the increase in soybean acreage is consistently less than the increase in the no-climate-change case. Wheat acreage declines under this scenario, but the decline is similar to that found in the no-climate-change scenario.

Table 4--Percentage change in regional net farm revenue from 1980 for selected decades under the three climate scenarios

Location	Percentage change in average net revenue from 1980								
	2030			2050			2070		
	Base	MCC	SCC	Base	MCC	SCC	Base	MCC	SCC
	Percent								
Iowa	62	14	33	108	41	46	155	78	43
Illinois	46	38	-6	84	42	-16	123	70	-30
Minnesota	50	31	24	95	76	41	143	130	154
Nebraska	37	48	35	77	82	58	120	131	76
Ohio	90	73	82	143	80	102	199	122	201
North Carolina	75	51	45	131	47	50	189	91	101
Georgia	58	37	10	109	36	-9	162	47	-43

Note: Base is the no-climate-change scenario, MCC is the mild climate-change scenario, and SCC is the severe climate-change scenario.

Table 5--Percentage change in optimal regional crop mix from 1980 for selected decades under the three climate scenarios

	Percentage change in crop mix, 1980-2030			Percentage change in crop mix, 1980-2050			Percentage change in crop mix, 1980-2070		
	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
					Percent				
No climate change:									
Iowa	-38	53	NA	-50	68	NA	-59	81	NA
Illinois	-37	55	-45	-49	73	-55	-58	88	-73
Minnesota	-17	43	-41	-27	61	-53	-38	78	-62
Nebraska	-17	43	-41	-27	61	-53	-38	78	-62
Ohio	-41	47	-34	-52	61	-47	-61	72	-56
North Carolina	-40	52	-32	-51	68	-45	-61	81	-55
Georgia	-41	48	-41	-52	61	-51	-61	72	-61
Mild climate change:									
Iowa	-38	52	NA	-25	34	NA	5	-7	NA
Illinois	-37	55	-45	-37	57	-55	-24	38	-73
Minnesota	-5	25	-33	16	10	-46	39	-9	-56
Nebraska	13	18	-41	31	-5	-52	42	-21	-59
Ohio	-28	35	-34	-29	38	-47	-14	26	-56
North Carolina	-40	52	-32	-27	42	-45	-11	28	-55
Georgia	-26	38	-41	-10	33	-52	9	25	-61
Severe climate change:									
Iowa	-25	35	NA	-10	14	NA	-9	12	NA
Illinois	20	-28	-45	30	-41	-64	38	-52	-73
Minnesota	-16	42	-41	-32	67	-53	-45	86	-62
Nebraska	9	13	-28	30	-31	-29	38	-31	-42
Ohio	-40	48	-40	-40	48	-41	-50	60	52
North Carolina	-40	53	-33	-28	44	-47	-13	31	-56
Georgia	-28	37	-37	-15	35	-49	-6	33	-57

The general pattern for all crops and all locations is to shift to later maturing varieties over time in response to increasing temperatures. For several locations and crops, however, the latest maturing variety is selected as early as 1980 and is used for the entire 100-year period.

The effects of the severe climate-change scenario on optimal crop mix are similar to those of Scenario 2, but there are several differences. In Illinois, for example, corn acreage increases and soybean acreage decreases, in contract with the outcome in Scenario 2. In Minnesota, soybean acreage consistently increases over time at the expense of corn acreage, which is the opposite pattern of Scenario 2. The effect of this scenario on optimal cropping patterns in the other locations is similar to Scenario 2. As was true in Scenario 2, the general trend is to grow later maturing varieties as temperatures increase.

