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The Potential Effects Of Global Climate Change On The United States

Appendix C
Agriculture
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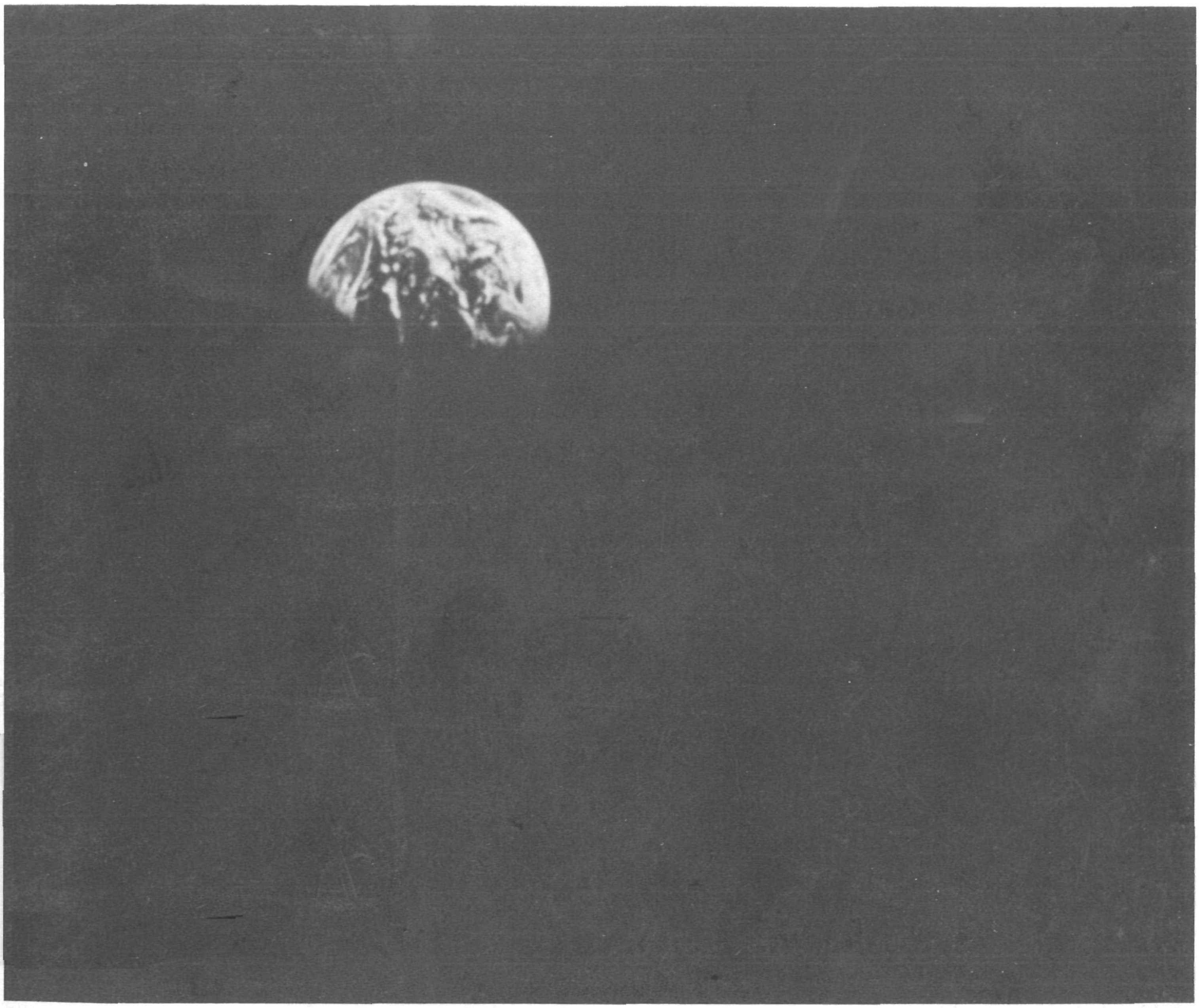

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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX C - AGRICULTURE

Editors: Joel B. Smith and Dennis A. Tirpak

OFFICE OF POLICY, PLANNING AND EVALUATION
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

MAY 1989

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PREFACE

The ecological and economic implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, members of Congress have held hearings on the greenhouse effect and have begun to examine its implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, committee members sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

To meet this request, EPA produced the report entitled *The Potential Effects of Global Climate Change on the United States*. For that report, EPA commissioned fifty-five studies by academic and government scientists on the potential effects of global climate change. Each study was reviewed by at least two peer reviewers. The Effects Report summarizes the results of all of those studies. The complete results of each study are contained in Appendices A through J.

Appendix	Subject
A	Water Resources
B	Sea Level Rise
C	Agriculture
D	Forests
E	Aquatic Resources
F	Air Quality
G	Health
H	Infrastructure
I	Variability
J	Policy

GOAL

The goal of the Effects Report was to try to give a sense of the possible direction of changes from a global warming as well as a sense of the magnitude. Specifically, we examined the following issues:

- sensitivities of systems to changes in climate (since we cannot predict regional climate change, we can only identify sensitivities to changes in climate factors)
- the range of effects under different warming scenarios
- regional differences among effects
- interactions among effects on a regional level

- o national effects
- o uncertainties
- o policy implications
- o research needs

The four regions chosen for the studies were California, the Great Lakes, the Southeast, and the Great Plains. Many studies focused on impacts in a single region, while others examined potential impacts on a national scale.

SCENARIOS USED FOR THE EFFECTS REPORT STUDIES

The Effects Report studies used several scenarios to examine the sensitivities of various systems to changes in climate. The scenarios used are plausible sets of circumstances although none of them should be considered to be predictions of regional climate change. The most common scenario used was the doubled CO_2 scenario ($2XCO_2$), which examined the effects of climate under a doubling of atmospheric carbon dioxide concentrations. This doubling is estimated to raise average global temperatures by 1.5 to 4.5°C by the latter half of the 21st century. Transient scenarios, which estimate how climate may change over time in response to a steady increase in greenhouse gases, were also used. In addition, analog scenarios of past warm periods, such as the 1930s, were used.

The scenarios combined average monthly climate change estimates for regional grid boxes from General Circulation Models (GCMs) with 1951-80 climate observations from sites in the respective grid boxes. GCMs are dynamic models that simulate the physical processes of the atmosphere and oceans to estimate global climate under different conditions, such as increasing concentrations of greenhouse gases (e.g., $2XCO_2$).

The scenarios and GCMs used in the studies have certain limitations. The scenarios used for the studies assume that temporal and spatial variability do not change from current conditions. The first of two major limitations related to the GCMs is their low spatial resolution. GCMs use rather large grid boxes where climate is averaged for the whole grid box, while in fact climate may be quite variable within a grid box. The second limitation is the simplified way that GCMs treat physical factors such as clouds, oceans, albedo, and land surface hydrology. Because of these limitations, GCMs often disagree with each other on estimates of regional climate change (as well as the magnitude of global changes) and should not be considered to be predictions.

To obtain a range of scenarios, EPA asked the researchers to use output from the following GCMs:

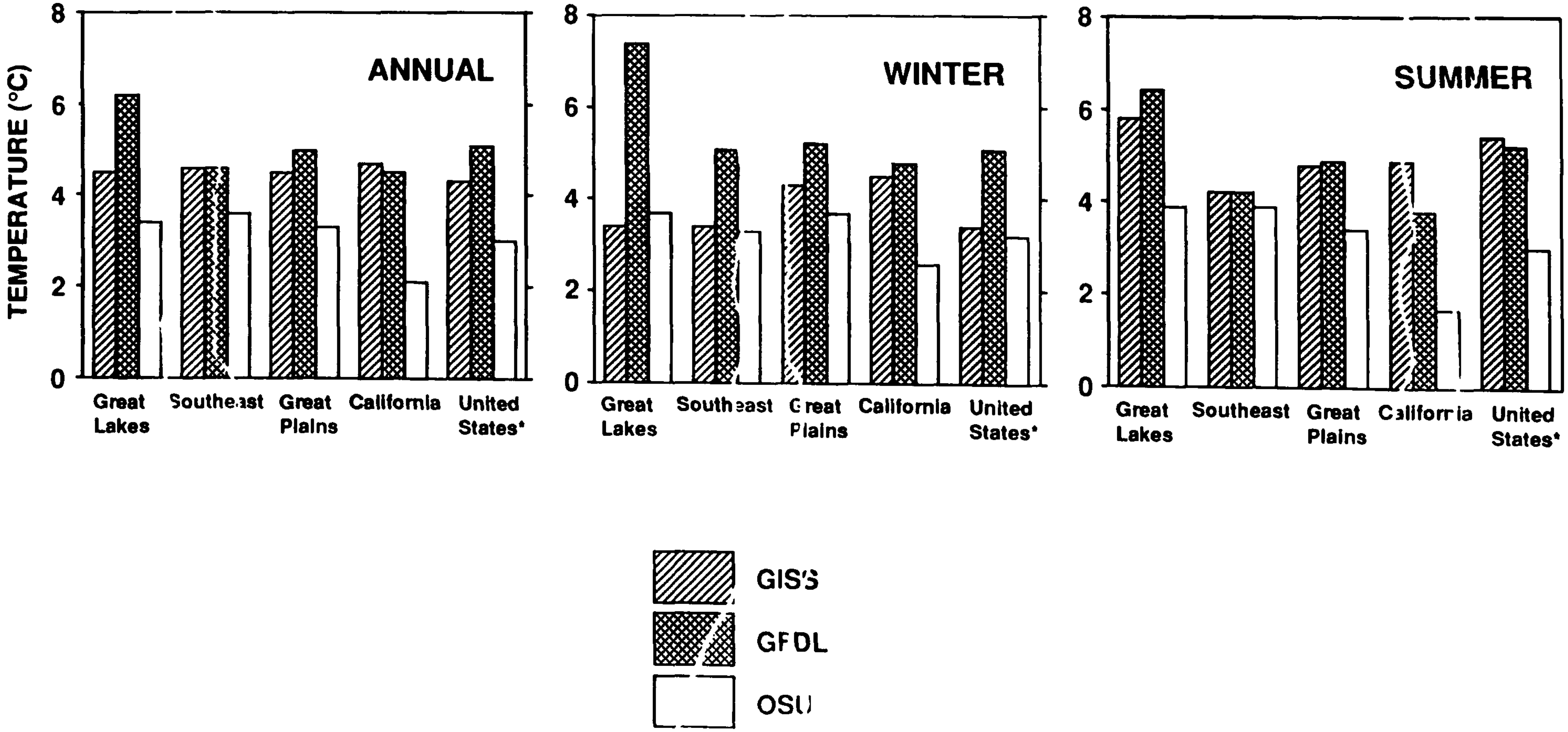
- o Goddard Institute for Space Studies (GISS)
- o Geophysical Fluid Dynamics Laboratory (GFDL)
- o Oregon State University (OSU)

Figure 1 shows the temperature change from current climate to a climate with a doubling of CO_2 levels, as modeled by the three GCMs. The figure includes the GCM estimates for the four regions. Precipitation changes are shown in Figure 2. Note the disagreement in the GCM estimates concerning the direction of change of regional and seasonal precipitation and the agreement concerning increasing temperatures.

Two transient scenarios from the GISS model were also used, and the average decadal temperature changes are shown in Figure 3.

FIGURE 1. TEMPERATURE SCENARIOS

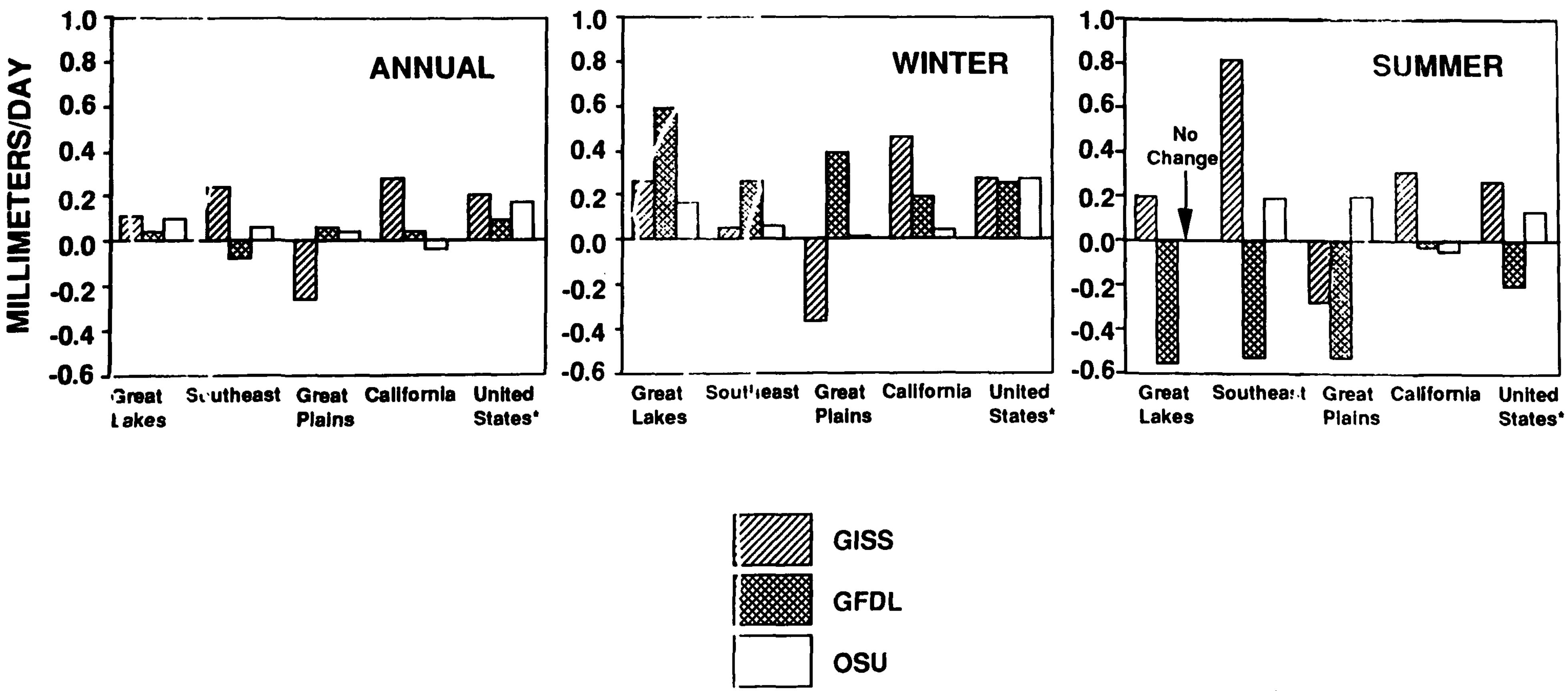
GCM Estimated Change in Temperature from $1xCO_2$ to $2xCO_2$



* Lower 48 States

FIGURE 2. PRECIPITATION SCENARIOS

GCM Estimated Change in Precipitation from $1xCO_2$ to $2xCO_2$



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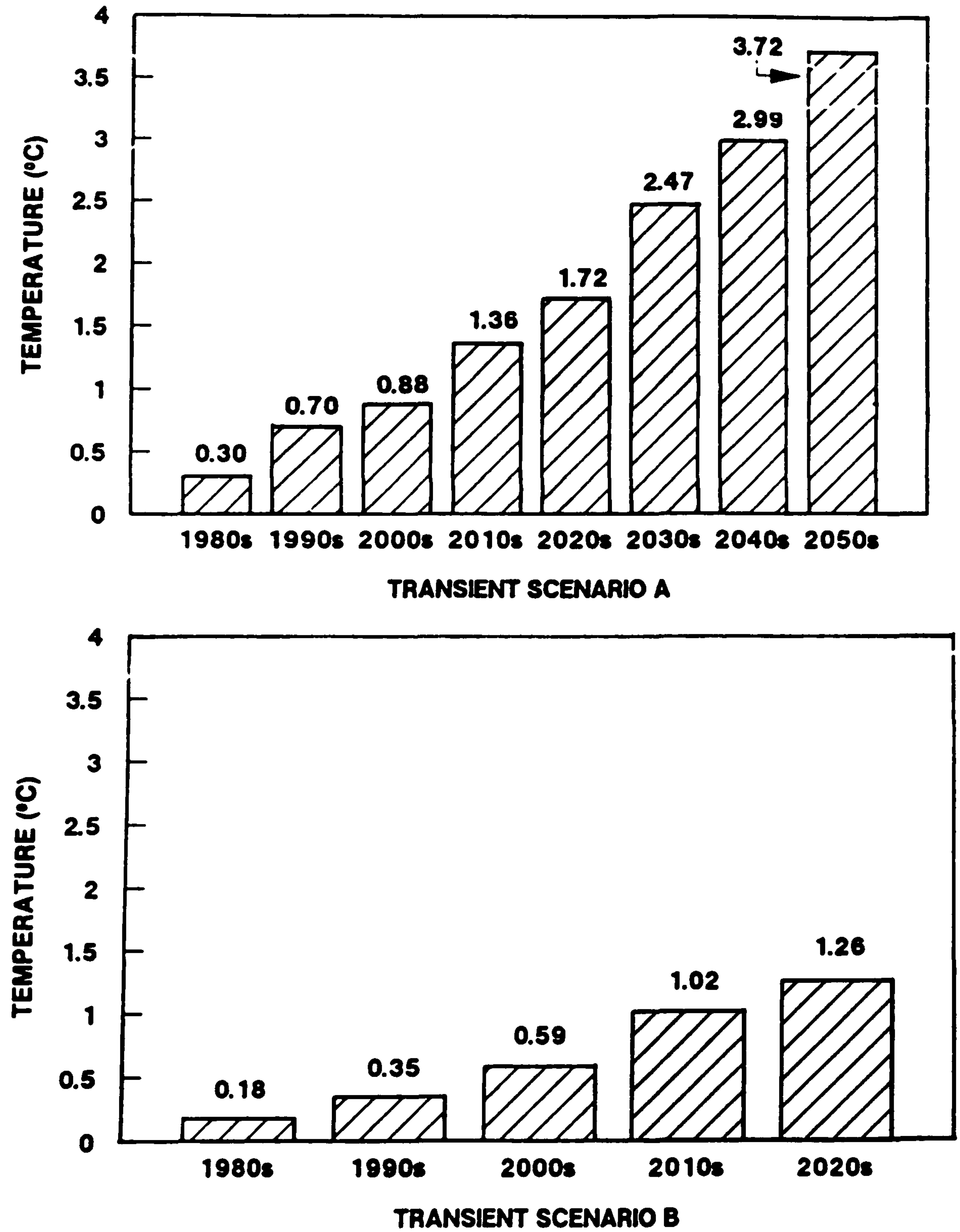

FIGURE 3. GISS TRANSIENTS "A" AND "B" AVERAGE TEMPERATURE CHANGE FOR LOWER 48 STATES GRID POINTS.

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in their studies. Many researchers, however, did not have sufficient time or resources to use all of the scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2
2. GFDL doubled CO_2
3. GISS transient A
4. OSU doubled CO_2
5. Analog (1930 to 1939)
6. GISS transient B

ABOUT THESE APPENDICES

The studies contained in these appendices appear in the form that the researchers submitted them to EPA. These reports do not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

EFFECT OF GLOBAL CLIMATE CHANGE ON AGRICULTURE GREAT LAKES REGION

by

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FINDINGS[1]

Using weather scenarios created from two climate models, Goddard Institute for Space Studies (GISS) and Geophysical Fluid Dynamics Laboratory (GFDL), and baseline observed weather data sets, corn and soybean production was simulated for normal and changed climates using the CERES-Maize[2] model and the SOYGRO soybean model. The primary analysis was completed without including the direct effects of CO_2 on photosynthesis and transpiration. Thus, changes in temperature and rainfall were the principal causes of yield changes. Further analysis included the direct effects of CO_2.

For the humid Great Lakes region, changes in temperature had the greatest effect on model-predicted crop yields. In most cases, an increase in temperature caused a decrease in the duration of crop life cycle. The more extreme GFDL weather change caused a decrease in yield ranging from 3% to 50% for irrigated corn with the decreases being greater for the more southern stations. The soybean model predicted less yield decreases than the corn model under the irrigated GFDL conditions, the decrease ranging from zero to a maximum of 30%. The maximum decreases occurred in the southernmost locations. In the most northern latitudes where the warmer conditions provided a longer frost-free growing season, the increased temperatures had a beneficial effect on simulated yields. Because the GISS model generated smaller temperature increases, the effects on yield were less extreme but followed the same general pattern as the GFDL model.

The rainfed crop yield under GFDL weather was reduced quite substantially when compared to irrigated crops at most sites. With a few exceptions, when using GISS weather with a slight increase of rain during the growing period, yield decreases were relatively small. The amount of irrigation water required for optimum yields was closely related to the amount of rainfall in the growing season. Water requirements increased an average of about 90% under GFDL conditions when compared to the baseline weather, and decreased an average of about 30% under GISS conditions.

At Fort Wayne a longer season corn cultivar adapted to a more southern climate could compensate for some of the lost yield due to climate change. Full compensation could not be obtained, however, because the grain-filling duration is not substantially different between corn cultivars.

The direct effects of CO_2 were studied by running versions of the maize and soybean models with modified photosynthesis and transpiration calculations. The direct effect of CO_2, as approximated in the modified crop models, increased yields when compared to weather effects alone for both crops at all locations. In some situations the direct effects overcame the predicted weather-related yield losses.

[1]Although the information in this report has been dunded wholly or partly by the U.S. Environmental Protection Agency under contract no. CR-814601-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

[2]The word maize refers to the crop Zea mays L. which, in the United States, is usually called corn.

CHAPTER 1

INTRODUCTION

DESCRIPTION OF THE ECOLOGICAL SYSTEM

Our part of the Global Climate Change study concentrated on corn and soybean production in the Great Lakes region, using weather from 18 sites in 10 states (the eight states bordering the Great Lakes, plus Iowa and Missouri). This region extends to the northern limit of the major growing region for corn and soybeans in North America. The long, cold winters throughout most of the region place a constraint on crop productivity because of the short growing season. However, corn production is high in the region. Variability of yields is also high owing to the variation in precipitation and temperature in the area.

The variation in the water-holding capacity of the soils in this region also contributes to the variability in yield.

RECENT LITERATURE

Simulation models of crop production and yield have been used to examine potential effects of CO_2 enrichment on crop production since at least 1970. Duncan and Barfield (1970) showed that while CO_2 was limiting photosynthesis at certain layers in a corn canopy under ambient CO_2 conditions, it was nonlimiting at concentrations of 600 parts per million.

In a U.S. Department of Commerce report (1975), yield simulation models were used extensively to evaluate the impact of climate change on the biosphere. The focus of that study was to determine how increased stratospheric flight would affect weather and crop production. The principal thrust of the report dealt with lowered temperatures, although some simulations of crop yield were done for elevated temperatures. In the same report, results of corn yield simulations (Benci et al., 1975) indicated that elevated temperatures would decrease the length of the growing season and move the corn belt northward. This led to the conclusion that U.S. corn production would increase with a small (2°C) temperature increase because a larger section of the northern states (Minnesota, Wisconsin, and Michigan) would have greater production possibilities. Results of the soybean yield simulation (Curry and Baker, 1975) indicated that a 2°C increase in temperature would decrease yield by 4% and 13% in Ohio and Indiana, respectively, and cause no change in Iowa yields. These projections were believed to be the combined result of a decreased growing season and an increased photosynthetic rate by the plant.

Crop models were used in Ontario, Canada, to study how crop yields would be affected by climate change as predicted by the GFDL and GISS models for doubled CO_2 (Smit, 1987). Their corn yield simulation using both scenarios indicated that corn could be produced in northern Ontario where the season at present is too short, and that yields in southern Ontario would be decreased by 10% to 35% for all but poorly drained soils. This latter finding primarily resulted from a shortening of the growing season due to an approximate 1.5°C increase in the average temperature as predicted by both global climate models.

Van Keulen et al. (1981) used dynamic crop growth simulation models to evaluate net assimilation and transpiration and their ratios for C3 (wheat) and C4 (corn) crops exposed to increased (430 ppm) CO_2. Their results demonstrated that stomatal behavior was the key factor in determining plant response to increased CO_2 under nonlimiting water and nutrient conditions when the length of the season was the same.

Other studies (World Meteorological Organization (WMO), 1984; Carter et al., 1984) evaluated the potential climate effects of increased CO_2 on crop production, exclusive of physiological effects. A meeting of experts organized by the WMO and the International Meteorological Institute in Stockholm concluded that studies with mechanistic crop models coupled with climate change scenarios are an appropriate first step approximation in studying the impacts of increasing CO_2 on crop growth and yield (WMO, 1984). Carter et al. (1984) tested the sensitivity of crop models to daily and monthly time resolutions and found that monthly climatic variables are adequate for limited crop modeling studies. They reported differences between short-term and long-term responses to climate change.

Few studies have considered both climatic and physiological effects simultaneously. Baker et al. (1985) adapted a detailed crop-climate model to investigate the interactive effects of CO_2, leaf area index (LAI), and the environment on midday crop water-use and water-use efficiency. The results showed that increased CO_2 in conjunction with increased LAI can offset the lowered transpiration caused by increased stomatal resistance. Stewart (1986) used results from a doubled CO_2 experiment to run a generalized crop growth model for Saskatchewan spring wheat with a 15% increase in photosynthetic capacity. Predicted climate changes caused a reduction in wheat yield even with the increase in photosynthetic capacity.

ORGANIZATION OF THIS REPORT

In this report we discuss the CERES-Maize and SOYGRO crop models, and how they were used with the global warming weather scenarios. The strengths and limitations of using these models with the predicted weather are examined. Eighteen sites in the Great Lakes region were chosen to represent a cross-section of the region for simulation of yields under the baseline weather and two GMC-modeled weather conditions with doubled CO_2. We also simulated irrigated yields in order to evaluate the impact of temperature changes alone on simulated yields. We briefly evaluated how changing genetic types can help compensate for some yield loss. In order to determine how direct effects of CO_2 increase may influence crop yields, separate runs were made to compare them with the more direct effects of temperature and rainfall alone on simulated yields. Appendices of model run output summaries and soil properties are included at the end of the report.

CHAPTER 2

METHODOLOGY

THE EFFECTS MODELS

Development of the Model

The CERES-Maize and SOYGRO simulation models are designed to predict the growth components and yield of different corn and soybean varieties for all cropping seasons and all types of environments where the crops are generally grown. The models are designed primarily to predict:

1. Phenological development or duration of growth stages as influenced by plant genetics, weather, and soil factors;
2. Apical development as related to morphogenesis of vegetative and reproductive structures;
3. Extension growth of leaves and stems and senescence of leaves;
4. Biomass production and partitioning;
5. Root system dynamics; and
6. The effect of soil-water deficit and nitrogen deficiency on the photosynthesis and photosynthate partitioning in the plant system.

The models simulate the values of the predicted variables over a sampling interval of one day, that is, these values are a sequence of numbers spaced at 24-hour intervals. The models are programmed in FORTRAN 77 and set up to run interactively on any IBM-compatible microcomputer with at least 256 kilobytes of random access memory (RAM). In a Compaq microcomputer with 640 kilobytes RAM, simulation time of one cropping season for the CERES-Maize model with N fertilizer as nonlimiting (i.e., nitrogen subroutines are shut off) takes about 15 to 20 seconds.

The input variables necessary to run the crop models can be divided into three categories: (1) the exogenous input variables, which are uncontrollable and may be stochastic in nature; (2) the controllable input variables, which are deterministic in nature; and (3) the system parameters, which are the coefficients in the analytical equations describing the model.

The exogenous input variables are the daily solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (^oC); and rainfall (mm day^{-1}).

The controllable input variables are the beginning day of the simulation; day of the year for sowing; plant population (plants m^{-2}); row spacing (m); depth of sowing (cm); day of the year and amount of irrigation (mm) (amount of irrigation can be automatically calculated by the program); and nitrogen fertilization status. For application of the model to climate change, nitrogen fertilizer is assumed to be nonlimiting.

The natural system parameters are the latitude of the production area, the soil parameters, and the initial conditions of the soil profile: soil albedo; upper limit of stage 1 soil evaporation (mm); soil-water drainage constant; and USDA Soil Conservation Service curve number to calculate runoff (CN2). There are also parameters for each soil layer: the lower limit of plant extractable soil water (volume fraction); drained upper limit soil water content (volume fraction); saturated water content (volume fraction); weighting factor for new root growth distribution; bulk density; and initial soil water content (volume fraction).

The system design parameters are the genetic coefficients of the variety. For CERES-Maize these coefficients are P1 (thermal time required from emergence to end of juvenile stage); P2 (rate of photo-induction; in degree-days per hour); P5 (thermal time required for grain filling); G2 (potential kernel number); and G3 (maximum daily rate of kernel fill, in mg per kernel). SOYGRO has similar types of coefficients to describe genetic variation in plant growth and development. These are described in more detail in another section of this report by Peart et al.

The simulation models were developed from experimental data and expert opinion (where experimental data are not available) from many locations over the past eight years. Because they are models with simplified functions representing mechanistic responses, they are not calibrated for any particular location, environment, or soil type.

The CERES-Maize model is documented in the book, CERES-Maize: A Simulation Model of Maize Growth and Development, edited by Jones and Kiniry (1986), and is available from the Texas A&M Press. The SOYGRO model is documented in a technical publication by Wilkerson et al. (1983). Users' guides are available from the primary developers of the models (Ritchie-Maize[3]; Jones-SOYGRO[4]).

However, since the published documentations were developed, both models have been modified and in the past three years, both models have been subjected to international testing.

Limitations Inherent in the Models

The limitations and/or assumptions of the crop models are (1) weeds, diseases, and insect pests are controlled to the extent that they have no economic effect; (2) except for nitrogen, all nutrients required for plant growth are nonlimiting; (3) there are no highly problematic soil conditions, such as high salinity and acidity, heavy compaction, or trace element deficiencies; (4) there are no catastrophic weather events such as hailstorm, tornado, flood, excessive rain, and typhoons; (5) the model, except as amended for a part of this study, does not consider the direct effects of CO_2 on photosynthesis and transpiration.

This latter limitation could cause the model to produce a lower estimate of yield for higher than normal CO_2. The photosynthetic rate at any light level would be greater than the value calculated unless increased canopy resistance offsets the expected photosynthetic increase. The transpiration rates may be lower than calculated as a result of increased stomatal resistance at elevated CO_2 levels.

The models attempt to account for the supply of biomass (photosynthesis) to support organ growth and respiration and as well as the demand for the biomass as determined by the potential growth rate of plant organs. The potential rate of expansion of leaves, stem, and grain is influenced by temperature. An increased supply of assimilate caused by high CO_2 may not cause a more rapid rate of aboveground organ growth, possibly canceling some of the benefit of increased photosynthesis.

Partitioning of assimilates into various growing organs follows a qualitative (Brouwer, 1965; Whisler et al., 1986) pattern of priorities. The primary principles are that (1) if the soil-supplied materials (water and nutrients) are nonlimiting, and the atmospheric-supplied energy and materials (light and CO_2) are in limited supply, the plant top parts have priority; and (2) if the atmospheric sources are nonlimiting but the soil-supplied materials are limited, the root system has priority for the assimilates. In general, the elevated CO_2 makes photosynthesis less limiting. The plant tops may be growing at an optimum rate and the extra assimilate supply may be partitioned to the root system, increasing its size and, thus, may have little influence on aboveground biomass growth rates, unless plants can develop tillers or new branches as a sink for the

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[4]Dr. Jim Jones, Department of Agricultural Engineering, University of Florida, Gainesville, FL 32611.

added assimilate supply. Since modern corn does not tiller or branch to any significant extent, there may be little net effect on growth rates of aboveground biomass caused by CO_2 increases. However, soybeans can branch more heavily if additional assimilate is available. Therefore, direct effects of CO_2 could cause a greater growth rate in soybean than in corn.

THE WEATHER SCENARIOS

The Scenarios Used

From baseline weather data (1951-1980) provided by National Center for Atmospheric Research, Boulder, Colorado, we used 18 weather stations in the 10 states of our study area. These stations (with the soils and cultivars used for the run of the models) are shown in Table 1A. The weather data from NCAR contained the maximum and minimum air temperatures and precipitation; solar radiation was generated from the temperatures and precipitation using equations from the weather generator program WGEN (Richardson, 1985).

For this study we used the predicted average temperature, precipitation, and solar radiation from the GISS and GFDL doubled CO_2 steady-state scenarios. We multiplied the baseline weather data by the percent changes between the model values for current averages in a grid cell to predicted future averages in the same cells. Table 1B shows the average changes from the baseline weather of all the GISS grid boxes that overlapped our study area. Table 1C shows the average climate change for three strips of GFDL grid cells that were in our study area.

Limitations of the Weather Scenarios

The crop models are sensitive to the dates of occurrence of precipitation as well as to the total amount of the rainfall. Since the scenarios simply multiply the daily baseline rainfall amount by the percent change in rainfall amount, the scenarios did not simulate change in frequency of rain occurrence. A month with fewer days of heavier rain might have more evapotranspiration and cause more plant stress than a month with an identical amount of rainfall over a greater number of days. Any rainfall frequency change could impact on frequency and duration of plant stress.

The changed maximum and minimum temperatures were calculated by multiplying the baseline temperatures by the change in average temperatures predicted by the climate models. Thus the change in average temperature assumes little change in daily variations in temperature. The temperature functions for plant development are linear between 8°C and 34°C. If the daily variations are incorrect from the GCM model assumptions, there would be little change in the model outcomes as long as the temperatures are within this range. Simulated yields would be more uncertain with the greater the duration within a day that the temperature is above 34°C. This condition would occur in a few days of July and August for the GFDL scenario in the southern regions of the Great Lakes area.

SIMULATIONS WITH THE MODEL

We generated a list of typical soils to be simulated. From that list we chose a soil that is most representative of the region for each of the 18 sites. A variety for each crop was chosen based on genetic parameters of maturity type and photoperiod that were suited for the current climate, but not necessarily the new climate. Runs of both crops were then made with the baseline weather, GISS doubled CO_2 weather, and the GFDL doubled CO_2 weather. Both rainfed and irrigated conditions were simulated. Irrigated yields were simulated for two reasons. One was to help assess the influence of temperature change alone on yields and the other was to provide information on how valuable irrigation would be as a management alternative for the changed climate. Yield, irrigation water demand, and season length for each year's simulation were used to do our analysis.

Table 1A. Weather Stations Used

Station	Soil Type	Cultivar Soybean	Cultivar Corn
Duluth, MN	Medium Sandy Loam	EVANS	EDO
Saint Cloud, MN	Medium Silty Loam	EVANS	EDO
Des Moines, IA	Deep Sandy Loam	MGAL2	PIO 3183
Springfield, MO	Medium Sandy Loam	MG-02	PIO 3147
Saint Louis, MO	Medium Silty Loam	MG-02	PIO 3147
Green Bay, WI	Medium Silty Clay	EVANS	EDO
Madison, WI	Medium Sandy Loam	EVANS	DEKAB XL71
Peoria, IL	Deep Sandy Loam	MG-02	PIO 3720
Fort Wayne, IN	Deep Silty Loam	MG-01	PIO 3720
Indianapolis, IN	Shallow Silty Loam	MG-04	PIO 3183
Flint, MI	Medium Silty Loam	MG-01	DEKALBXL45
Muskegon Co., MI	Medium Sandy Loam	EVANS	DEKALBXL45
Cleveland, OH	Deep Silty Clay	MG-01	PIO 3720
Columbus, OH	Deep Sandy Loam	MG-02	PIO 3183
Albany, NY	Deep Silty Loam	MG-01	DEKALBXL45
Buffalo, NY	Deep Silty Loam	MG-01	DEKALBXL45
Pittsburgh PA	Medium Silty Clay	MG-01	PIO 3720
Williamsport PA	Medium Silty Clay	MG-01	DEKALBXL45

Table 1B: Average GISS Climate Change for the Entire Region

	Temperature °C	Precipitation mm/month
March-May	4.5	5.5
June-August	3.5	3.4
Sept-Nov	4.3	-14.4

Table 1C: Average GFDL Climate Change for the East-West Sections of the Region

Latitude	44°-49°		40°-44°		36°-40°	
	Temp °C	Precip mm	Temp °C	Precip mm	Temp °C	Precip mm
May	3.6	8.9	3.6	9.4	2.4	12.5
June	9.4	-45.0	7.0	-9.2	6.4	-6.6
July	9.4	-30.8	8.0	-39.6	7.4	-10.7
Aug	8.1	-13.5	4.3	0.8	4.2	7.7

At one site we selected a variety of corn that would be better suited to the changed Fort Wayne climate. Plant breeders will continue to develop new adapted varieties as the climate changes. The variety chosen for simulation was one that is presently a longer season type adapted to Missouri and southern Indiana.

Relatively simple modifications were made to the CERES-Maize and the SOYGRO models to take into account the direct effects of CO_2 on photosynthesis and transpiration in maize and soybean plants. These modifications were designed to simulate the increase in stomatal resistance as it affects photosynthesis and transpiration. The modifications were also done to determine the influence of increased CO_2 in the efficiency of biomass production. These modified models were run with the two weather scenarios for all sites.

A more technical description of the modifications made for the direct effect of CO_2 can be found in the Southeastern agriculture section of this report by Peart et al. These modified models were run with the two weather scenarios for all sites.

CHAPTER 3

RESULTS

DIRECT EFFECTS NOT CONSIDERED

Yield

The response of irrigated corn yield to temperature change (the irrigated crops should not be affected by precipitation changes) was negative at all latitudes simulated except for the 46°-48° degree zone represented by Duluth (Tables 3 and 6). With the GISS model the mean yields decreased an average of 11%, but the percentage change ranged from -3% at Green Bay to -28% at Springfield. At Duluth, the GISS scenarios increased yields by 86% (Table 6). With the more drastic increase in temperature predicted by the GFDL scenario, irrigated corn yields decreased an average of 43% except for Duluth, which had a 36% increase predicted (Table 3). These irrigated yields represent the best that presently adapted varieties can do.

Rainfed corn yields followed the trend of decreases in irrigated yields, with decreases in most latitude zones except the most northern ones (Tables 2 and 5). The GISS simulation decreases averaged about 16% for most locations (Table 5) with the increase at Duluth being about 49%. For the GFDL runs the rainfed corn yield decreases averaged about 50%, with no increase at any latitude (Table 2). This reduction was primarily associated with lower precipitation, although higher temperatures contributed to shorter growth duration.

Soybean yields under irrigation changed much less than the irrigated corn yields. With the GISS runs, on average there was little change at all locations except Duluth, which had a 181% increase (Table 12). The GFDL runs for irrigated soybeans had yield decreases averaging about 14% except for Duluth, which has a 175% increase, and Buffalo with a 3% increase (Table 9).

Rainfed soybean yields with the GISS were reduced (by an average of 13%) for two- thirds of all locations, while the other locations had an increase of yield ranging from 0.1% for Des Moines to 118% for Duluth (Table 11). The GFDL weather reduced rainfed yields by about 55%, with Duluth increasing 6% (Table 8).

Irrigation Water Demand

Water demand represents the amount of irrigation required to produce the irrigated yields. This assumes 100% efficiency of application and availability of water at the desired time. Both of these conditions are usually not possible to achieve because of unevenness of water applied by an irrigation system and an inability to deliver the water at the exact time of need.

The baseline irrigation amounts for corn varied from between 46 mm at Buffalo to 288 mm at Indianapolis (Tables 4 and 7). The GISS weather resulted in quite a mixture of changes in water required at different locations, but on average there was little significant change (4.4%). This probably results from a mixture of changing the growing season precipitation along with increasing temperatures and also decreasing the duration of the total growing season. Water-holding capacity of the soil chosen for each location also has an influence on irrigation water requirements.

For the GFDL scenario, irrigation water requirements were much higher owing to the large decrease in rainfall in that model. Percentage increases for irrigation averaged about 50%, but the range of percent change was very large, going from -7.4% in Indianapolis to +174% in Duluth (Table 4).

For soybeans, the baseline irrigation requirement was somewhat less variable than for corn, with mean values ranging from 84 mm at Duluth to 288 mm at Indianapolis (Tables 10 and 13). The GISS scenario primarily caused an increase in water demand in the range of 10-40%, but at Springfield there was a -4% change in demand for irrigation water (Table 13). The GFDL weather also caused large increases in soybean irrigation demand, averaging about 90% increase (Table 10).

We are confident that the model's predicted direction of irrigation demand change is accurate. The primary concern with regard to both water demand and yield is the possible direct effect of CO_2 on photosynthesis and transpiration as discussed in Chapter 2. In the section below we show the results of the models modified to account for the direct effects of CO_2. Also, we expect that new varieties will be found to partially offset reduced yields. This point is discussed further in Chapter 4.

DIRECT CO_2 EFFECTS CONSIDERED

The direct effect of CO_2, in combination with the weather of the GISS and GFDL scenarios, lessens the impact on yield caused by change of the weather alone. The direct effect had a larger beneficial influence on soybean yields than it did on corn yields. Decreases in irrigated corn yield were somewhat less with the direct effects than with the effects of weather alone (Tables 3 and 6). The range of irrigated corn yield changes was approximately +5% to -48%, except in Duluth where there was an increase of 100% due to the longer season. The rainfed corn usually yielded higher under the direct effect because of a better water supply resulting from lowered transpiration. The rainfed yield changes ranged around -40% to +160% (Tables 2 and 5). In general the northern sites had more positive yield changes than sites in the southern region of the Great Lakes.

For most sites, rainfed and irrigated soybean in the GISS scenario (Table 11 and 12) and irrigated soybeans in the GFDL scenarios (Table 9), the yield actually increased over the baseline yields. Yield increases ranged from 12% to 465% with the greater increases being at the northern sites where the season length is critical (Tables 9, 11, and 12). For rainfed soybean in the GFDL scenarios, the yield increase caused by the direct effects was not enough to overcome the yield decrease caused by the extreme weather in about half the cases. The change in yields ranged from +163% to -84% with no clear geographic trend, probably because of the strong influence soil type has on rainfed yield (Table 8).

The direct effect of CO_2 decreased the irrigation water demand for corn. The greater decreases in water demand were in the southern region (Tables 4 and 7) where as much as 172 mm less water would be required for the soil and weather used for Indianapolis. The soybean GISS runs showed a decrease in irrigation need when compared to weather effects alone, but most sites still had an increased demand when compared to baseline. The direct effects of CO_2 with the GISS weather changed soybean irrigation demand from the baseline by values ranging from -13% to +32%, compared to the weather effects alone, which changed demand in a range from -4% to +42% (Table 13). Under GFDL, the direct CO_2 effects caused a slight increase in demand in the north and a slight decrease in demand in the south when compared to weather effects alone (Table 10). However, in all cases there was an increased demand (from 40% to 200%) from the baseline weather.

FIGURES AND TABLES

Because the yield and irrigation water requirements vary both in space and time, we decided to provide graphic information on the temporal variations in some important aspects of the corn study for a central Great Lakes location: Fort Wayne, Indiana. This type of information helps to visualize the response more easily than is possible in the summary tables.

The relatively small year-to-year differences in irrigated corn yield (Fig. 1) are mostly caused by variations in growing season temperature. The yields produced by GISS weather change vary with the baseline yields in most years, while the yields with the GFDL weather change are considerably lower, have less temporal variation, and do not follow the pattern of the baseline. This results from a shorter growing season due to the approximate 8°C temperature increase predicted by the GFDL model.

The year-to-year variations in rainfed corn yield (Figure 2) are much greater than the irrigated yield variations. Yields for GISS weather yields are somewhat more stable with almost the same mean as the baseline yields. Yields from GFDL are also more stable than the baseline, but have a considerably reduced mean value. This decrease is the result of both shorter seasons and less rainfall.

The influence of the length of the growing season on irrigated corn yield at Fort Wayne is shown in Figure 3. Each datum point is a one-year simulation result for the three weather scenarios. This information clearly demonstrates idea that a temperature increase causes decreases in yield by decreasing the growing season in regions where the baseline temperature is high enough to provide a full season corn crop. The season length varies considerably between weather patterns, with the baseline season averaging 138 days, the GISS 116 days, and the GFDL 92 days.