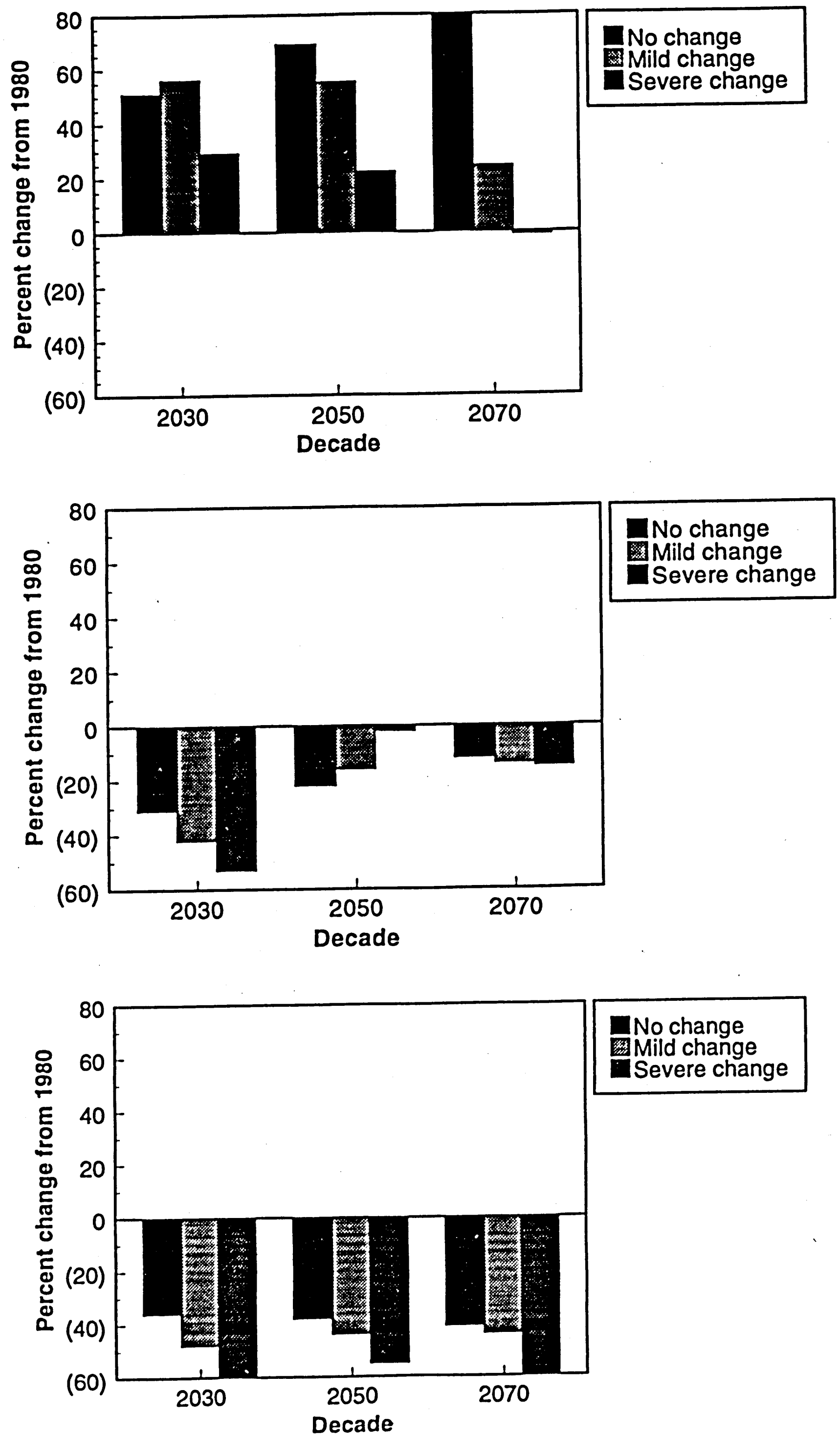
To estimate how grain production might change under the assumed climate-change scenarios, crop mix for each location was multiplied by the modeled yields. The resulting change in national production is based on the weighted seven-site average. These results should be interpreted with some care since they are based on an aggregation of only seven representative farms from seven States. While extrapolating farm-level production to regional and national changes in production in this way is simplistic, it does provide an approximation of how climate change could affect production.

Figure 2 presents the percentage change from 1980 in national grain production over time for all three climate scenarios. The results parallel the crop mix results. Under the no-climate-change scenario, national soybean production increases steadily over time, and by 2070 is 84 percent higher than 1980 levels. Both corn and wheat production decrease in this scenario, with corn production falling by 53 percent and wheat production declining by 59 percent by 2070. Of the three climate scenarios modeled, the one with no climate change results in the largest shift in crop mix and production among the three crops.