The CERES-Maize and SOYGRO models calculate a soil-water deficit factor every day in order to modify the calculated potential growth and transpiration rates for water deficit conditions. Equations in the soil-water submodel calculate the potential transpiration rate and the potential root absorption rate. The soil-water deficit factor is zero when the potential absorption rate equals or exceeds the potential transpiration rate. When the potential absorption is less than the potential transpiration rate, the soil-water deficit factor increases as the absorption rate decreases. The deficit conditions are averaged for various stages of plant development to help interpret the extent to which water deficits influence yield. The water deficit factor is calculated so that a value of zero means no deficit during the season and a value of one means very large plant-water deficit. For the rainfed corn simulation at Fort Wayne, the largest soil water deficit conditions are for the GFDL weather with its lower summer rainfall (Figure 4 and Table 1C). GISS and baseline weather have rather similar average deficit factors, with minimum values at or near zero and maximum values at about 0.2 and 0.3, respectively. This result is in agreement with observations that rainfed corn yields are quite good in much of the Great Lakes region because of the reliable supply of rainfall during the growing season.

The year-to-year variations in irrigation water demand were so great that it seemed most appropriate to express the results in cumulative irrigation amounts (Figure 5) for corn at Fort Wayne. The GISS weather pattern, on average, required less irrigation than the baseline or the GFDL. Average yearly irrigation amounts were about 67, 87, and 120 mm for the GISS, baseline, and GFDL scenarios, respectively. The drier years with greatest demands would require about 175% of the averages.

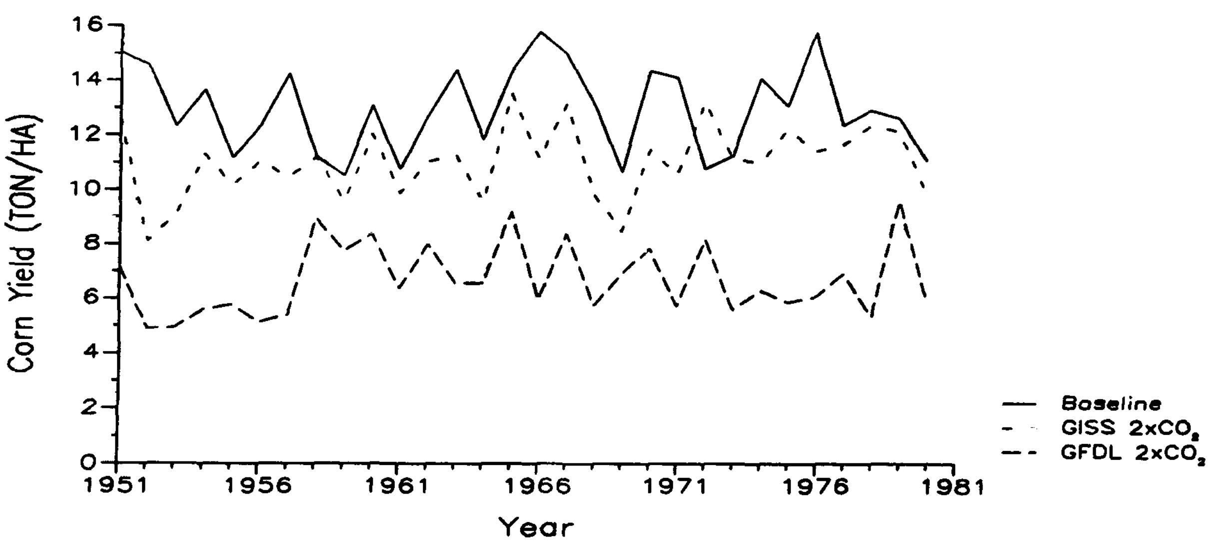

Figure 1. **Annual variation in irrigated corn yield over 30 years comparing baseline weather with GISS and GFDL weather.**

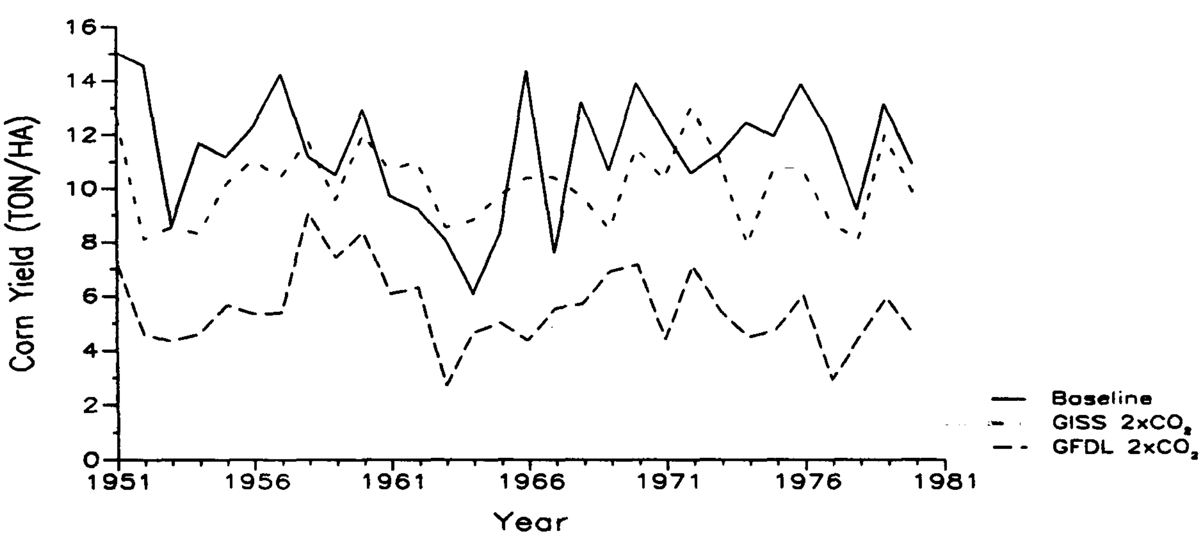

Figure 2. Annual variation in rainfed yield over 30 years comparing baseline weather with GISS and GFDL weather.

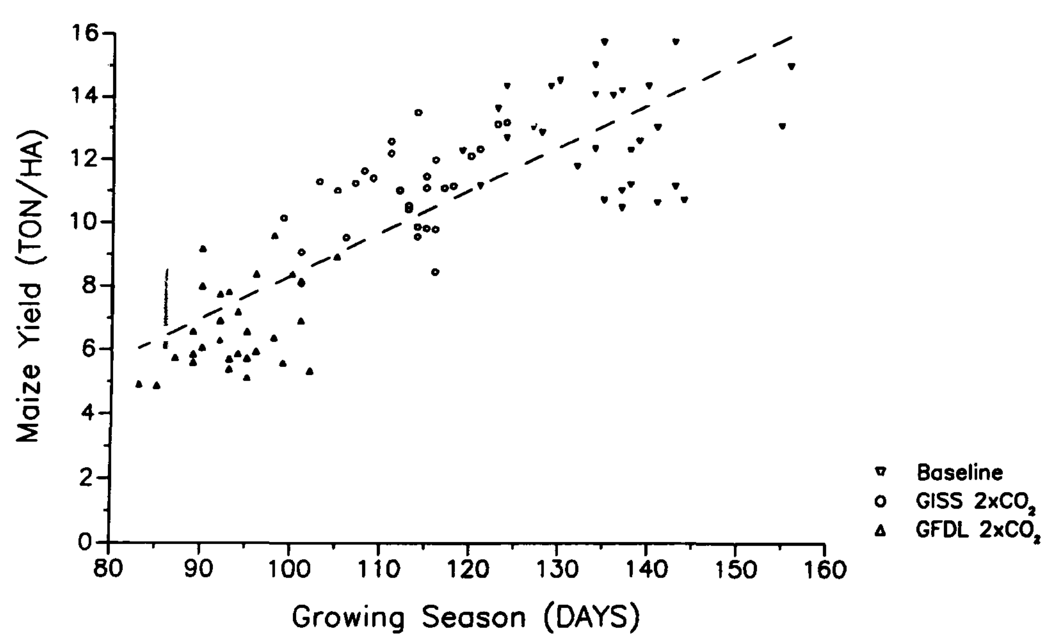

Figure 3. **Yield of irrigated corn for baseline, GISS, and GFDL weather as influenced by growing season length.**

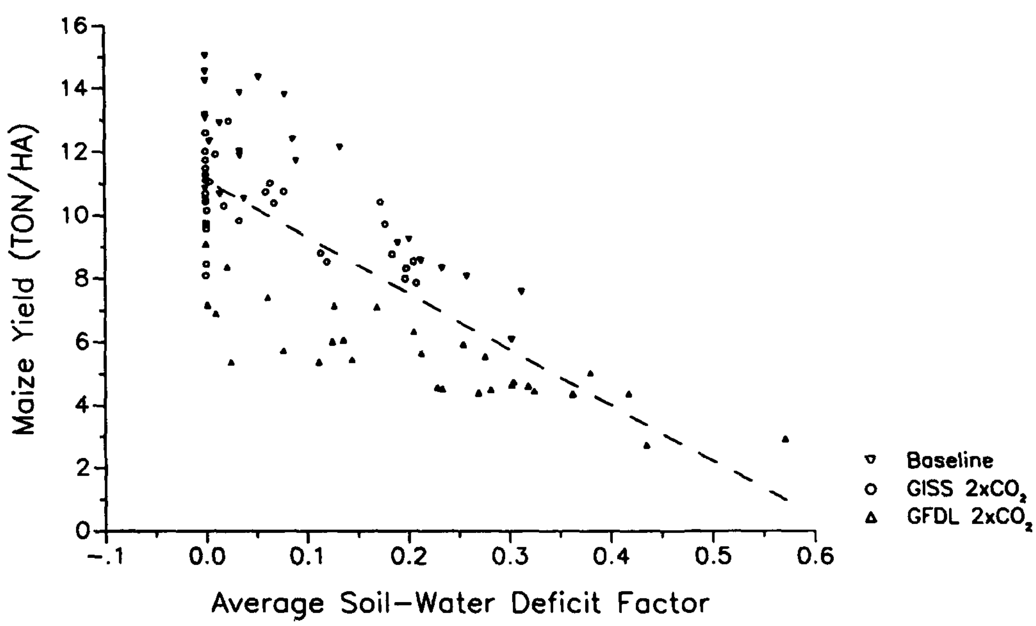

Figure 4. Average water stress compared to corn yield for present, GISS, and GFDL weather.

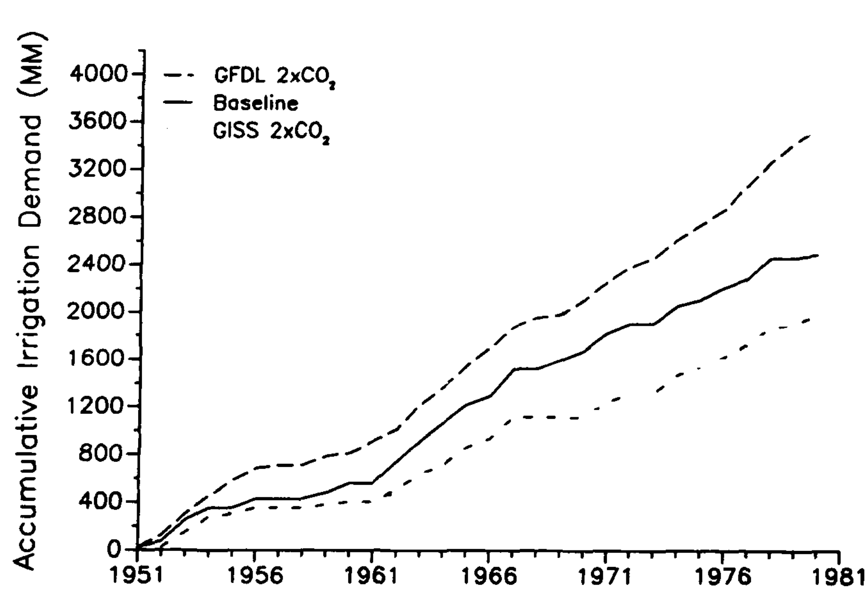

Figure 5. Water demand for irrigated corn accumulated over 30 years for corn under baseline, GISS, and GFDL weather.

As an estimation of a possible way to compensate for the lower yields caused by shorter seasons, longer season corn cultivar (B73 * M017) was compared with the adapted one chosen for the present study (PIO 3720) at Fort Wayne. For comparison, Figures 6 and 7 show the temporal variation in the irrigated and rainfed corn yields of PIO 3720 for baseline and GFDL weather. For this comparison, we chose GFDL because of the two climate models GFDL has the more extreme temperature differences from the baseline. Note that although the compensation due to cultivar change does not bring the yield to the baseline, this result provides evidence that already existing cultivars can be introduced into a region that will help overcome some of the detrimental effects of higher temperature on corn yields. The primary reason why the compensation was not better is that the grain filling period has less genetic variation available than the vegetative growth period. However, as climate changes in the future, plant breeders may be able to find sources of breeding material with longer grain fill duration that can be incorporated into high yielding corn for better yields at higher temperatures.

SUMMARY GRAPH

The most significant information from this study are yields of corn and soybean under the different climate scenarios (Figures 8 and 9). The irrigated yields are presented because they provide information on how temperature change alone affects yields. The latitude of the sites studied had some influence on baseline yields and on yield response to climate change. Baseline yields of corn are a maximum in the 44°-46°. latitude zone, although those in the 40°-44° zones are almost as good. These zones include the present corn belt. With the GISS temperature increase of about 4°C during the growing season, the maximum irrigated yields shift farther north, being maximum at 46°-48°. The GFDL temperature increase of about 6° to 8°C in the region lowered average yields compared to the other scenarios, and also shifted the maximum yielding area to latitudes farther north.

Irrigated soybean yields generally tend to be higher at the lower latitudes for both climate change scenarios and for the baseline. This is likely the result of a greater dependence of the soybean's season length on photoperiod than is the case with corn. The 4°C GISS temperature increase greatly improved the higher latitude yields over the baseline yields by increasing the otherwise unusually short and uncertain growing season length. The GFDL temperature increases reduced yields by about 20% at all latitudes except the 46°-48° latitude region.

LIMITATIONS

The primary limitations on the results from this study center on four issues:

1. Direct effects of increased CO_2 on photosynthesis and biomass production rates: Higher temperatures increase plant respiration, but higher CO_2 increases gross photosynthesis. Research to date indicates that the net biomass production rates will be greater for most crop plants with higher CO_2. Since the CERES-Maize model primarily produced yield reductions of corn due to shorter seasons, the bias in this limitation would cause a low estimate of biomass production in corn without greatly affecting yields. Grain filling rates at temperatures above 18°C are constant, yet the temperature influences duration of grain fill in the range from 8°C to 34°C.

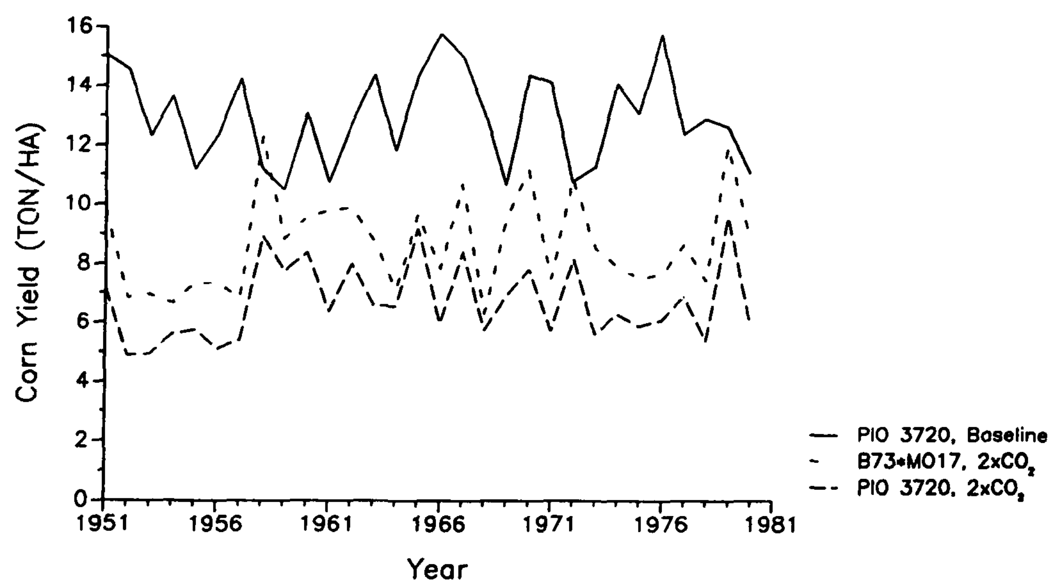

Figure 6. **Yield of irrigated corn (variety PIO 3720) grown under baseline and GFDL weather conditions and variety B73*MO17 grown under GFDL weather conditions.**

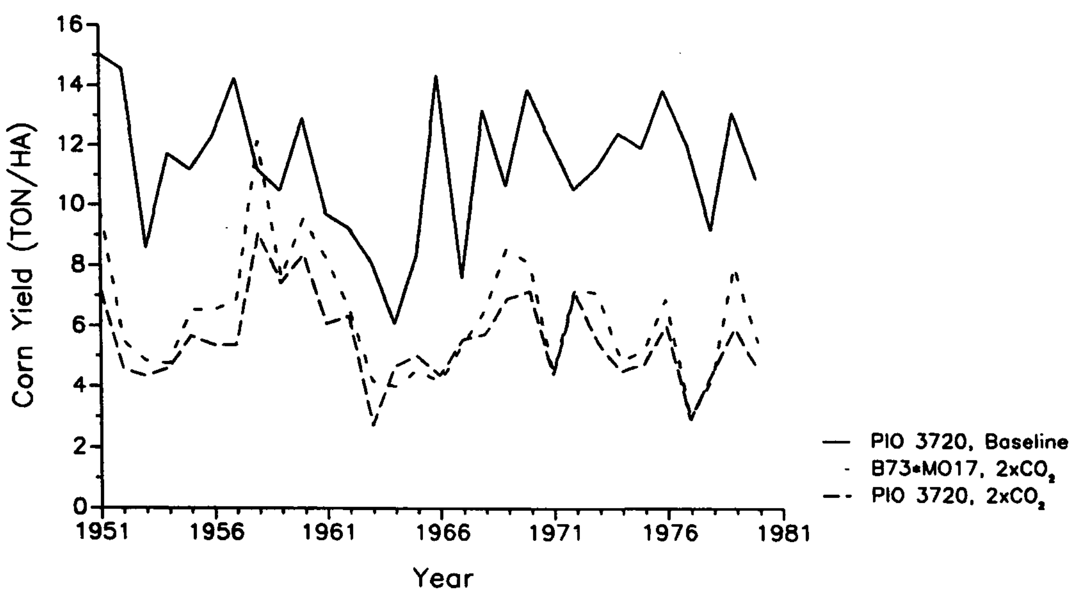

Figure 7. Yield of dryland corn (variety PIO 3720) grown under baseline and GFDL weather conditions and variety B73*MO17 grown under GFDL weather conditions.

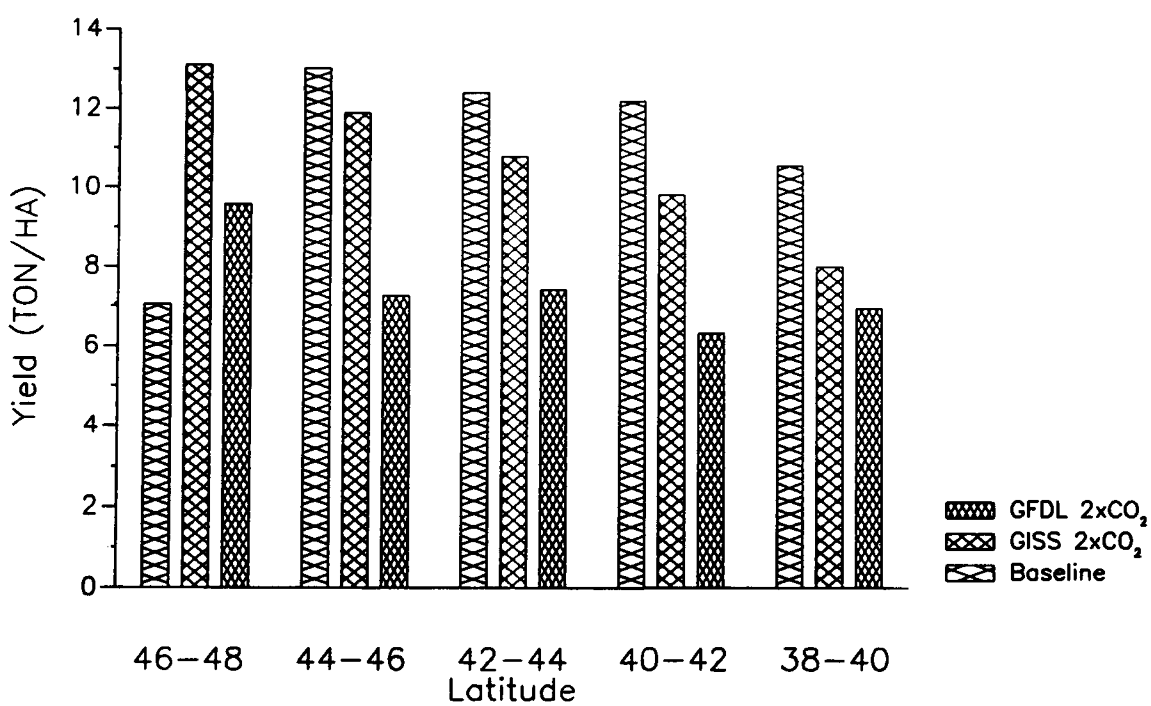

Figure 8. Comparison of average irrigated corn yield for five latitude zones in the Great Lakes region with baseline, GISS, and GFDL weather.

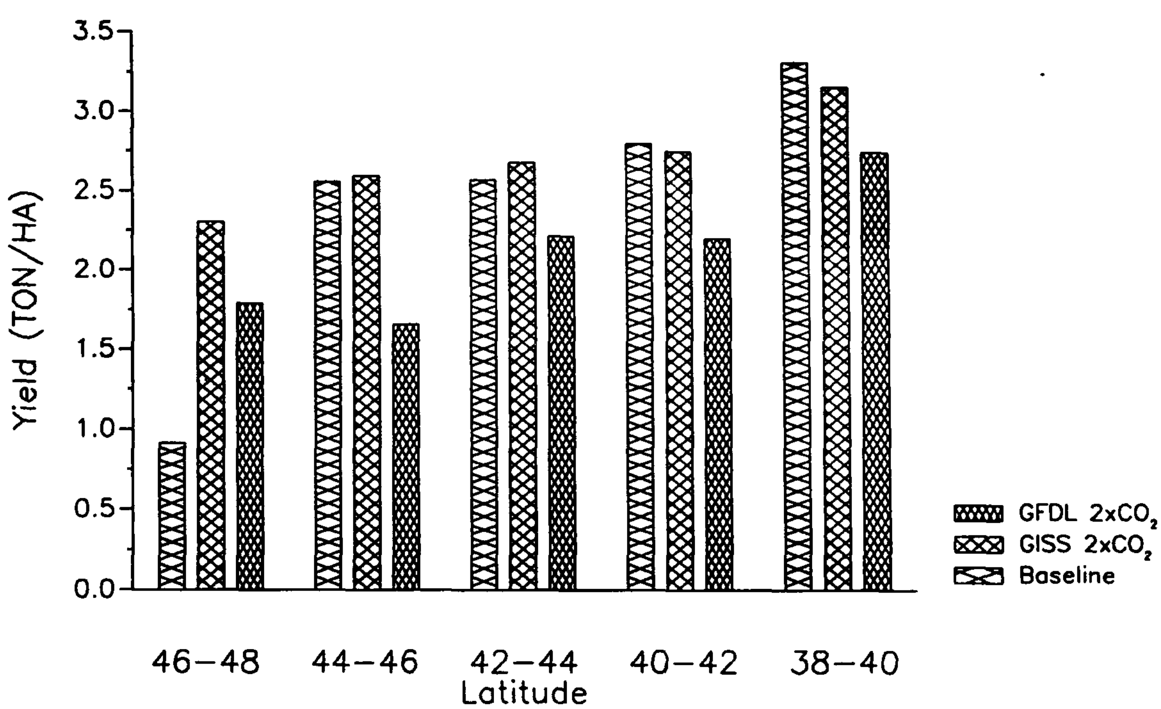

Figure 9. Comparison of average irrigated soybean yield for five latitude zones in the Great Lakes region with baseline, GISS, and GFDL weather.

2. Direct effects of increased CO_2 on transpiration: In rainfed crop production, the possible direct effect of CO_2 causing a reduction in transpiration would result in some yield improvement over the present modeled values as demonstrated in the direct effect results. However, this would occur only in years and locations where a significant soil water deficit reduced yields in the baseline analysis.

3. Effects of changing climate on pests: The assumption that pests do not affect yields is always a limitation in yield estimation. Increased temperatures will create different environments for diseases, insects, and weeds such that difficult, new pest problems may emerge. Any associated humidity changes will also affect pests, especially leaf diseases. Higher temperatures without higher vapor pressures would lower the relative humidity, thus decreasing some disease susceptibility.

4. Technical limitations in the model assumptions and relationships exclusive of pest problems: The limitations inherent in the models were discussed in an earlier section of this document and will not be repeated here. However, three limitations that could influence the results of this study need further discussion.

   A. Biomass production rates are calculated using the concept of a constant light conversion efficiency. This efficiency is expressed in grams biomass per megajule of intercepted photosynthetic radiation. Temperature extremes and soil-water deficits decrease the efficiency. This simplified analysis of biomass production assumes that respiration is proportional to the gross photosynthesis. Since respiration increases at higher temperatures, the bias in the modeled biomass without the direct affects of CO_2 would be toward lower production than predicted.

   B. Partitioning of the biomass is one of the greatest uncertainties in model descriptions of a complex biophysical system. Partitioning is dynamic and has feedback systems that are difficult to measure and model. The CERES-Maize model calculates a potential rate of growth of aboveground organs at various stages of growth. This potential rate is independent of biomass production rate and is usually dependent on temperature. It is only when the biomass production rate cannot support the potential organ growth rates that top growth is reduced. Otherwise, biomass not needed for top growth produces extra root growth. The balancing of this dynamic partitioning of biomass between growing organs on a plant is probably the major source of error in simulation models.

   C. Determination of the number of seed or kernels that will fill is a major determinant of yield. This number is usually determined during a relatively short time when plants change from growing leaves to growing grains. In CERES-Maize, grain number is calculated as a function of the rate of biomass production during pollination and cob growth. This is about 20 days in the Great Lakes region with baseline temperatures and would be somewhat shorter with increased temperatures.

CHAPTER 4

INTERPRETATION OF THE RESULTS

In our analysis of climate change in the Great Lakes region, it seems clear that the increase in temperature is the major cause of yield reduction of both corn and soybeans. The smaller temperature increase of the GISS model caused smaller yield reductions compared to those calculated using the GFDL model. The primary exception to this trend was the northernmost location, Duluth, which has a short and variable frost-free growing season for corn and soybeans under the baseline conditions. With temperature increases, northern areas can have longer, more stable seasons, thus providing an improved environment for crop production.

The changes in precipitation for the two climate scenarios studied had a relatively minor influence on the results of the study as is evident from the rainfed yields for both corn and soybeans. The small increase in precipitation during most of the growing season for the GISS model actually decreased the duration of water deficit periods as compared to the baseline weather. The major reductions in precipitation during June and July for the GFDL weather increased water deficit durations when compared to the baseline weather. However, because of the considerably shorter plant life cycle caused by higher temperatures, the water deficit influence was of secondary importance.

The water deficit problem caused by the GFDL weather would be more important on soils with low water holding capacity in the root zone such as sandy soils, shallow soils, or soils with high water tables in the spring that lower during the summer.

If higher temperatures reduce general crop production capability in much of the U.S., the Great Lakes region should become more critical for crop production because of water availability for supplemental irrigation. Crops grown in humid regions have lower irrigation water requirements than crops in arid regions that presently depend heavily on diminishing water supplies for crop production. If the humid regions are to provide a stable supply of food, supplemental irrigation will be needed in many soils to produce the yield levels that were simulated for this report. In drier years in the Great Lakes region water needs are approximately 25 cm for baseline corn and soybean irrigation, but the average need is less than 10 cm. However, the irrigation systems and water supply must be designed for the more severe drought conditions.

We have attempted to demonstrate that a part of the yield reduction in corn related to shorter seasons can be overcome with selection of new cultivars that have a longer growing season. There is a limit, however, to the degree of genetic material that is available for selection of cultivars that completely compensate for weather changes. When the limit of season length change for cultivars of a crop is reached and there is still more growing season left, then double cropping can be practiced to increase annual production. This is a common practice in the southeastern U.S. where soybeans often follow a winter wheat crop or where two corn crops are grown in one season.

The CERES-Maize and SOYGRO models are sensitive to temperature as it affects plant development and to the soil water balance as it affects plant stress. Gradual changes in these two variables should be properly accounted for in the models. The direct effects of CO_2 on photosynthesis and transpiration were unaccounted for in versions of the models developed from field data in recent literature.

However, the direct effects as incorporated in the model usually provided some compensation for yield losses caused by shortened seasons. It would be rather certain that for much of the season when leaf area index is relatively low, there would be less water used by the crop and thus there would be a reduction in plant stress and irrigation water requirement.

CHAPTER 5

IMPLICATION OF RESULTS

ENVIRONMENTAL IMPLICATIONS

With temperature changes predicted by the GISS and GFDL models used, there would be major changes in the best type of crop to grow, especially in the northernmost latitudes of the eastern U.S. and the central latitudes around 38°. The northern states would become much more productive for annual crops like corn and soybeans because of the lengthening of the frost-free period. However, many of the glacial till soils in the northern latitudes are not as productive as the corn belt soils. Thus, large increases in crop production would require irrigation to supplement rainfall and create a greater need for chemical fertilizers.

The careless use of both irrigation and fertilizers in humid regions on sandy soils creates a definite environmental hazard to the region's groundwater. It would be necessary to carefully manage water and fertilizer in such a way that chemical concentrations of water-soluble nutrients, like nitrogen and potash, would be kept to a minimum to prevent leaching, yet be kept high enough to support good plant growth. This goal can be achieved by frequently applying the fertilizers in small quantities to "spoon-feed" the plants as they need the nutrients rather than by applying everything at once and expecting the soil to retain it until the plants use it. Most major commercial farmers currently apply fertilizer once before planting to save time and money. Improved soil and water management policy would need to deal with this problem if more of the fragile lands along the eastern U.S.-Canada border are to be cultivated.

The increased length of the growing season in the northern United States could increase the demand for farmland in this region. Because of the presence of forests and wetlands in the northern U.S., care will have to be taken to choose land most suitable for cropland. Environmental impact studies, with a view toward ground and surface water contamination problems, will need to be conducted before starting drainage projects and deforestation to create new cropland.

In the southern Great Lakes region, the frost-free seasons would be lengthened considerably and the crop growth cycles would be shortened. To cope with this, new varieties would be needed to lengthen the growing cycle. However, there is a limit to how much this would achieve within a crop species. One alternative would be to plant crops such as perennials that can be grown as annuals, e.g. cotton, a crop that continues its growing cycle through the whole season. Another alternative would be to grow two crops within one season in the southern Great Lakes region. Soils there are usually quite good.

The water supply for the irrigation needed to stabilize production in the humid regions would come from both surface and subsurface sources. Detailed studies would be needed to evaluate the impact of irrigation on streamflow and water table levels. The main problem will be to have a stable water supply when the region is quite dry during droughts. Storage sites and use of water from the Great Lakes would also need to be considered.

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APPENDIX A: PROPERTIES OF SOILS USED

For each soil there are various lines of information. Line one contains:

Bare soil albedo, unitless.

Upper limit of stage 1 soil evaporation, mm.

Soil water drainage constant, fraction drained per day.

SCS curve number used to calculate daily runoff, unitless.

For the remaining lines there is information about each of the n soil layers:

Thickness of soil layer, cm.

Lower limit of plant-extractable soil water of soil layer, cm^3/cm^3.

Drained upper limit soil water content for soil layer, cm^3/cm^3.

Saturated water content for soil layer, cm^3/cm^3.

Initial soil water content for soil layer cm^3/cm^3.

Weighting factor for soil layer to determine new root growth distribution, unitless.

Moist bulk density of soil in soil layer, g/cm^3.

Organic carbon concentration in soil layer, %.

MEDIUM SILTY CLAY

.11	6.00	.20	87.00

10.	.215	.361	.416	.361	1.000	1.35	1.74
15.	.216	.361	.415	.361	.819	1.36	1.66
20.	.218	.361	.414	.361	.607	1.36	1.45
25.	.221	.361	.412	.361	.407	1.37	1.12
30.	.225	.360	.409	.360	.247	1.37	.73
30.	.228	.360	.407	.360	.135	1.38	.37

DEEP SILTY CLAY

.11		6.00		.30		85.00	
10.	.215	.361	.416	.361	1.000	1.35	1.74
15.	.216	.361	.415	.361	.819	1.36	1.66
25.	.218	.361	.414	.361	.607	1.36	1.45
30.	.221	.361	.412	.361	.368	1.37	1.09
30.	.225	.360	.409	.360	.202	1.38	.65
30.	.229	.360	.407	.360	.111	1.38	.29
30.	.231	.360	.405	.360	.061	1.39	.09
30.	.231	.360	.405	.360	.033	1.39	.01

SHALLOW SILTY LOAM

.12		6.00		.20		81.00	
10.	.096	.245	.415	.245	1.000	1.36	1.16
15.	.097	.245	.415	.245	.819	1.36	1.10
15.	.098	.245	.414	.245	.607	1.36	.97
20.	.100	.245	.413	.245	.449	1.36	.77

MEDIUM SILTY LOAM

.12		6.00		.30		79.00	
10.	.096	.245	.415	.245	1.000	1.36	1.16
15.	.097	.245	.415	.245	.819	1.36	1.10
20.	.098	.245	.414	.245	.607	1.36	.97
25.	.100	.245	.413	.245	.407	1.36	.75
30.	.103	.245	.411	.245	.247	1.37	.49
30.	.105	.245	.409	.245	.135	1.37	.24

DEEP SILTY LOAM

.12		6.00		.40		77.00	
10.	.096	.245	.415	.245	1.000	1.36	1.16
15.	.097	.245	.415	.245	.819	1.36	1.10
25.	.098	.245	.414	.245	.607	1.36	.97
30.	.100	.245	.412	.245	.368	1.36	.72
30.	.103	.245	.411	.245	.202	1.37	.43
30.	.105	.245	.409	.245	.111	1.37	.20
30.	.107	.245	.408	.245	.061	1.38	.06
30.	.107	.245	.408	.245	.033	1.38	.01

SHALLOW SANDY LOAM

.13		6.00		.40		74.00	

10.	.082	.211	.342	.211	1.000	1.58	.70
15.	.083	.211	.342	.211	.819	1.58	.66
15.	.083	.211	.341	.211	.607	1.59	.58
20.	.085	.211	.340	.211	.449	1.59	.46

MEDIUM SANDY LOAM

.13		6.00		.50		70.00	

10.	.082	.211	.342	.211	1.000	1.58	.70
15.	.083	.211	.342	.211	.819	1.58	.66
20.	.083	.211	.341	.211	.607	1.59	.58
25.	.085	.211	.340	.211	.407	1.59	.45
30.	.086	.211	.339	.211	.247	1.59	.29
30.	.088	.211	.338	.211	.135	1.60	.15

DEEP SANDY LOAM

.13		6.00		.50		68.00	

10.	.082	.211	.342	.211	1.000	1.58	.70
15.	.083	.211	.342	.211	.819	1.58	.66
25.	.083	.211	.341	.211	.607	1.59	.58
30.	.085	.211	.340	.211	.368	1.59	.43
30.	.087	.211	.339	.211	.202	1.59	.26
30.	.088	.211	.338	.211	.111	1.60	.12
30.	.089	.211	.337	.211	.061	1.60	.04
30.	.089	.211	.337	.211	.033	1.60	.01
30.	.089	.211	.337	.211	.018	1.60	.00

SHALLOW SAND

.15		4.00		.40		75.00	

10.	.030	.106	.319	.106	1.000	1.66	.29
15.	.031	.106	.319	.106	.819	1.66	.28
15.	.031	.106	.318	.106	.607	1.66	.24
20.	.031	.106	.318	.106	.449	1.66	.19

MEDIUM SAND

.15		4.00 -		.50			70.00
10.	.030	.106	.319	.106	1.000	1.66	.29
15.	.031	.106	.319	.106	.819	1.66	.28
20.	.031	.106	.318	.106	.607	1.66	.24
25.	.031	.106	.318	.106	.407	1.66	.19
30.	.032	.106	.317	.106	.247	1.66	.12
30.	.033	.106	.317	.106	.135	1.66	.06

DEEP SAND

.15		4.00		.60			65.00
10.	.030	.106	.319	.106	1.000	1.66	.29
15.	.031	.106	.319	.106	.819	1.66	.28
25.	.031	.106	.318	.106	.607	1.66	.24
30.	.032	.106	.318	.106	.368	1.66	.18
30.	.032	.106	.317	.106	.202	1.66	.11
30.	.033	.106	.317	.106	.111	1.66	.05
30.	.033	.106	.316	.106	.061	1.66	.01
30.	.033	.106	.316	.106	.033	1.66	.00
30.	.033	.106	.316	.106	.018	1.66	.00

APPENDIX B: TABLES OF RUN RESULTS

For both crops for each of the two scenarios there are three tables comparing results of the new weather with the baseline weather at each of the stations. These three tables compare non-irrigated yields, irrigated yields, and water demand for the irrigated crops. The stations are broken up into five groups based on latitude:

Group 1	46°-48°
Group 2	44°-46°
Group 3	42°-44°
Group 4	40°-42°
Group 5	38°-40°

For each station there are 10 columns of information (5 each for weather effects and weather effects with direct effects of CO_2) about either crop yield or water demand:

Mean of variable (yield or water demand) for 30 years under baseline weather.

Mean of variable under new weather conditions (GISS or GFDL).

Mean of the difference between present and new weather.

Percent change of variable from baseline weather to the new weather.

Percent of uncertainty of the change from present to new weather. Uncertainty is calculated to be the quotient of the standard deviation of the difference of the means divided by the mean of the baseline value. This allows a relative comparison between the variability of yield and irrigation demand differences due to climate changes.

Table 2: Great Lakes Corn Yield (Kg/ha) -- Baseline and GFDL 2xCO2 -- Rainfed

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	5804.5	4049.5	-1754.9	-30.2	13.2	5804.5	9652.7	3848.3	66.3	13.6
II.	St. Cloud, MN	3769.2	945.2	-2824.0	-74.9	13.1	3769.2	3487.3	-281.9	-7.5	16.7
	Green Bay, WI	5986.1	2375.1	-3611.0	-60.3	10.6	5986.1	6598.2	612.1	10.2	11.6
III.	Madison, WI	8651.1	3744.4	-4906.7	-56.7	7.0	8651.1	7220.9	-1430.2	-16.5	7.0
	Flint, MI	7006.6	3678.1	-3328.5	-47.5	9.4	7006.6	7993.7	987.2	14.1	9.4
	Muskegon Co., MI	2940.9	845.9	-2095.0	-71.2	15.5	2940.9	3079.8	138.9	4.7	18.0
	Albany, NY	11054.8	5470.0	-5584.8	-50.5	4.0	11054.8	10307.6	-747.2	-6.8	4.2
	Buffalo, NY	12068.5	6380.1	-5688.4	-47.1	2.8	12068.5	8502.3	-3566.2	-29.5	2.7
IV.	Peoria, IL	7429.3	2427.4	-5001.9	-67.3	8.4	7429.3	6027.8	-1401.5	-18.9	9.0
	Des Moines, IA	7751.8	3518.7	-4233.2	-54.6	7.9	7751.8	5060.1	-2691.7	-34.7	7.6
	Fort Wayne, IN	11357.7	5555.7	-5802.1	-51.1	4.3	11357.7	7312.6	-4045.1	-35.6	4.3
	Cleveland, OH	10943.2	5457.9	-5485.4	-50.1	5.3	10943.2	7987.9	-2955.3	-27.0	4.9
	Pittsburgh, PA	9037.2	4094.6	-4942.6	-54.7	7.1	9037.2	7886.7	-1150.5	-12.7	6.7
	Williamsport, PA	8939.6	4006.1	-4933.5	-55.2	6.8	8939.6	7500.9	-1438.6	-16.1	6.4
V.	Springfield, MO	6069.1	4805.0	-1264.1	-20.8	12.6	6069.1	7164.1	1095.1	18.0	12.0
	St. Louis, MO	6399.3	4270.3	-2129.1	-33.3	11.0	6399.3	7347.1	947.8	14.8	10.8
	Indianapolis, IN	3595.7	2135.4	-1460.3	-40.6	16.2	3595.7	4853.3	1257.6	35.0	18.4
	Columbus, OH	9358.7	5043.0	-4315.7	-46.1	3.7	9358.7	5753.2	-3605.5	-38.5	3.8

Table 3: Great Lakes Corn Yield (Kg/ha) -- Baseline and GFDL 2xCO2 -- Irrigated

		Weather Effects Alone					Weather and Direct CO2 Effects				
Group	Weather Station	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	7046.0	9592.7	2546.7	36.1	11.5	7046.0	10562.3	3516.3	49.9	11.7
II.	St. Cloud, MN	13424.8	7441.2	-5983.6	-44.6	2.9	13424.8	8255.2	-5169.6	-38.5	2.9
	Green Bay, WI	12601.7	7094.4	-5507.3	-43.7	3.5	12601.7	7820.9	-4780.8	-37.9	3.6
III.	Madison, WI	12734.9	6942.3	-5792.6	-45.5	3.0	12734.9	7692.5	-5042.4	-39.6	3.2
	Flint, MI	12462.5	7737.4	-4725.1	-37.9	3.5	12462.5	8567.3	-3895.1	-31.3	3.7
	Muskegon Co., MI	12509.5	7941.9	-4567.6	-36.5	2.6	12509.5	9141.7	-3367.8	-26.9	2.7
	Albany, NY	11912.7	6800.8	-5112.0	-42.9	2.8	11912.7	7500.9	-4411.8	-37.0	2.8
	Buffalo, NY	12402.8	7756.0	-4646.7	-37.5	2.8	12402.8	8502.2	-3900.6	-31.4	2.8
IV.	Peoria, IL	12709.5	6196.2	-6513.3	-51.2	2.9	12709.5	7107.0	-5602.6	-44.1	3.2
	Des Moines, IA	9793.8	4634.6	-5159.2	-52.7	3.3	9793.8	5089.0	-4704.8	-48.0	3.4
	Fort Wayne, IN	12979.0	6694.1	-6284.9	-48.4	2.9	12979.0	7310.9	-5668.1	-43.7	3.0
	Cleveland, OH	12912.0	7328.6	-5583.4	-43.2	2.7	12912.0	7991.4	-4920.6	-38.1	2.8
	Pittsburgh, PA	12956.9	7156.8	-5800.1	-44.8	2.6	12956.9	7828.4	-5128.4	-39.6	2.7
	Williamsport, PA	11771.2	7056.7	-4714.5	-40.1	3.1	11771.2	7706.3	-4064.9	-34.5	3.2
V.	Springfield, MO	11632.6	6923.2	-4709.4	-40.5	3.7	11632.6	7538.3	-4094.4	-35.2	3.9
	St. Louis, MO	11304.5	6932.0	-4372.5	-38.7	4.2	11304.5	7608.7	-3695.8	-32.7	4.4
	Indianapolis, IN	9705.6	6044.8	-3660.7	-37.7	3.4	9705.6	6590.1	-3115.5	-32.1	3.5
	Columbus, OH	9608.1	5278.5	-4329.5	-45.1	3.4	9608.1	5724.9	-3883.2	-40.4	3.5

Table 4: Great Lakes Corn Irrigation Demand (mm/year) -- Baseline and GFDL 2xCO_2