In the mild climate-change scenario, soybean production again increases over time. Unlike the previous scenario, however, the rate of increase declines toward the end of the 100-year period. Corn production declines through most of the simulation, but is close to 1980 levels by 2070. On the other hand, wheat production declines monotonically over time, as in the previous scenario.

The percentage increase in soybean production is lowest under the severe climate-change scenario. In fact, by 2070, soybean production falls back to 1980 levels. Corn production is quite stable over time under severe climate-change, ranging from 12-14 percent lower than 1980 levels. Likewise, wheat production, while lower than 1980 levels, is fairly stable between 2030 and 2070. It appears that the severe climate-change scenario results in the least amount of relative change in crop mix and production among the three crops.

Figure 2.
Percentage change in soybean, corn and wheat crops for selected decades



Summary

This report has examined potential agronomic and economic effects of several climate-change scenarios on grain farming in the United States. The analysis was based on a protocol that linked climatic, agronomic, and economic models to form an integrated model. Three climate scenarios were investigated over a 100-year period (1980-2079) for their relative effects on crop yields, cropping patterns, and farm-level profitability: (1) a baseline no-climate-change scenario, (2) a mildly warmer and wetter climate-change scenario, and (3) a more severe hotter and drier climate- change scenario. To consider how various regions of the United States may be affected by climate change, the climate scenarios were simulated for representative farms in Iowa, Illinois, Nebraska, Minnesota, Ohio, Georgia, and North Carolina.

The agronomic results indicated that the milder climate change of Scenario 2 had little negative effect on crop yields, and that farmers could adapt to increasing temperatures and precipitation by selecting later-maturing varieties. Corn and soybean yields were negatively affected at all sites in the harsher Scenario 3. However, this yield reduction would have been even greater without options for farm management adaptation. Corn yields were generally more negatively affected than soybean and wheat yields among regions. There were several regional patterns of climate change effects on crop yields for the two scenarios. The most striking regional pattern of climate change effects occurred for soybean yields. In the mild climate-change case, the only negative yield effects occurred in the two Southern States, while all five Northern States experienced positive yield effects. Under severe climate change, the negative effects on soybean yields in the two Southern States were two-to-three times as severe as those occurring in the Northern States.

The economic results suggest that crop prices are fairly sensitive to the rate and the form of the assumed climate-change scenario. In the no-change scenario, both soybean and corn prices increased, while wheat prices decreased over time. The increase in soybean and corn prices was attributed to the projected increase in real income. The decrease in wheat prices was mainly attributable to the assumption that support prices would decline by 1 percent per year over the period 1990-2070. Under the milder climate change of Scenario 2, soybean and corn prices again increased and wheat prices decreased. However, the corn price increased much more, while the increase in the soybean price was substantially less than under no climate change. In the more severe climate change of Scenario 3, soybean and corn prices had the highest increases over time, while the wheat price decreased the least of all three scenarios.

Net farm revenue was lower under climate change than in the no-change case. In the milder Scenario 2, net revenue for the representative farms in all States except Nebraska was lower than in the no-climate-change scenario, with Southern States in a worse economical condition than Northern States. In the more severe Scenario 3, net revenue for representative farms in Georgia and Illinois was substantially lower than in both Scenarios 1 and 2.

Under all climate scenarios, corn and wheat acreage and production declined consistently over the 100-year period due to declining profitability relative to soybeans. Soybean acreage and production

increased over time in all three scenarios. Interestingly, the largest relative shifts in crop mix and production among the three crops occurred in the no-climate-change scenario, while the lowest percentage shift occurred in the severe climate-change case.

While the representation of the national grain economy presented here is highly simplified, it does illustrate important interactions between climate changes, local decisionmaking, and the larger context within which local decisions must be made. The specific results should not be regarded as predictions, but they do illustrate that some regions will be better able to adapt to a changing climate than others. Different forms of possible climate changes result in different distributions of losses and gains among the regions. These results underscore the need to consider distributional effects when estimating effects of climate changes, rather than focusing only on larger scale, national consequences.

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