Group	Weather Station	Weather Effects Alone					Weather and Direct CO_2 Effects				
		Mean Baseline	Mean 2xCO_2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO_2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	73.6	201.6	127.9	173.7	20.1	73.6	54.3	-19.4	-26.3	17.1
II.	St. Cloud, MN	238.7	281.2	42.5	17.8	5.8	238.7	135.5	-103.2	-43.2	5.5
	Green Bay, WI	193.0	234.5	41.5	21.5	8.5	193.0	78.7	-114.4	-59.2	7.9
III.	Madison, WI	132.8	169.3	36.5	27.5	12.1	132.8	47.3	-85.5	-64.4	10.4
	Flint, MI	156.7	188.9	32.2	20.6	11.1	156.7	48.3	-108.4	-69.2	9.9
	Muskegon Co., MI	253.2	266.7	13.5	5.3	5.9	253.2	133.8	-119.4	-47.2	5.2
	Albany, NY	59.2	122.7	63.5	107.2	22.9	59.2	.0	-59.2	-100.0	17.0
	Buffalo, NY	45.7	110.9	65.2	142.8	26.7	45.7	5.9	-39.8	-87.1	19.5
IV.	Peoria, IL	163.5	214.2	50.6	31.0	9.1	163.5	80.5	-83.1	-50.8	8.4
	Des Moines, IA	131.2	176.1	44.9	34.2	14.4	131.2	38.8	-92.4	-70.4	13.0
	Fort Wayne, IN	82.9	118.4	35.5	42.8	19.6	82.9	6.7	-76.2	-91.9	15.4
	Cleveland, OH	80.4	135.5	55.1	68.6	20.9	80.4	14.3	-66.0	-82.2	16.2
	Pittsburgh, PA	144.8	190.4	45.6	31.5	12.1	144.8	40.6	-104.2	-71.9	10.9
	Williamsport, PA	111.8	184.5	72.7	65.1	17.8	111.8	44.8	-67.0	-59.9	16.1
V.	Springfield, MO	179.5	166.0	-13.5	-7.5	10.7	179.5	55.8	-123.7	-68.9	9.0
	St. Louis, MO	180.4	187.1	6.7	3.7	9.4	180.4	56.6	-123.7	-68.6	8.2
	Indianapolis, IN	287.9	266.7	-21.2	-7.4	5.4	287.9	116.0	-171.9	-59.7	5.1
	Columbus, OH	61.8	125.3	63.5	102.9	24.4	61.8	10.1	-51.6	-83.6	18.8

Table 5: Great Lakes Corn Yield (Kg/ha) -- Baseline and GISS 2xCO2 -- Rainfed

		Weather Effects Alone					Weather and Direct CO2 Effects				
Group	Weather Station	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	5804.5	8635.6	2831.1	48.8	15.9	5804.5	14241.9	8437.4	145.4	12.1
II.	St. Cloud, MN	3769.2	3943.3	174.1	4.6	17.2	3769.2	10066.6	6297.4	167.1	20.2
	Green Bay, WI	5986.1	5547.6	-438.4	-7.3	12.9	5986.1	13075.1	7089.0	118.4	10.6
III.	Madison, WI	8651.1	7588.3	-1062.8	-12.3	8.5	8651.1	11998.8	3347.7	38.7	7.6
	Flint, MI d,	7006.6	5790.0	-1216.6	-17.4	11.3	7006.6	11096.1	4089.6	58.4	10.1
	Muskegon Co., MI	2940.9	2522.9	-418.0	-14.2	18.4	2940.9	7785.9	4845.0	164.7	26.9
	Albany, NY	11054.8	8874.0	-2180.8	-19.7	5.5	11054.8	11613.1	558.4	5.1	4.6
	Buffalo, NY	12068.5	8948.1	-3120.4	-25.9	3.5	12068.5	11191.9	-876.6	-7.3	3.0
IV.	Peoria, IL	7429.3	6517.4	-911.9	-12.3	10.0	7429.3	11238.5	3809.2	51.3	9.5
	Des Moines, IA	7751.8	6549.7	-1202.1	-15.5	8.4	7751.8	8371.8	620.0	8.0	7.5
	Fort Wayne, IN	11357.7	10141.1	-1216.7	-10.7	4.3	11357.7	12074.5	716.7	6.3	4.4
	Cleveland, OH	10943.2	8133.0	-2810.3	-25.7	6.5	10943.2	11583.3	640.0	5.8	5.1
	Pittsburgh, PA	9037.2	7087.9	-1949.3	-21.6	9.1	9037.2	11331.0	2293.8	25.4	7.2
	Williamsport, PA	8939.6	7245.1	-1694.4	-19.0	8.0	8939.6	10401.4	1461.8	16.4	6.8
V.	Springfield, MO	6069.1	6674.0	604.9	10.0	13.4	6069.1	8923.1	2854.1	47.0	12.0
	St. Louis, MO	6399.3	6302.5	-96.9	-1.5	12.3	6399.3	9261.4	2862.0	44.7	10.9
	Indianapolis, IN	3595.7	3630.4	34.7	1.0	18.2	3595.7	7316.2	3720.5	103.5	18.6
	Columbus, OH	9358.7	6998.1	-2360.6	-25.2	3.8	9358.7	7925.0	-1433.7	-15.3	3.6

Table 6: Great Lakes Corn Yield (Kg/ha) -- Baseline and GISS 2xCO2 -- Irrigated

		Weather Effects Alone					Weather and Direct CO2 Effects				
Group	Weather Station	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	7046.0	13116.1	6070.1	86.2	10.8	7046.0	14308.5	7262.5	103.1	10.8
II.	St. Cloud, MN	13424.8	11633.4	-1791.4	-13.3	2.4	13424.8	12777.7	-647.1	-4.8	2.5
	Green Bay, WI	12601.7	12167.7	-434.0	-3.4	3.2	12601.7	13286.4	684.7	5.4	3.3
III.	Madison, WI	12734.9	11025.4	-1709.5	-13.4	3.1	12734.9	12070.9	-664.0	-5.2	3.3
	Flint, MI	12462.5	10775.2	-1687.3	6 -13.5	3.6	12462.5	11867.9	-594.6	-4.8	3.8
	Muskegon Co., MI	12509.5	11350.2	-1159.4	-9.3	2.7	12509.5	12651.1	141.6	1.1	2.9
	Albany, NY	11912.7	10659.9	-1252.9	-10.5	3.4	11912.7	11627.2	-285.5	-2.4	3.7
	Buffalo, NY	12402.8	10231.1	-2171.7	-17.5	3.0	12402.8	11191.9	-1210.9	-9.8	3.2
IV.	Peoria, IL	12709.5	10517.9	-2191.6	-17.2	3.1	12709.5	11833.5	-876.0	-6.9	3.3
	Des Moines, IA	9793.8	7685.1	-2108.7	-21.5	3.2	9793.8	8405.4	-1388.4	-14.2	3.4
	Fort Wayne, IN	12979.0	11015.0	-1963.9	-15.1	3.0	12979.0	12074.5	-904.5	-7.0	3.1
	Cleveland, OH	12912.0	10403.7	-2508.4	-19.4	2.9	12912.0	11589.9	-1322.1	-10.2	3.0
	Pittsburgh, PA	12956.9	10467.7	-2489.2	-19.2	3.0	12956.9	11383.9	-1572.9	-12.1	3.2
	Williamsport, PA	11771.2	9395.9	-2375.3	-20.2	3.4	11771.2	10307.6	-1463.7	-12.4	3.6
V.	Springfield, MO	11632.6	8398.2	-3234.5	-27.8	3.9	11632.6	9220.8	-2411.8	-20.7	4.1
	St. Louis, MO	11304.5	8586.3	-2718.2	-24.0	4.3	11304.5	9412.2	-1892.3	-16.7	4.5
	Indianapolis, IN	9705.6	7806.2	-1899.4	-19.6	3.1	9705.6	8504.8	-1200.8	-12.4	3.3
	Columbus, OH	9608.1	7244.7	-2363.4	-24.6	3.2	9608.1	7925.0	-1683.1	-17.5	3.4

Table 7: Great Lakes Corn Irrigation Demand (mm/year) -- Baseline and Giss 2xCO2

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	73.6	133.7	60.1	81.6	22.7	73.6	11.8	-61.9	-84.0	14.4
II.	St. Cloud, MN	238.7	217.5	-21.2	-8.9	6.5	238.7	75.4	-163.3	-68.4	5.4
	Green Bay, WI	193.0	200.0	6.9	3.6	8.6	193.0	31.3	-161.7	-83.8	7.4
III.	Madison, WI	132.8	124.3	-8.5	-6.4	13.0	132.8	18.5	-114.3	-86.0	10.0
	Flint, MI	156.7	159.2	2.5	1.6	12.3	156.7	31.3	-125.3	-80.0	9.8
	Muskegon Co., MI	253.2	244.8	-8.4	-3.3	6.2	253.2	94.8	-158.4	-62.6	5.7
	Albany, NY	59.2	93.2	34.0	57.3	25.7	59.2	4.2	-55.0	-92.9	17.7
	Buffalo, NY	45.7	66.9	21.2	46.4	27.6	45.7	.8	-44.8	-98.2	18.7
IV.	Peoria, IL	163.5	145.7	-17.8	-10.9	10.4	163.5	32.2	-131.4	-80.3	8.3
	Des Moines, IA	131.2	114.2	-17.0	-12.9	15.3	131.2	12.6	-118.6	-90.4	12.0
	Fort Wayne, IN	82.9	65.9	-17.0	-20.5	19.7	82.9	.0	-82.9	-100.0	15.1
	Cleveland, OH	80.4	93.2	12.8	15.9	21.5	80.4	5.9	-74.5	-92.7	15.4
	Pittsburgh, PA	144.8	145.7	.8	.6	13.1	144.8	17.8	-127.1	-87.7	10.5
	Williamsport, PA	111.8	115.1	3.3	3.0	19.9	111.8	16.9	-94.8	-84.8	15.0
V.	Springfield, MO	179.5	122.8	-56.7	-31.6	10.8	179.5	35.5	-144.0	-80.2	8.4
	St. Louis, MO	180.4	143.1	-37.3	-20.7	10.0	180.4	34.7	-145.6	-80.7	7.7
	Indianapolis, IN	287.9	253.1	-34.7	-12.1	5.5	287.9	97.4	-190.5	-66.2	5.2
	Columbus, OH	61.8	59.2	-2.5	-4.1	23.9	61.8	.8	-60.9	-98.7	17.7

Table 8: Great Lake Soybean Yield (Kg/ha) -- Baseline and GFDL 2xCO2 -- Rainfed

		Weather Effects Alone					Weather and Direct CO2 Effects				
Group	Weather Station	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	705.0	748.3	43.3	6.1	19.6	705.0	1858.3	1153.3	163.6	30.6
II.	St. Cloud, MN	1818.0	103.7	-1714.3	-94.3	13.2	1818.0	298.0	-1520.0	-83.6	13.4
	Green Bay, WI	1481.3	593.7	-887.7	-59.9	8.6	1481.3	1351.3	-130.0	-8.8	12.2
III.	Madison, WI	1569.3	690.0	-879.3	-56.0	11.1	1569.3	1641.3	72.0	4.6	14.9
	Flint, MI	1846.7	939.7	-907.0	-49.1	9.5	1846.7	1934.3	87.7	4.7	12.6
	Muskegon Co., MI	1336.3	520.0	-816.3	-61.1	9.1	1336.3	1289.0	-47.3	-3.5	12.0
	Albany, NY	2365.7	993.7	-1372.0	-58.0	6.7	2365.7	2158.0	-207.7	-8.8	8.4
	Buffalo, NY	2316.3	1192.7	-1123.7	-48.5	7.3	2316.3	2700.7	384.3	16.6	9.1
IV.	Peoria, IL	1942.0	675.0	-1267.0	-65.2	8.5	1942.0	1647.3	-294.7	-15.2	11.3
	Des Moines, IA	1772.0	622.7	-1149.3	-64.9	8.6	1772.0	1495.7	-276.3	-15.6	10.9
	Fort Wayne, IN	2398.3	1061.3	-1337.0	-55.7	6.6	2398.3	2343.0	-55.3	-2.3	8.3
	Cleveland, OH	2314.3	1035.3	-1279.0	-55.3	7.9	2314.3	2360.3	46.0	2.0	10.2
	Pittsburgh, PA	2311.3	1022.3	-1289.0	-55.8	8.9	2311.3	2256.7	-54.7	-2.4	11.0
	Williamsport, PA	2173.3	1014.0	-1159.3	-53.3	9.1	2173.3	2051.3	-122.0	-5.6	11.5
V.	Springfield, MO	1805.7	1281.0	-524.7	-29.1	12.8	1805.7	2540.3	734.7	40.7	17.0
	St. Louis, MO	2079.0	1180.7	-898.3	-43.2	10.7	2079.0	2335.0	256.0	12.3	14.0
	Indianapolis, IN	1147.7	634.3	-513.3	-44.7	17.5	1147.7	1220.3	72.7	6.3	20.1
	Columbus, OH	2215.7	924.0	-1291.7	-58.3	8.5	2215.7	2123.0	-92.7	-4.2	10.7

Table 9: Great Lakes Soybean Yield (Kg/ha) -- Baseline and GFDL 2xCO2 -- Irrigated

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	877.3	2408.3	1531.0	174.5	18.8	877.3	4957.3	4080.0	465.0	17.5
II.	St. Cloud, MN	2625.0	1926.7	-698.3	-26.6	6.4	2625.0	4395.7	1770.7	67.5	5.7
	Green Bay, WI	2619.7	2370.7	-249.0	-9.5	5.7	2619.7	4442.3	1822.7	69.6	7.5
III.	Madison, WI	2552.0	2165.3	-386.7	-15.2	7.8	2552.0	4398.3	1846.3	72.3	8.6
	Flint, MI	2930.7	2750.0	-180.7	-6.2	4.8	2930.7	4641.3	1710.7	58.4	6.4
	Muskegon Co., MI	2522.0	2299.3	-222.7	-8.8	4.9	2522.0	4597.7	2075.7	82.3	7.1
	Albany, NY	3179.3	2919.7	-259.7	-8.2	2.0	3179.3	4554.0	1374.7	43.2	2.5
	Buffalo, NY	3011.3	3094.0	82.7	2.7	4.5	3011.3	4903.3	1892.0	62.8	4.5
IV.	Peoria, IL	3205.3	2505.0	-700.3	-21.8	3.2	3205.3	4462.3	1257.0	39.2	3.3
	Des Moines, IA	3385.7	2350.7	-1035.0	-30.6	3.2	3385.7	4118.3	732.7	21.6	4.2
	Fort Wayne, IN	3261.0	2739.3	-521.7	-16.0	2.9	3261.0	4537.0	1276.0	39.1	3.0
	Cleveland, OH	3051.3	2865.7	-185.7	-6.1	4.6	3051.3	4824.7	1773.3	58.1	4.6
	Pittsburgh, PA	2973.0	2848.3	-124.7	-4.2	5.8	2973.0	4887.3	1914.3	64.4	5.7
	Williamsport, PA	2866.3	2737.0	-129.3	-4.5	4.5	2866.3	4525.3	1659.0	57.9	4.6
V.	Springfield, MO	3340.0	2952.0	-388.0	-11.6	4.0	3340.0	4957.7	1617.7	48.4	
	St. Louis, MO	3526.3	2945.7	-580.7	-16.5	3.6	3526.3	4753.0	1226.7	34.8	4.4
	Indianapolis, IN	3084.3	2265.3	-819.0	-26.6	4.2	3084.3	3218.3	134.0	4.3	4.6
	Columbus, OH	3079.3	2811.7	-267.7	-8.7	5.7	3079.3	4680.0	1600.7	52.0	5.8

Table 10: Great Lakes Soybean Irrigation Demand (mm/year) -- Baseline and GFDL 2xCO2

		Weather Effects Alone					Weather and Direct CO2 Effects				
Group	Weather Station	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	83.9	244.4	160.5	191.4	20.2	83.9	257.2	173.3	206.7	21.7
II.	St. Cloud, MN	202.5	439.4	236.9	117.0	14.4	202.5	482.2	279.7	138.1	12.2
	Green Bay, WI	193.7	405.0	211.3	109.1	12.8	193.7	405.6	211.9	109.4	15.1
III.	Madison, WI	126.2	247.3	121.2	96.0	18.2	126.2	258.8	132.6	105.1	17.7
	Flint, MI	169.5	303.1	133.6	78.8	15.7	169.5	280.7	111.2	65.6	15.4
	Muskegon Co., MI	157.4	263.1	105.7	67.2	11.3	157.4	258.5	101.1	64.3	11.3
	Albany, NY	150.3	330.9	180.6	120.2	15.9	150.3	299.6	149.3	99.3	15.5
	Buffalo, NY	134.6	288.4	153.8	114.2	14.7	134.6	268.2	133.6	99.2	14.7
IV.	Peoria, IL	166.2	333.0	166.8	100.4	12.3	166.2	319.6	153.4	92.3	12.7
	Des Moines, IA	206.8	395.0	188.2	91.0	10.8	206.8	376.1	169.2	81.8	10.8
	Fort Wayne, IN	155.0	305.2	150.2	96.9	13.7	155.0	288.7	133.7	86.2	13.3
	Cleveland, OH	147.4	347.3	199.9	135.6	16.8	147.4	317.5	170.1	115.4	17.4
	Pittsburgh, PA	139.2	329.7	190.5	136.8	16.5	139.2	313.2	174.0	125.0	17.6
	Williamsport, PA	135.4	361.1	225.7	166.6	25.1	135.4	332.8	197.4	145.8	25.5
V.	Springfield, MO	193.4	279.3	85.8	44.4	15.0	193.4	270.0	76.6	39.6	15.9
	St. Louis, MO	204.8	336.5	131.7	64.3	15.1	204.8	321.8	117.0	57.1	15.1
	Indianapolis, IN	287.6	414.1	126.5	44.0	12.7	287.6	400.8	113.3	39.4	12.5
	Columbus, OH	127.7	309.4	181.7	142.3	16.9	127.7	289.2	161.5	126.5	17.6

Table 11: Great Lake Soybean Yield (Kg/ha) -- Baseline and GISS 2xCO2 -- Rainfed

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	705.0	1542.0	837.0	118.7	26.4	705.0	3454.3	2749.3	390.0	32.9
II.	St. Cloud, MN	1818.0	873.3	-944.7	-52.0	15.3	1818.0	2032.0	214.0	11.8	19.0
	Green Bay, WI	1481.3	1644.7	163.3	11.0	11.1	1481.3	3492.3	2011.0	135.8	13.9
III.	Madison, WI	1569.3	1599.0	29.7	1.9	14.0	1569.3	3529.7	1960.3	124.9	16.1
	Flint, MI	1846.7	.0	-1846.7	-100.0	7.6	1846.7	3460.7	1614.0	87.4	14.5
	Muskegon Co., MI	1336.3	1241.3	-95.0	-7.1	12.9	1336.3	2871.7	1535.3	114.9	20.1
	Albany, NY	2365.7	1882.3	-483.3	-20.4	8.4	2365.7	3765.3	1399.7	59.2	9.7
	Buffalo, NY	2316.3	2208.0	-108.3	-4.7	8.6	2316.3	4363.7	2047.3	88.4	9.2
IV.	Peoria, IL	1942.0	1890.3	-51.7	-2.7	10.5	1942.0	3843.7	1901.7	97.9	13.3
	Des Moines, IA	1772.0	1774.0	2.0	.1	10.6	1772.0	3731.3	1959.3	110.6	1
	Fort Wayne, IN	2398.3	2414.3	16.0	.7	7.5	2398.3	4442.0	2043.7	85.2	7.9
	Cleveland, OH	2314.3	2075.3	-239.0	-10.3	9.3	2314.3	4194.7	1880.3	81.2	10.4
	Pittsburgh, PA	2311.3	2171.0	-140.3	-6.1	10.4	2311.3	4193.0	1881.7	81.4	11.7
	Williamsport, PA	2173.3	1993.0	-180.3	-8.3	10.5	2173.3	3717.3	1544.0	71.0	12.3
V.	Springfield, MO	1805.7	2110.7	305.0	16.9	14.7	1805.7	3765.3	1959.7	108.5	18.8
	St. Louis, MO	2079.0	2201.0	122.0	5.9	12.9	2079.0	3860.0	1781.0	85.7	16.5
	Indianapolis, IN	1147.7	901.0	-246.7	-21.5	18.0	1147.7	1543.7	396.0	34.5	21.3
	Columbus, OH	2215.7	2065.7	-150.0	-6.8	9.6	2215.7	4156.0	1940.3	87.6	10.2

Table 12: Great Lakes Soybean Yield (Kg/ha) -- Baseline and GISS 2xCO2 -- Irrigated

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	877.3	2466.0	1588.7	181.1	21.1	877.3	4477.7	3600.3	410.4	25.6
II.	St. Cloud, MN	2625.0	3002.0	377.0	14.4	6.0	2625.0	5184.0	2559.0	97.5	5.2
	Green Bay, WI	2619.7	3023.0	403.3	15.4	4.9	2619.7	5073.0	2453.3	93.7	4.8
III.	Madison, WI	2552.0	2698.0	146.0	5.7	8.1	2552.0	5001.7	2449.7	96.0	6.1
	Flint, MI	2930.7	3219.3	288.7	9.9	3.3	2930.7	5228.3	2297.7	78.4	3.4
	Muskegon Co., MI	2522.0	2610.3	88.3	3.5	5.3	2522.0	4800.3	2278.3	90.3	7.4
	Albany, NY	3179.3	3266.0	86.7	2.7	1.8	3179.3	5099.7	1920.3	60.4	2.0
	Buffalo, NY	3011.3	3412.3	401.0	13.3	4.4	3011.3	5349.3	2338.0	77.6	4.4
IV.	Peoria, IL	3205.3	3255.0	49.7	1.5	2.5	3205.3	5317.3	2112.0	65.9	2.2
	Des Moines, IA	3385.7	3297.7	-88.0	-2.6	2.5	3385.7	5431.7	2046.0	60.4	2.2
	Fort Wayne, IN	3261.0	3270.3	9.3	.3	3.0	3261.0	5217.0	1956.0	60.0	2.7
	Cleveland, OH	3051.3	3254.7	203.3	6.7	4.7	3051.3	5269.3	2218.0	72.7	4.3
	Pittsburgh, PA	2973.0	3265.3	292.3	9.8	5.6	2973.0	5263.7	2290.7	77.0	5.6
	Williamsport, PA	2866.3	2982.0	115.7	4.0	4.5	2866.3	4916.7	2050.3	71.5	4.8
V.	Springfield, MO	3340.0	3344.7	4.7	.1	3.4	3340.0	5361.7	2021.7	60.5	3.3
	St. Louis, MO	3526.3	3451.3	-75.0	-2.1	2.8	3526.3	5330.0	1803.7	51.1	3.1
	Indianapolis, IN	3084.3	2704.3	-380.0	-12.3	4.1	3084.3	3818.7	734.3	23.8	4.5
	Columbus, OH	3079.3	3279.7	200.3	6.5	5.6	3079.3	5222.7	2143.3	69.6	5.7

Table 13: Great Lakes Soybean Irrigation Demand (mm/year) -- Baseline and GISS 2xCO2

Group	Weather Station	Weather Effects Alone					Weather and Direct CO2 Effects				
		Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change	Mean Baseline	Mean 2xCO2	Mean Diff	Mean %change	Uncer %change
I.	Duluth, MN	83.9	113.7	29.8	35.5	19.7	83.9	111.1	27.2	32.4	18.9
II.	St. Cloud, MN	202.5	216.2	13.7	6.8	11.2	202.5	199.1	-3.4	-1.7	11.0
	Green Bay, WI	193.7	218.1	24.4	12.6	11.3	193.7	195.1	1.4	.7	11.2
III.	Madison, WI	126.2	139.6	13.5	10.7	16.0	126.2	137.5	11.4	9.0	14.7
	Flint, MI	169.5	211.9	42.3	25.0	14.4	169.5	183.4	13.9	8.2	14.0
	Muskegon Co., MI	157.4	167.8	10.4	6.6	10.8	157.4	156.0	-1.4	-.9	10.9
	Albany, NY	150.3	213.8	63.5	42.2	15.1	150.3	184.7	34.4	22.9	15.5
	Buffalo, NY	134.6	183.5	48.9	36.4	13.3	134.6	161.1	26.5	19.7	13.4
IV.	Peoria, IL	166.2	183.5	17.3	10.4	11.6	166.2	155.0	-11.2	-6.8	11.7
	Des Moines, IA	206.8	211.9	5.1	2.5	9.3	206.8	193.4	-13.4	-6.5	8.8
	Fort Wayne, IN	155.0	166.3	11.3	7.3	13.1	155.0	139.2	-15.9	-10.2	12.0
	Cleveland, OH	147.4	206.0	58.6	39.8	16.2	147.4	175.3	27.9	19.0	16.1
	Pittsburgh, PA	139.2	188.4	49.1	35.3	16.6	139.2	159.9	20.6	14.8	16.7
	Williamsport, PA	135.4	182.9	47.5	35.0	23.0	135.4	162.0	26.5	19.6	22.5
V.	Springfield, MO	193.4	185.2	-8.2	-4.3	14.7	193.4	167.8	-25.6	-13.2	14.5
	St. Louis, MO	204.8	212.4	7.6	3.7	14.1	204.8	192.0	-12.9	-6.3	13.8
	Indianapolis, IN	287.6	365.6	78.1	27.1	12.0	287.6	347.5	59.9	20.8	11.7
	Columbus, OH	127.7	162.1	34.4	26.9	14.8	127.7	139.1	11.4	9.0	14.6

IMPACT OF CLIMATE CHANGE ON CROP YIELD IN THE SOUTHEASTERN U.S.A.: A SIMULATION STUDY

by

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CONTENTS

FINDINGS[1]

Simulations of soybean and corn (maize) growth for the southeastern U.S.A. were run for 30 years of weather data, 1951-80, for 19 locations, with and without supplemental irrigation, and then with weather data sets adjusted for climatic changes predicted by the GISS and the GFDL General Circulation Models for a doubling of the carbon dioxide concentration. Then the crop models SOYGRO and CERES-Maize were modified to account for the increase in photosynthesis and decrease in transpiration due to increased carbon dioxide.

In general, the climatic variable effects alone caused decreases in yields in the range of 25% for rainfed soybeans under the GISS scenario, but the GFDL weather dropped rainfed soybean yields 73%. For rainfed corn (maize), GISS weather lowered yields only 8%, but the GFDL weather cut yields by 65%.

Adding the effect of the carbon dioxide enrichment changed these yield results significantly for soybeans, but not for corn (maize). For the GISS weather scenarios and rainfed soybeans, yields for doubled carbon dioxide at 6 of the 19 locations had yield increases of over 24%; 5 of the 19 had decreases of 10 to 17%; and the average change over all locations was an increase of 9%. The GFDL weather scenario was in general more drastic (higher temperatures and lower rainfall at critical reproductive-growth periods), and the average yield reduction was 55%. Corn (maize) results were roughly the same as for the simulations with climate effects only.

Irrigation mitigated the weather effects somewhat, and soybeans yielded about 18% less than the base weather under both doubled carbon dioxide scenarios when only climate effects were included, but they yielded about 14% more when the combined climatic and direct effects were in the model. Irrigated corn (maize) yielded about 20% less under all combinations.

Irrigation demand was based on the accumulated irrigation water applied during each simulation run. For the base weather case, the averages were:

rainfall - 508 mm,
evapotranspiration - 590 mm,
irrigation requirement - 224 mm.

For runs made using the SOYGRO model incorporating the combined climate effect and the direct CO_2 effects on the plant, the GISS scenario increased the potential irrigation demand by 33%, while the GFDL scenario increased the demand by 133%.

Water-use efficiency was studied at several locations, and results, compared with base weather results, ranged from very significant reductions in efficiency to some cases of little change. Water-use efficiency was directly correlated with yield.

An obvious, but striking, conclusion is the great difference in results from use of the two different weather scenarios. It is very important to the future of southeastern U.S.A. agriculture to have acceptable estimates of these future weather trends. This cannot be solved in a short-term project, but should be carried on for a number of years, so that actual data can be used to validate the accuracy of the forecasts.

A second important conclusion is the value of physiologically based crop simulation as a method to study this type of problem. Simulation can handle changing environmental variables, even when these variables have different and sometimes opposite effects on yield. One prevalent view is that higher temperatures of the changed

[1]Although the information in this report has been funded wholly by the U.S. Environmental Protection Agency under Contract No. CR814600, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

climate will drastically reduce yields, while another view points to the increased photosynthesis under higher concentrations of carbon dioxide. Neither simplified view can make accurate forecasts of effects on actual yields.

Third, to perhaps oversimplify our results, corn yields in the southeastern U.S.A. would be reduced by the weather changes associated with doubling carbon dioxide, either moderately or drastically, depending on the weather scenario. Soybean yields would be affected little or cut in half, depending on the weather scenario. Both statements are based on the more common rainfed, nonirrigated situation.

Fourth, under either scenario, irrigation water demand would be greatly increased for two reasons: (1) crops currently irrigated would require much more water, the amount depending on the scenario; and (2) more acreage would be irrigated as weather changes cause more frequent crop failures.

A fifth conclusion should be stressed, and that is the annual variability of weather and its amplifying effect on crop yields. For example, the GISS scenario at Memphis, 1951-60, had yearly yields both higher and lower than the base weather. Therefore, with only modest changes in average yield, some drastic year-to-year variations will occur and will have important economic impact on the areas affected (see Adams et al. chapter in this report).

CHAPTER 1

INTRODUCTION

DESCRIPTION OF THE ECOLOGICAL SYSTEM

This study covers soybean and corn production in the southeastern U.S.A., and it is based on simulations by the SOYGRO V5.41 and the CERES-Maize models using actual weather data for 1951-1980 and the same data except for modification for the effect of doubled carbon dioxide on the weather.

This southeastern region studied is shown in Figure 1 and includes Louisiana, Arkansas, Kentucky, Virginia, Florida, Alabama, Mississippi, Tennessee, Georgia, North Carolina, and South Carolina. For summarizing results, the region was subdivided into Delta, Uplands, and Coastal Plains areas, where the locations share some soil and climate similarities.

The southeastern region includes the practical southern limit for corn and soybean production in the U. S. High temperatures and variability of precipitation produce significant stress on these crops in a normal year in the Southeast. Soils are quite variable, and many have a low water-holding capacity, further amplifying the potential crop stress problem. Table 1 lists the sites, the soil types used in the simulation, and the soybean varieties used in SOYGRO.

For soybeans in particular, there is a distinct relationship between the effect of temperature and rainfall at the time of reproductive fruit growth. Soybean varieties have been adapted to most areas of the region. Irrigation is not in widespread use for at least two reasons, lack of a reliable water source and a low benefit/cost ratio. On the other hand, excess water may have a destructive effect on yield, particularly during plant establishment time and during harvest.

LITERATURE REVIEW

There has been no agreement as to the combined effect of carbon dioxide changes on crop production, especially on the interaction of direct effects and indirect effects. The presence of carbon dioxide in the atmosphere could cause changes in important weather variables such as temperature, solar radiation and precipitation. The plant also responds directly to increased carbon dioxide with increased rates of photosynthesis and somewhat reduced transpiration. Waggoner (1983) predicted that a warmer and drier climate would reduce crop production, but he added that this does not take into account increased photosynthesis rates due to the increase in carbon dioxide.

Soybean growth and development simulators reported in the literature include: SOYMOD, developed at the Ohio Agricultural Research and Development Center/The Ohio State University (Meyer et al. 1979); SOYGRO, developed at the University of Florida (Wilkerson et al. 1985); and GLYCYM, developed by USDA (Acock et al., 1983). All are physiologically based simulators. SOYMOD and GLYSYM have a more detailed physiological structure and operate on an hourly time step. SOYGRO operates on a daily time step, is more user-friendly, and has been much more widely validated and used than the other two. More details about SOYGRO and reasons for chosing it for this study are given in a later section in this report.

Dynamic crop growth simulation was used by van Keulen et al. (1981) to show that stomatal behavior was the key factor in determining plant response to increased carbon dioxide under nonlimiting water and nutrient conditions. Stewart (1986) ran a generalized crop growth model for Saskatchewan spring wheat with a 15% increase in photosynthetic capacity, using results from a doubled carbon dioxide experiment, and he found that with the predicted climate changes, a net reduction in wheat yield was indicated, even with the increase in photosynthetic capacity.

Table 1. List of Study Sties Soil Types and Varieties

SITE	CITY	SOIL TYPE	VARIETY
BIAL	BIRMINGHAM, AL	DEEP SILT LM	FORREST
MBAL	MOBILE, AL	MED SANDY LM	BRAGG
MGAL	MONTGOMERY,AL	MED SANDY LM	BRAGG
LRAR	LITTLE ROCK, AR	MED SILT LM	FORREST
TLFL	TALLAHASSEE, FL	ORGB SNDY LM	BRAGG
ATGA	ATLANTA, GA	DEEP SILT LM	FORREST
MCGA	MACON, GA	MED SANDY LM	BRAGG
LUKY	LOUISVILLE, KY	MED SILT LM	ESSEX
BRLA	BATON ROUGE, LA	SHL SILTY CLY	TRACY
SHLA	SHREVEPORT, LA	MED SILT LM	FORREST
MEMS	MERIDIAN, MS	MED SILT LM	FORREST
CHNC	CHARLOTTE, NC	MED SILT LM	FORREST
RANC	RALEIGH, NC	MED SANDY LM	TRACY
CLSC	COLUMBIA, SC	MED SANDY LM	BRAGG
MPTN	MEMPHIS, TN	MED SILT LM	FORREST
NSTN	NASHVILLE, TN	MED SILT LM	ESSEX
LBVA	LYNCHBURG, VA	MED SILT LM	ESSEX
NOVA	NORFORK, VA	MED SILT LM	ESSEX
WINC	WILMINGTON, NC	MED SANDY LM	TRACY

*RUNS FOR MAIZE MADE WITH SAME SOIL TYPES AS FOR SOYBEANS.
FOR MAIZE ONLY ONE VARIETY USED - MCCURDY 84AA.

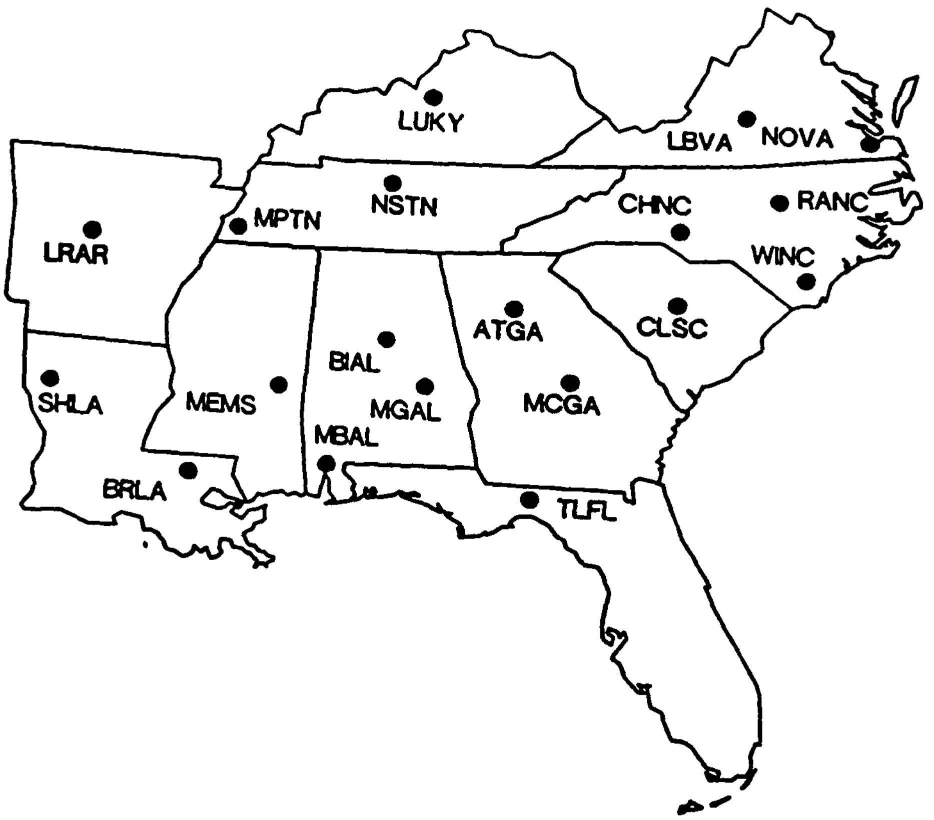

Figure 1. Location of study sites.

Bisbal (1987) found in Florida an increase in soybean yield at doubled carbon dioxide levels in controlled chambers with other environmental conditions ideal. Allen et al. (1987) predicted that soybean yields would increase about 32% with a doubling of carbon dioxide, which is in general agreement with Kimball's (1983) conclusions of an increase of about 33% ±6%.

The two general circulation models that were used to provide the $2xCO_2$ climate senarios were developed by (1) Goddard Institute for Space Studies (GISS) (Hansen et al., 1988); and (2) the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe et al., 1987). The characteristics of these two types of GCMs have been analyzed by Schlesinger and Mitchell (1985).

ORGANIZATION OF THIS REPORT

The remainder of this report will describe the methodology used to obtain data on yields for soybeans and corn for base weather (1951-1980) and for the climate modified by doubled carbon dioxide in the atmosphere. Results are presented for 30 years of weather data for 19 southeastern U.S. locations in 11 states for current or base levels of carbon dioxide, both with and without irrigation, and also for two sets of weather data based on doubled carbon dioxide ($2xCO_2$). Results are given for the climate effects only, and also for the climate effects plus the carbon dioxide enrichment effect on photosynthesis and on transpiration.

Some interpretation is made of these results. Environmental and socioeconomic implications are suggested, and policy recommendations are made.

CHAPTER 2

METHODOLOGY

THE EFFECTS MODEL

The effects of climate change on soybean and corn yields in the southeastern U.S.A. were studied using existing models for these two crops. The SOYGRO V5.41 and CERES-Maize models were chosen to simulate soybean and corn, respectively, for several seasons. First, these models have been available and documented for several years. Second, these models respond to the major climate variables of solar radiation, temperature, and precipitation and include the effects of soil characteristics on water availability for crop growth. Third, they have been validated for a range of soil and climate conditions in the U.S.A. and other countries, and are being used by scientists at various research institutions. Fourth, these models were developed with compatible data structures so that the same soil and climate data bases could easily be used with both crop models. Finally, both these models have user-oriented interfaces to facilitate their use in studies such as this. These factors were important for this study, which attempted to provide credible estimates of the impact in a very short time period of 6 months.

The impact of climate change on crop growth and yield includes the direct effect of CO_2 changes on the crop as well as indirect effects of this and other atmospheric gases on climate variables such as rainfall and temperature. This study was divided into two parts. First, the original SOYGRO and CERES-Maize models were used without modification to estimate the effects of temperature, solar radiation, and rainfall changes suggested by two General Circulation Models (GISS and GFDL) on crop yield. The second part of the study involved the development of equations to change crop photosynthesis and evapotranspiration processes in both SOYGRO and CERES-Maize due to increased CO_2, and the use of these modified models to estimate the combined direct and indirect effects of CO_2 on crop growth and yield. These two models were not originally developed to account for CO_2 effects at normal ambient concentrations.

Next, a description is given of the original SOYGRO and CERES-Maize models with emphasis on how climate variables affect yield estimates. Then, the modifications of the models to include direct effects of CO_2 on photosynthesis and transpiration are presented.

Crop Model Description

CERES Maize and SOYGRO Common Features: The SOYGRO and CERES-Maize models were designed to simulate crop growth and yield under a range of soil and climate conditions where these crops are normally grown. Both models predict the phenological development or duration of vegetative and reproductive growth stages as affected by variety, weather, and soils. Photosynthesis and the production and partitioning of biomass into leaves, stems, roots, and fruit are estimated daily depending on these crop, soil, and weather factors. A component model of the soil-root system integrates the effects of rainfall, root growth dynamics, and climate-induced evapotranspiration to predict day to day water availability to the plants and the resulting development of water stress. Water stress causes reductions in canopy development, photosynthesis, partitioning of biomass, and senescence or abortion of plant material, depending on the timing and severity of stresses. The models were developed primarily using field data from experiments over a range of locations and time.

The SOYGRO crop growth model was first described by Wilkerson et al. (1983) and subsequent modifications by Wilkerson et al. (1985) and Jones et al. (1988a). Version 5.41 includes the basic carbon and nitrogen balances described by Wilkerson et al. (1983), but major modifications to the original model were made for describing phenological development, soil-water balance, and effects of temperature, radiation, and daylength on process rates. The soil water model in version 5.41 was adopted from Ritchie (1985) and is the same as that used in the CERES-Maize model. The phenology model used in SOYGRO V5.41 is described in detail by Jones et al. (1988b).

The inputs to the models include the natural system inputs, management inputs, crop and genetic input variables used in the model equations, and initial conditions.

The original CERES-Maize model was described by Jones and Kiniry (1986). Modifications in the input-output structure and user-interface of the original version were made to conform to the standard crop model inputs and outputs developed by IBSNAT (1986). The SOYGRO V5.41 model also used this input-output structure, which made it possible to simulate both crops using the same natural system (weather and soil) inputs, and the outputs could be analyzed by the same procedures.

The natural system inputs consist of weather and soil data and the site latitude. Weather is considered an uncontrollable input consisting of daily solar radiation (MJ/m^2-day), maximum and minimum air temperatures (°C), and rainfall (mm/day). Daylength is computed from the day of year and latitude. The soil parameters include the soil albedo, a soil water drainage rate constant, upper limit of stage 1 soil evaporation (mm), a runoff curve number, and characteristics describing each layer in a one-dimensional profile. For each layer, the layer depth, lower limit of plant-extractable water, drained upper limit of soil water, and saturated water content (in volume fractions) are inputs. In addition, a root growth weighting factor is input for each layer for use in distributing new root growth as the season progresses. By changing these natural system inputs, the crop models can simulate growth and yield for existing conditions where these inputs are available or for hypothetical conditions where these inputs are estimated to represent those conditions, e.g., estimated future climate changes.

The management inputs are the beginning day of the simulation; planting day; plant density ($plants/m^2$); row spacing (m); depth of planting (cm); whether irrigated automatically, according to a particular experiment or schedule, or not at all; and, if irrigated according to a particular schedule, the dates and amounts of water applied. Nitrogen was assumed to be nonlimiting for all simulations, although the CERES-Maize model has the capability to vary this management variable as well. In SOYGRO, nitrogen supply to the plant is through the nitrogen fixation process, which occurs in proportion to carbohydrate availability. Initial condition inputs are values of soil water in each zone and initial plant weight at emergence.

The crop and genetic inputs are different for the soybean and corn models. In SOYGRO, a file of crop coefficients supplies all the values for basic growth processes such as photosynthesis, respiration requirements for synthesis of different plant parts, effects of temperature on development, photosynthesis, and seed growth rates, the effect of solar radiation on photosynthesis, the effect of leaf nitrogen content on photosynthesis, and the effects of phenological stage on partitioning under ideal, nonstressed conditions. These inputs remain the same for all soybean cultivars. This file remained unchanged in all the climate change simulations. A second input file in SOYGRO contains parameters for a wide range of cultivars adapted to latitudes ranging from about 8°N to 44°N latitude. These coefficients are inputs to those processes that vary significantly among soybean cultivars, and can be divided into those related to reproductive development and those related to biomass accumulation and partitioning. The reproductive development coefficients are (1) the sensitivity of the cultivar to photoperiod and (2) the thermal or photothermal time thresholds required for each stage to occur. Jones et al. (1988b) described the development model and the coefficients. The photoperiod sensitivity changes significantly among cultivars and is the major determinant of the range of latitudes for which each cultivar is adapted. The biomass and partitioning parameters describe the differences among cultivars using maximum seed and shell growth rate (mg/day), leaf size, and maximum rate of flower and pod addition.

The CERES-Maize model has a similar input file for describing each cultivar's sensitivity to photoperiod, duration of stages, and biomass coefficients, although they are different parameters. These are described by Jones and Kiniry (1986).

<u>Sensitivity of SOYGRO to Changes in Weather Conditions.</u> In order to understand the results from crop simulation studies in which several climate variables are changed, it is useful to study the effects of each variable acting alone on the overall growth and yield of a crop. A sensitivity analysis was conducted by Boote et al. (1988) to study the effects of temperature, solar radiation, and photoperiod on soybean growth and yield using SOYGRO V5.41. Since temperature and radiation are two of the weather variables projected to change by the General Circulation Models, a summary of the results of this study is presented here.

Daily development and biomass accumulation rates are the results of various processes in the model. Each of these processes may be affected by temperature in different ways. For example, vegetative node development rate increases with temperature up to 28 to 30°C (Hesketh et al., 1973), whereas reproductive development rate is optimal for temperatures of 21 to 28°C (Parker and Borthwick, 1943). Table 2 lists the sources of data used to develop the relationships between process rates and temperature, solar radiation, and daylength in SOYGRO.

Table 2. Processes Affected by Temperature, Radiation, and Daylength in SOYGRO V5.41

1. Temperature
   a. Photosynthesis (Hofstra and Hesketh, 1975)
   b. Maintenance Respiration (McCree, 1974)
   c. Vegetative Node Development (Hesketh et al., 1973)
   d. Leaf area growth (Thomas and Raper, 1978)
   e. Duration of Reproductive Stages (Parker and Borthwick, 1943)
   f. Pod and Seed Addition Rates (Thomas and Raper, 1981)
   g. Seed Growth Rates (Egli and Wardlaw, 1980)
   h. Evapotranspiration (Priestly and Taylor, 1972)

2. Solar Radiation
   a. Evapotranspiration (Priestly and Taylor, 1972)
   b. Photosynthesis (Ingram et al., 1981)

3. Daylength
   a. Duration of Reproductive Stages (Thomas and Raper, 1976)
   b. Pod and Seed Addition Rates (Fisher, 1963)
   c. Partitioning of Carbon to Fruit (Cure et al., 1982)

In the sensitivity analysis, all weather variables were held constant for a baseline run and then each variable was varied one at a time. The Bragg cultivar was used, no water stress was allowed, and temperature was set to 28°C. Photon flux density was set to 35 moles/m^2-day. Two cases were simulated to evaluate temperature effects. Daylength was fixed at 12 h and temperature varied. In the second case, daylength was held to 14 h for 50 days then switched to 12 h for the remainder of the season. In the first case, an incomplete canopy occurred in some years, but in the second case, the 50-day period at 14 h ensured that a full canopy would develop at all temperatures.

The integrated results of temperature changes are shown in Figure 2a-e. Days to flower decreased as temperature increased to about 30°C, after which days to flower started increasing. The number of nodes on the plant increased from 7 to over 11 for the same temperature range (Figure 2b). The effects of increasing temperature on duration of growth stages depended on temperature. For example, increasing temperature between 15 and 25°C had a major effect on time to flower, whereas increasing from 25 to 35°C had very little effect.

In order to evaluate independent temperature effects on seed growth and yield without the effect of temperature on vegetative growth and canopy size, simulations were run with a 14-h daylength for the first 50 days to ensure a full canopy.

Seed yield increased rapidly as temperature increased from 15 to 20°C and was optimal at about 24°C (Figure 2c). Decreases in seed yield between 24 and 34°C can be attributed to a combination of shortened seed

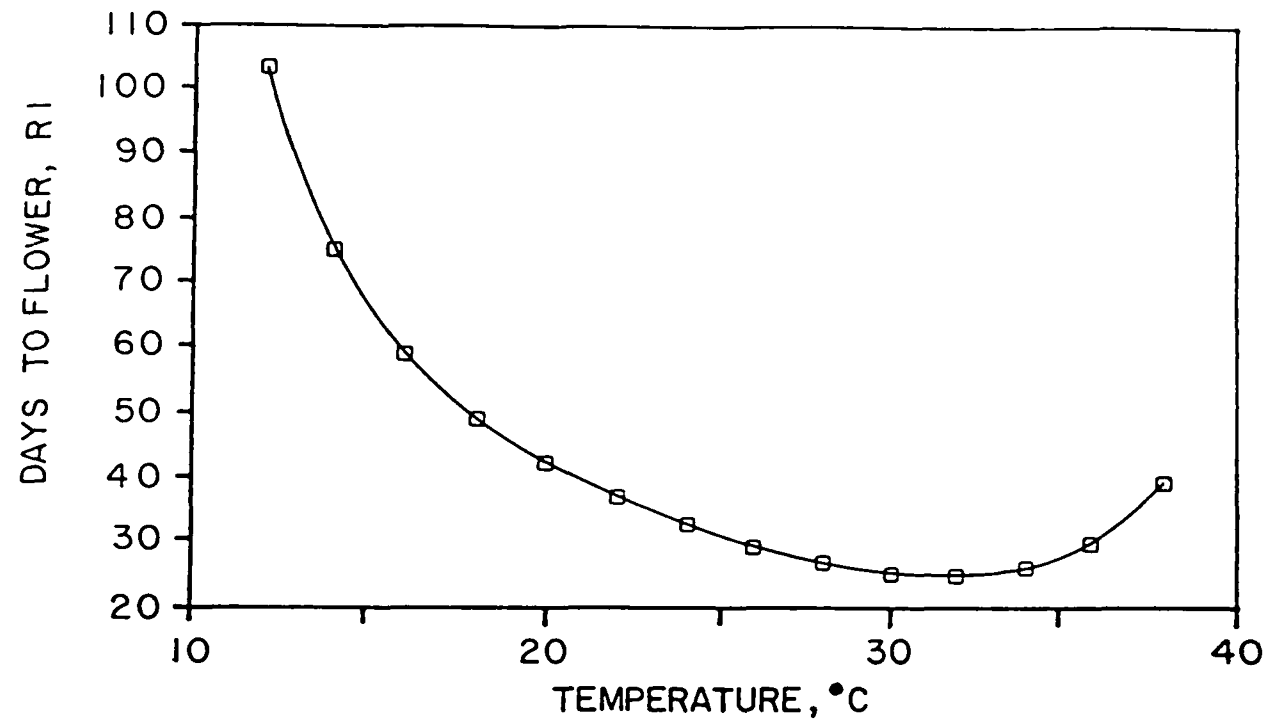

Figure 2a. Simulated days to flower for soybean at various constant air temperatures.

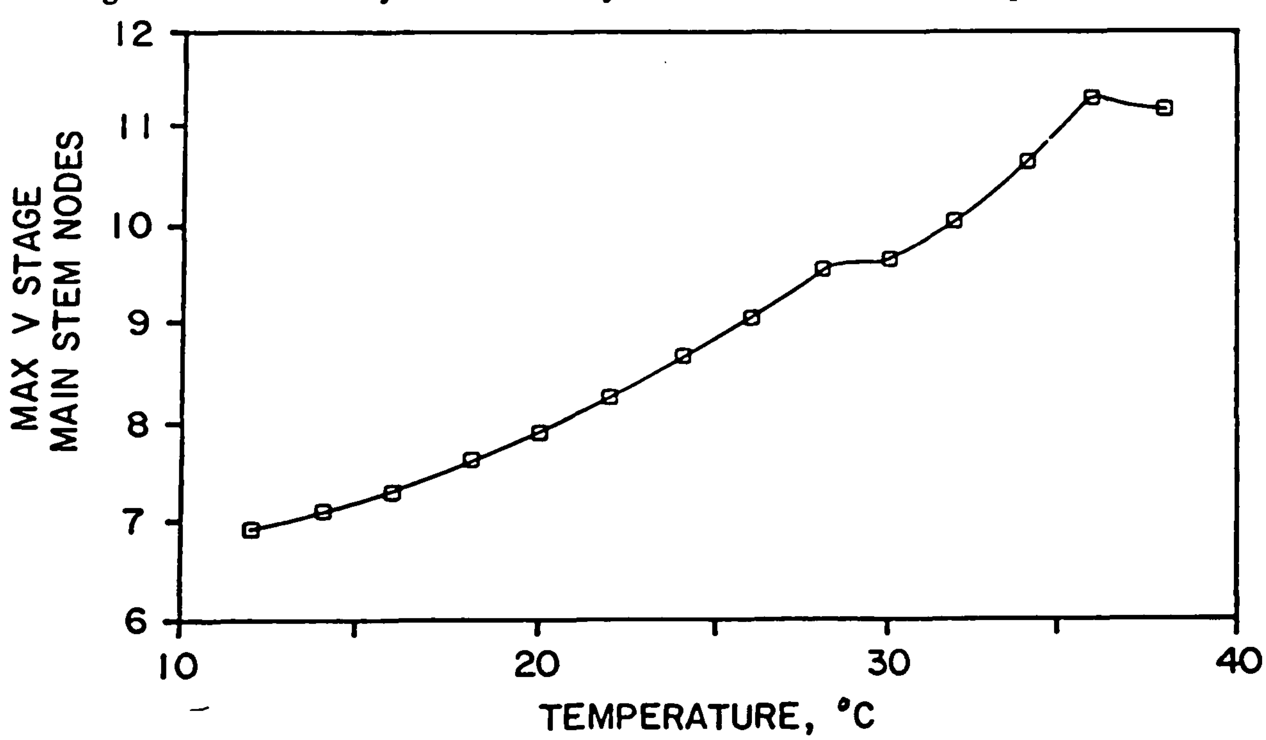

Figure 2b. Simulated relationship between maximum V stage (main stem nodes) of soybeans at various constant air temperatures.

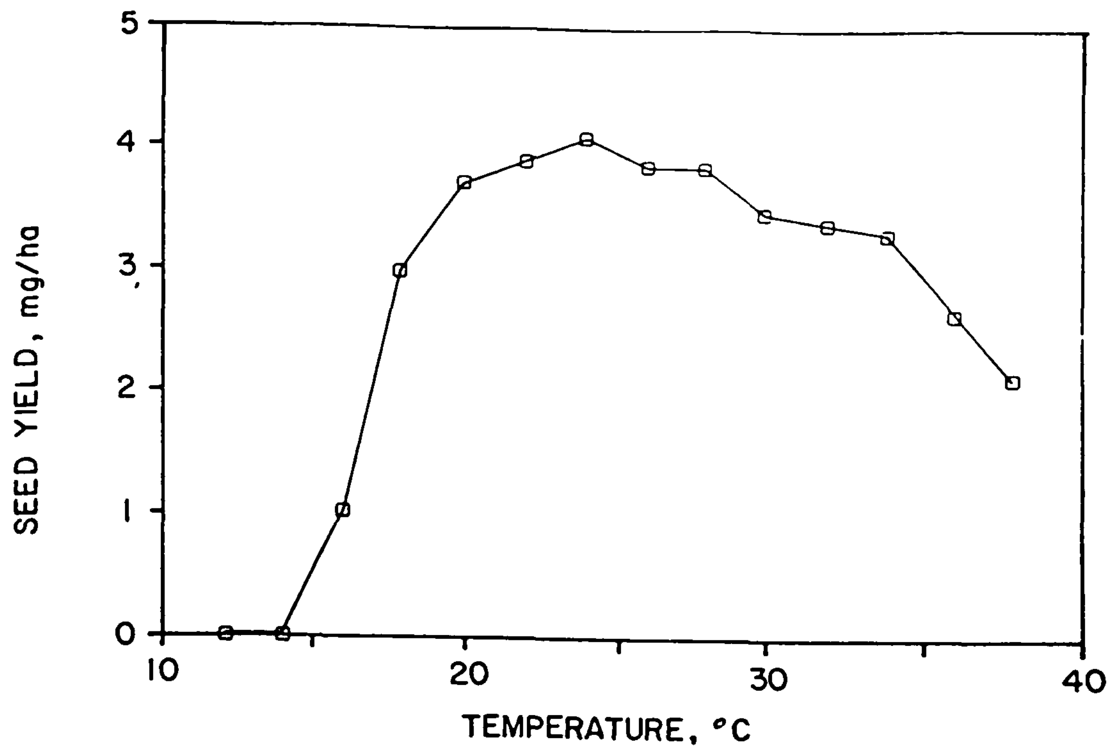

Figure 2c. Simulated seed yield of soybeans as a function of various season-long, constant air temperatures.

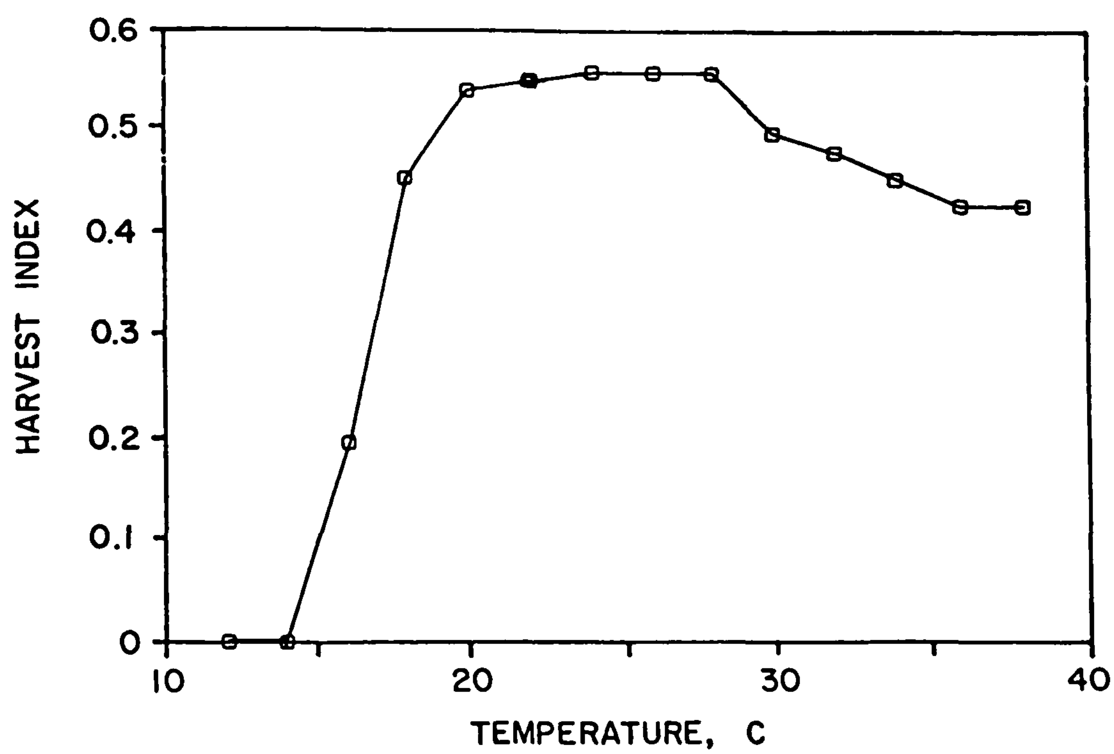

Figure 2d. Simulated harvest index of soybeans (seed yield divided by total above ground biomass) as a function of various season-long air temperatures.

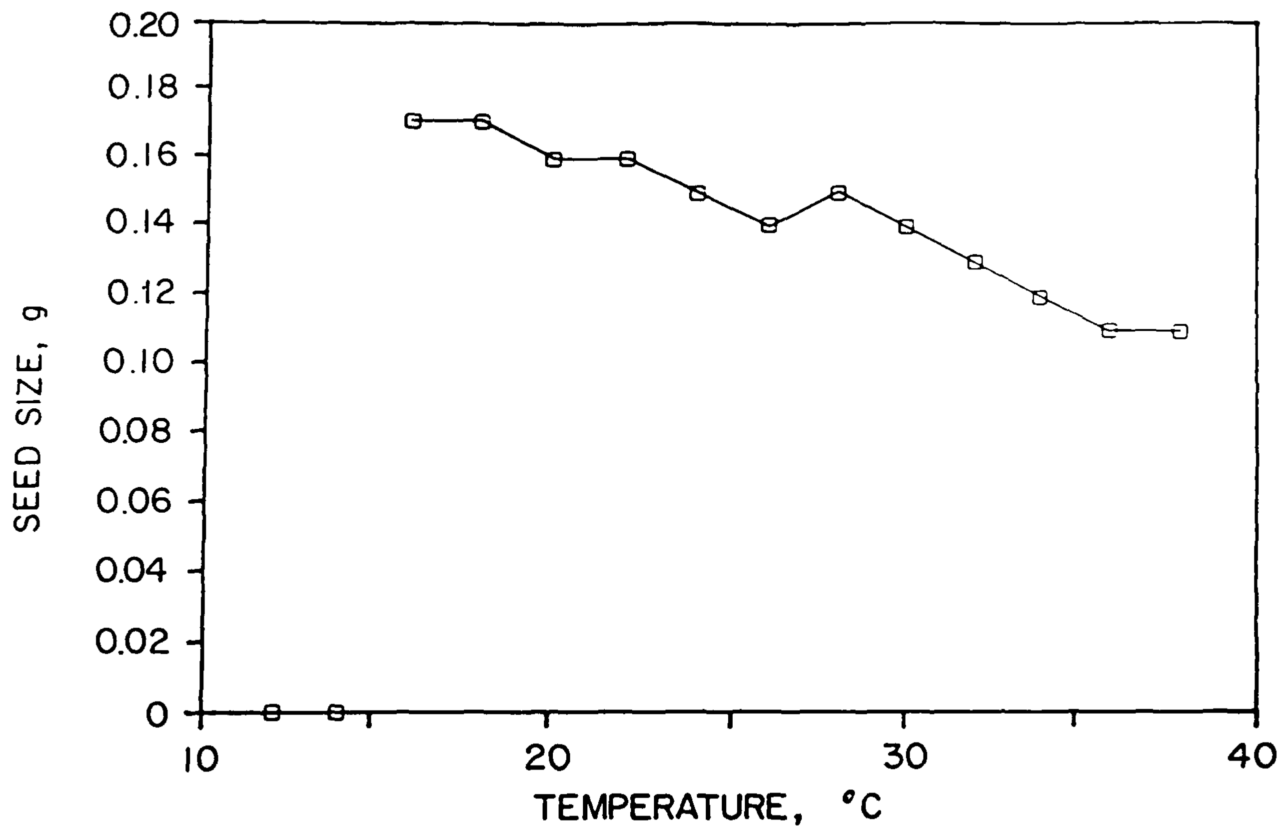

Figure 2e. Simulated effect of season-long constant temperatures on soybean seed size.

fill duration and reduced seed growth rate. The rapid decrease in yield above 34°C is attributed to the modeled effects of temperature on photosynthesis. Harvest index (seed weight/total above-ground biomass) was shown by Baker et al. (1988) to decrease from 0.52 to 0.46 as temperature was increased from 23 to 33°C for soybeans when averaged over 330 and 660 vpm CO_2 concentration. Simulated results (Figure 2d) show an increase in harvest index, HI, as temperature increased from 14 to 20°C, no change between 20 and 28°C, then a decrease for temperatures above 28°C. The increases in seed yield and harvest index as temperature increased between 14 and 20° were due in large part to the function derived from data of Thomas and Raper (1981), which causes decreased pod and seed setting in this range of temperatures. Average seed size also decreased with temperature (Figure 2e) in the simulated results, which is consistent with literature (e.g., Baker et al., 1988).

Figure 3 shows the effect of solar radiation (expressed as moles/m^2-day) on total biomass and seed yield. There was a maximum yield at about 45 to 50 moles/m^2-day.

These results of SOYGRO sensitivity analyses showed one major effect relevant to the climate changes predicted by the GCMs. Increases in temperature on the order of 4 to 6°C could cause significant increases in soybean yield if the baseline weather was cool, such as in the northern latitudes, and significant decreases in yield if the base line temperatures were already in the range of 25-30°C. At constant day and night temperature of 30°C, yield was roughly 20% lower than that at 24°C, and at 36°C, it was 35-40% lower. These results were obtained without taking into account the effect of increases in temperature on crop water use and the possibility for increased water stress and additional yield reductions. They were also obtained, however, using air temperature as the determinant of growth processes in the model. Increases in air temperature can cause increases in atmospheric vapor pressure deficit, which should increase plant canopy transpiration rates. The increase in transpiration rates will cause foliage-to-air temperature difference to increase (Allen, 1986; Idso, 1987). However, the actual foliage temperature will actually always increase as air temperature increases. Furthermore, elevated CO_2 will cause partial stomatal closure and induce a higher foliage temperature also.

<u>Direct Effects of CO_2 Enrichment</u>. The climate change scenarios predicted by GCMs were for conditions expected under doubled atmospheric CO_2 concentrations. The effects of temperature, solar radiation, and precipitation on crop growth processes were discussed in the previous section. CERES-Maize and SOYGRO were first used to simulate changes in crop yields across the southeastern U.S. caused by changes in these climate variables alone. However, since CO_2 also directly affects plant growth processes, final assessment of the impact of doubling CO_2 concentration can only be made by considering both climate and direct effects on plants.

When plants are exposed to increases in CO_2 concentration, there are both immediate and long-term effects on crop growth, all other conditions being equal (Acock and Allen, 1985; Allen, 1986; Cure and Acock, 1986). One immediate effect is that leaf stomatal resistance increases and plants tend to lose less water for the same environmental conditions (Rogers et al., 1983; Valle et al., 1985a,). However, the anticipated decrease in water use by plants in high CO_2 is moderated by increases in leaf temperatures caused by partial stomatal closing, which increases the vapor pressure of water inside the leaves. The increase in atmospheric CO_2 concentration also results in higher gradients for diffusion of CO_2 into plant leaves and increases photosynthetic rates. This increase in photosynthesis occurs even though there is partial closure of stomata, and the magnitude of the increase varies with the plant's pathway for fixing carbon (C_3 vs. C_4). In the longer term, increased photosynthesis may increase biomass growth rates significantly and development rates slightly, and modify other anatomical features of the plant, such as starch storage and specific leaf weight (Bisbal, 1987; Allen et al., 1988). There is also an interaction between these longer-term changes in canopy growth and development and crop water use. Plant canopies under elevated CO_2 produce leaf area faster, capture more of the incoming energy, and thus tend to transpire at a higher rate than would be expected if one only considered the short-term stomatal resistance effect on lowering canopy water use.

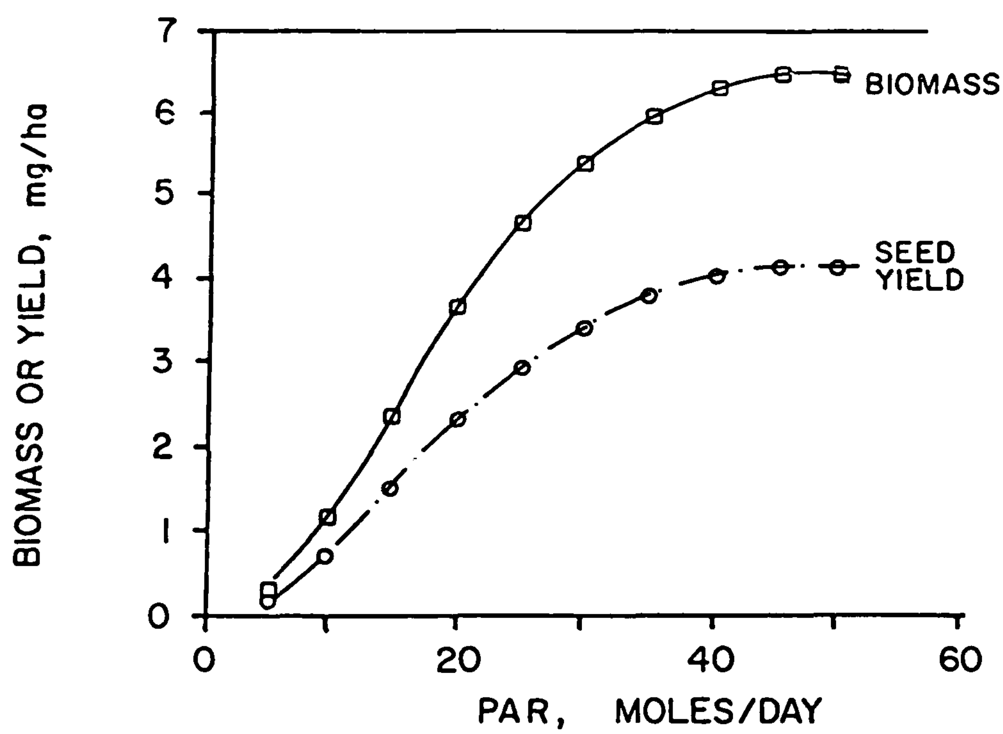

Figure 3. Simulated effect of total daily accumulated photosynthetically active solar radiation (PAR) on total biomass and seed yield in soybeans.

In the CERES and SOYGRO models, increased growth over the long run is accounted for in the original models. However, the direct effects of CO_2 on photosynthesis and evapotranspiration were not included in these models. Our objective here was to develop a method that will give a first approximation of the changes in canopy photosynthesis and the transpiration rates by plants exposed to elevated CO_2 in comparison with those same plants if exposed to normal atmospheric CO_2 levels under the same climate conditions. Our approach was to compute ratios of daily photosynthesis and evapotranspiration rates of a canopy exposed to elevated CO_2 to those rates of the same canopy if exposed to ambient CO_2 conditions.

i) Photosynthesis. Increases in photosynthesis rates by plants under elevated CO_2 concentrations are well documented (Rogers et al., 1983; Cure, 1985; Cure and Acock, 1986). Although process-level models that describe changes in photosynthesis by plants under various light and CO_2 conditions exist, the crop models used in this study did not include the direct effects of CO_2 on photosynthesis rates. Therefore, modifications were made in both SOYGRO and CERES-Maize models to cause increases in photosynthesis under the double CO_2 scenarios.

Various sources of literature were reviewed to obtain the best estimates of increases in canopy photosynthesis rates for both soybean and corn. Soybean has a C-3 carbon fixation pathway and thus is more responsive to increases in atmospheric CO_2 than is corn. Table 3 shows values of percentage increase in soybean photosynthesis for double CO_2 reported by various authors. The values reported by Allen et al. (1987) for mid-day, high-light conditions were about 50% increase in canopy photosynthesis for double CO_2. This increase would not, however, represent the daily total photosynthesis increase of a canopy because of the similarity of the photosynthesis values under low-light conditions and the fact that light levels go through cycles during the daytime. This was demonstrated by simulating hourly values of tomato (a C-3 plant) canopy photosynthesis using the model derived by Acock et al. (1978) fit to tomato canopy photosynthesis data taken by J. W. Jones and E. Dayan in Gainesville, FL. These values were summed over each day to obtain daily canopy rates. The percent increase in the daily canopy photosynthesis rates of tomato under double CO_2 conditions (+21%) was less than the increase of instantaneous canopy photosynthesis under high light (+31%) (Jones, J.W. and E. Dayan, unpublished). In other words, the increase in daily integrated photosynthesis was 33% less than the increase in instantaneous mid-day photosynthesis rate. This relationship between relative increases in instantaneous mid-day canopy rates and daily total canopy rates varied with total daily radiation. Reducing the relative increase in instantaneous soybean canopy photosynthesis under high light by 33% results in a relative daily response. Therefore, we felt justified in reducing the relative response from a 50% increase (instantaneous) to a 35% increase (daily canopy) in photosynthesis under double CO_2 conditions. This value is also consistent with the short-term net assimilation rate increase in soybean in contrast to the instantaneous increase in leaf carbon exchange of 78% by soybean reported by Cure (1985). Using this value for Gainesville weather data, seed yield increases of 40% occurred, which are similar but about 5% higher than the increases in yield reported by Allen et al. (1987) for soybean under double CO_2 conditions.

A similar evaluation of corn canopy photosynthesis was conducted and a value of +15% was selected. This value was also reduced by 33% to +10%, which is more representative of daily integral canopy values and similar to the 9.0% increase in short-term net assimilation rate for corn reviewed by Cure and Acock (1986).

In the crop models, factors of 1.35 and 1.10 were multiplied by photosynthesis rates computed under current CO_2 concentrations for soybean and corn, respectively. It was assumed for this first approximation that the relative increase in photosynthesis was independent of other factors. The effects of water stress, temperature, and leaf area were handled exactly as before in the two models.

ii) Evapotranspiration. Estimates of crop water use in the crop models are based on a simplified energy balance approach that depends on net radiation (R_N) and temperature using the Priestly-Taylor (1972) method. A schematic of the current method for computing crop water use (soil evaporation and plant transpiration) is given in Figure 4. Both models use this method, which was developed and implemented originally by J.T. Ritchie (1985).

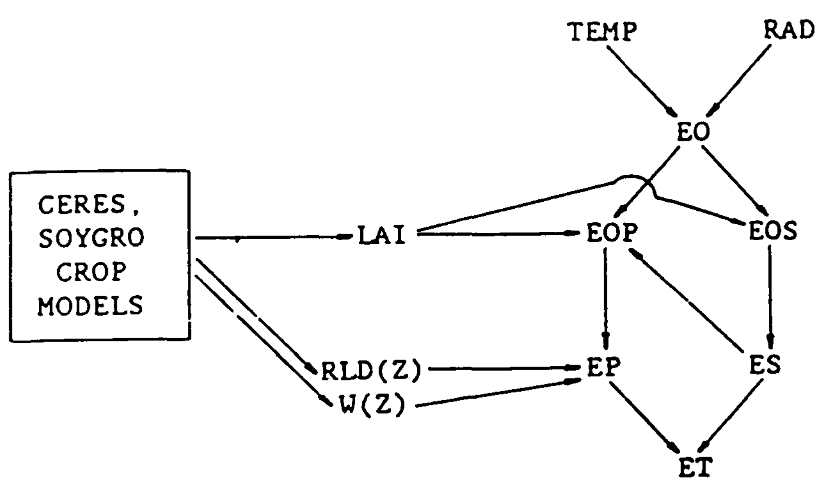

Figure 4. Variable Dependency Diagram showing how EP, ES, and ET are computed in the CERES and SOYGRO models. Directions of arrows show functional dependence, i.e., EOS = f(EO, LAI).

Table 3. Response of Soybean Photosynthesis and Growth to Doubled Atmospheric CO_2 Concentration From Several Selected Literature Sources

	SOURCE	RELATIVE INCREASE	COMMENTS
1.	Idso et al. (1987)	1.30	Based on crop growth rate.
2.	Baker et al. (1988)	1.30	Based on final crop yield.
3.	Acock et al. (1985)	1.65-1.80	Based on measurements ofgross (Gross leaf photosynthesis).
4.	Elwell et al. (1987)	1.75	Sensitivity analysis of SOYMOD (Gross leaf photosynthesis).
5.	Elwell et al. (1987)	1.60	Sensitivity analysis of SOYMOD (Final yield).
6.	Allen et al. (1987)	1.50	Based on midday measurements of total canopy photosynthesis.
7.	Allen et al. (1987)	1.30	Based on yield summary of 6 locations.
8.	Acock (per. comm.)	1.30	Growth chamber measurement, total shoot growth.

In this method, a potential evapotranspiration rate (EO) is first computed for the entire canopy (soil plus plants), using the Priestly-Taylor equation. Potential soil evaporation (EOS) is then computed by partitioning EO based on energy captured by the plants - a function of leaf area index (LAI). Actual soil evaporation (ES) depends on the time from the last soil wetting and on availability of water in the top soil zones. Then, potential plant transpiration (EOP) is computed by partitioning EO as a function of leaf area index. Existing root length density, RLD(Z), and water content, W(Z), distributions in the soil are used to estimate the maximum supply of water to the plant. When supply is greater than EOP, then actual transpiration (EP) is set equal to EOP. When supply is less than EOP, then stomata closure would have occurred some time during the day because of water stress, and EP would be set equal to supply from the root system and would be less than EOP. Finally, actual ET is the sum of ES and EP, and is always less than or equal to EO.

The Penman-Monteith equation, which uses net radiation (R_n) as an input, was used as the basis for a ratio to modify evapotranspiration under elevated CO_2 conditions (taken from France and Thornley, 1986):

$$\lambda E = \frac{s\,R_n + c_p\,\rho\,(p_s(T_a) - p_a)\,g_a}{s + \gamma(1 + g_a/g_c)} \qquad (1)$$

where λE is evapotranspiration rate in energy units, s is the slope of the saturated vapor pressure vs. temperature curve, γ is the psychometric constant, R_n is net radiation, c_p is specific heat of the air at constant pressure, ρ is air density, $(p_s(T_a) - p_a)$ is vapor pressure deficit of the air, g_a is the boundary layer conductance between the canopy and the bulk air, and g_c is the canopy conductance to water vapor.

If this equation is applied twice to the same canopy and same environment except for CO_2 concentration, then the only variable that changes in equation 1 is g_c, the canopy resistance to vapor transport. In other words, R_n, c_p, ρ, T_a, $p(T_a)$, p_a, wind speed (u), leaf area, plant height, and g_a would be the same for both cases. Therefore, when we take a ratio of λE^c (under elevated CO_2 levels) to λE, we obtain:

$$\text{RATIO} = \frac{\lambda E^c}{\lambda E} = \frac{s + \gamma\,(1+g_a/g_c)}{s + \gamma\,(1+g_a/g_c^{\,c})} \qquad (2)$$

where $g_c^{\,c}$ is the canopy conductance to water vapor under elevated CO_2 conditions. Aerodynamic methods for computing $g_a(= 1/R_a)$ based on Thom (1972), as implemented by Jagtap (1987), are used.

The canopy resistance, R_c, is computed by assuming all leaves act as parallel resistances, and

$$R_c = (r_L + r_b)/LAI \qquad (3)$$

where r_L is the leaf stomatal resistance, s/m, and LAI is leaf area index, and r_b is the leaf boundary layer resistance. Leaf resistances r_L are computed as functions of CO_2 concentrations for r_L for corn and soybean using the equations developed by Rogers et al. (1983). Then, g_c and $g^c{}_c$ (canopy conductance under elevated CO_2) can be computed:

$$g_c = 1/R_c \qquad (4)$$

$$g^c{}_c = 1/R^c{}_c \qquad (5)$$

The computation of RATIO requires temperature, wind speed, LAI, and CO_2, but is independent of solar radiation. LAI is obtained directly from the CERES and SOYGRO models.

Figure 5 shows a schematic of the modifications required to adjust EOP in CERES and SOYGRO. It is assumed that the potential plant transpiration (EOP) is changed under elevated CO_2 conditions due to increased stomatal closure and changes in the partitioning of energy captured by the canopy. This also assumes that the overall evapotranspiration of a full canopy is directly affected by CO_2 through its effect on EOP. This is shown in the diagram (Figure 5) by the computation of RATIO (using Equation 2 and the calculated values for g_a, g_c, and $g^c{}_c$ which depend on LAI, wind speed, temperature and CO_2). Once RATIO is computed, EOP^c is computed and EP, EOS, ES, and ET are computed as before, but using EOP^c instead of EOP. This procedure will result in a lower transpiration rate for higher CO_2 levels, and a lower ET on a daily basis, but may or may not change seasonal ET by the same proportion because of the altered LAI growth under elevated CO_2 conditions.

In Table 4, this procedure was compared with changes in ET under elevated CO_2 conditions from more detailed simulations using the SPAM model (Allen, 1986). The responses of RATIO to CO_2 and to temperature were similar to those reported by Allen for a full canopy (LAI = 4) and wind speed of 3.6 m/s. Under very low LAI values, the RATIO for double CO_2 approached the RATIO of leaf stomatal resistances, which was about 0.68 for soybean. For higher LAI values, the RATIO approached 0.98.

Limitations Inherent in the Models. The results obtained in this study were based on two crop simulation models and are thus subject to the assumptions and limitations of these models. The models were developed under a range of soil and climate conditions and tested over others. However, neither of the models has been tested under the conditions suggested by the GCMs. The models do account for changes in solar radiation, temperature, and precipitation.

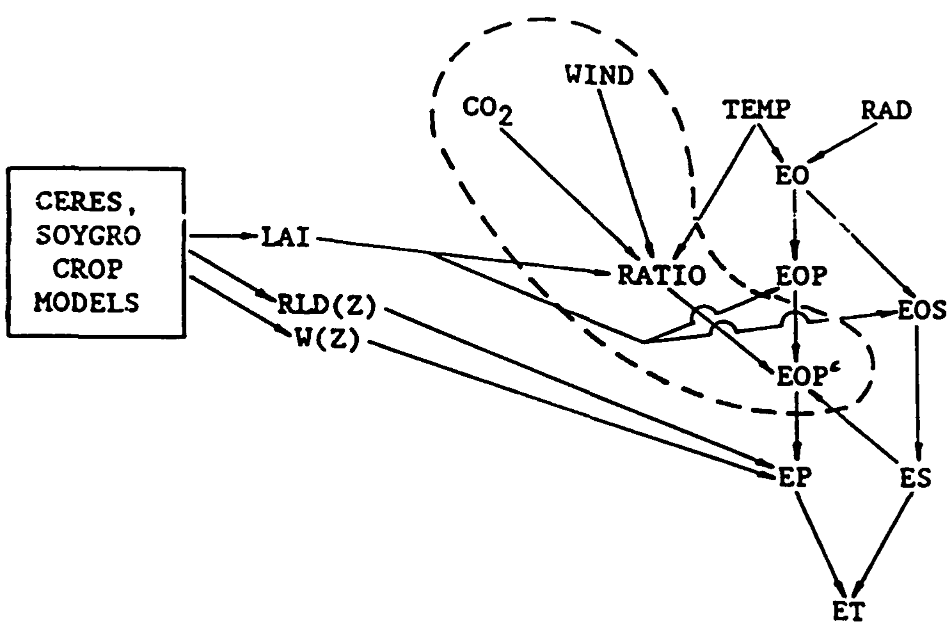

Figure 5. Variable Dependency Diagram showing how potential transpiration (EOP) is modified under elevated CO_2 levels in SOYGRO and CERES crop models.

However, most of the data used to derive the relationships affecting processes in the models were for temperatures below 35°C. In many cases, the two GCMs projected temperatures above 35 and even 40°C. Relationships of processes to temperatures in this range are extrapolated. In SOYGRO, much of the yield decline occurred because of lower seed growth rates, pod setting, and photosynthesis above 35°. In CERES-Maize, much of the yield decrease in this temperature range was due to shorter seed filling periods.

The models have been tested over a wide range of rainfall and irrigation conditions, but do not account for flooding, which could occur during time periods when increases in precipitation occur. The models also assume that soil nutrients and micronutrients are not limiting and that there are no major soil problems such as acidity, high compaction, or salinity. The models also assume that pests (insects, diseases, weeds) are controlled and pose no limitation to crop growth and yield. Therefore, the results of the models should be used as an indicator of the relative effects of climate change on yield. Absolute yields harvested by farmers over an area may be lower than simulated yields because of the occurrences of some of these limitations to crop growth over time and space.

The first approximation of the direct effects of CO_2 were included as an estimate of combined effects of climate and plant response to changes in CO_2. Modifications to the models were made to compute photosynthesis and evapotranspiration rates under increased CO_2 but other parameters, such as rate of leaf appearance, appears to be affected also for soybean (Baker et al., 1988) and other crops such as tomatoes (E. Dayan, J.W. Jones, unpublished data, Gainesville, FL). Interactions between photosynthesis, temperature, and solar radiation occur in the models because these variables affect the same growth processes. An overall climate change may have higher CO_2, tending to increase photosynthesis, and higher temperature, which decreases photosynthesis. The combined effect could be higher or lower photosynthesis rates.

However, the methods used to implement changes in photosynthesis and transpiration in these models need to be improved for future studies. The ratio method for computing changes in ET due to stomatal closure under elevated CO_2 conditions mimicked the results of more detailed models. However, changes in atmospheric vapor pressure were not included in the current model, and changes in plant temperature due to stomatal closure under elevated CO_2 conditions were not computed or used to modify plant growth processes. It is not clear at this time just how much difference those limitations would cause. Allen (1986) showed that increases in CO_2 to 800 vpm could cause plant temperatures to be 2-3°C higher than if they were under 330 vpm for the same climate conditions.

Table 4. Comparison of the Ratio of Soybean Canopy ET Under Elevated CO_2 Concentrations Using the Derived RATIO in This Paper and the More Detailed Simulations by Allen (1986) Using the SPAM Model (Leaf Area Index = 4.0; Average Wind Speed = 3.6 m/s; Leaf Boundary Layer Resistance of 10 s/m.)

CO_2	Temp = 31°C		Temp = 18°C	
	RATIO1/	LHA2/	RATIO1/	LHA2/
450	.977	0.970	.966	0.960
600	.950	0.938	.926	0.938
800	.916	0.903	.878	0.897

1/Ratio of plant transpiration under elevated CO_2 to that under ambient CO_2 conditions computed using the ratio of Penman-Monteith equations.
2/From Allen, L.H., Jr. 1986.

Similarly, changes in photosynthesis rates under doubled CO_2 were modeled by increasing gross photosynthesis rates by 35% for soybean and 10% for corn on a daily, canopy basis. Auxiliary simulations with a canopy photosynthesis model were used to demonstrate the adequacy of these values relative to published canopy rates under high-light, mid-day conditions. However, this increase for both crops depends on light intensities, and changes in cloudiness over time or under the proposed climate scenarios could significantly reduce the beneficial effects of CO_2 on canopy photosynthesis rates because of the shapes of plots of photosynthesis vs. light intensity under various CO_2 concentrations.

The models do account for increased growth rates resulting from CO_2 increases. For soybean, the data reported by Baker et al. (1988) provide a basis for comparing the realism of the model to simulate physiological responses under combinations of CO_2 and temperature. The time constraints of this study did not allow for a detailed comparison, but general comparisons between SOYGRO results and those data were good. For example, simulated increases in LAI under doubled CO_2 were similar to those reported by Baker et al. (1988), and decreases in harvest index and seed size were similar. Seed yield increases in the Baker et al. (1988) study were about 45, 24, and 15% for the low (26/19), medium (31/24), and high (36/29) temperature treatments, respectively. Under ambient temperatures in Gainesville, increases in seed yield were about 40% with the modifications under well-watered conditions.

THE WEATHER SCENARIOS

The Scenarios Used

In this study we used three weather scenarios:

a) Standard weather data for 30 years (1951/80) for 19 locations in 11 states in the southeastern U.S.A.

b) Standard weather modified by the ratios provided by the GISS GCM model for two grid points near Charlotte, NC, and Memphis, TN. Using rectangles to delineate the applicable range of each grid point, we identified which locations were in the respective rectangles for the Charlotte and Memphis grid points and applied the ratios to the solar radiation, temperature, and precipitation data for these locations. No interpolations were made between grid points.

c) Standard weather was modified by ratios provided by the GFDL GCM model for eight grid points, near St. Louis, MO, Greenville, MS, New Orleans, LA, Huntington, WV, Augusta, GA, Gainesville, FL, Washington, DC, and a grid point in the Atlantic Ocean off the Virginia coast. The same system of rectangles centered on grid points was used to apply specified ratios to data for sites within the rectangles. No interpolations were made between these grid points. Ratios for temperature, solar radiation, and precipitation were used in both cases. The standard weather data was provided by NCDC, Asheville, NC, by way of NCAR, Boulder, CO, with the help of Roy Jenne. This standard weather data included only temperature and precipitation. Solar radiation was generated by a synthesis program, WGEN, developed by Richardson (Richardson and Wright, 1984, Richardson, 1985) and modified by Hodges et al. (1985).

Table 5 gives the location data as well as the appropriate GISS and GFDL grid points. Figures 6 and 7 provide the location of the grid points for the two weather scenarios for doubled carbon dioxide.

Issues Resulting from the Scenarios

Limitations of the Weather Scenarios

i) Precipitation variability. When considering rainfall and crop growth, a serious question arises related to changes in rainfall such as suggested in the scenarios used in this study. Will the change in rainfall be reflected in more/fewer rainfall events or the same number of events with higher/lower amounts in each event? The

Table 5. List of Study Sites With Related GISS and GFDL Grid Box Mid-Points

SITE	CITY	LAT	LNG	GISS	GFDL
BIAL	BIRMINGHAM, AL	33.34	86.45	MEMPHIS	GREENVILLE, MS
MBAL	MOBILE, AL	30.41	88.15	MEMPHIS	NEW ORLEANS, LA
MGAL	MONTGOMERY, AL	32.18	86.24	MEMPHIS	AUGUSTA, GA
LRAR	LITTLE ROCK, AR	34.44	92.14	MEMPHIS	GREENVILLE, MS
TLFL	TALLAHASSEE, FL	30.23	84.22	CHARLOTTE	GAINESVILLE, FL
ATGA	ATLANTA, GA	33.39	94.26	CHARLOTTE	AUGUSTA, GA
MCGA	MACON, GA	32.42	83.39	CHARLOTTE	AUGUSTA, GA
LUKY	LOUISVILLE, KY	38.11	85.44	MEMPHIS	ST. LOUIS, MO
BRLA	BATON ROUGE, LA	30.32	91.09	MEMPHIS	NEW ORLEANS, LA
SHLA	SHREVEPORT, LA	32.28	93.49	MEMPHIS	GREENVILLE, MS
MEMS	MERIDIAN, MS	32.20	88.45	MEMPHIS	GREENVILLE, MS
CHNC	CHARLOTTE, NC	35.10	80.5	CHARLOTTE	AUGUSTA, GA
RANC	RALEIGH, NC	35.52	78.47	CHARLOTTE	AUGUSTA, GA
CLSC	COLUMBIA, SC	33.57	81.07	CHARLOTTE	AUGUSTA, GA
MPTN	MEMPHIS, TN	35.03	89.59	MEMPHIS	GREENVILLE, MS
NSTN	NASHVILLE, TN	36.07	86.41	MEMPHIS	ST. LOUIS, MO
LBVA	LYNCHBURG, VA	37.20	79.12	CHARLOTTE	HUNTINGTON, WV
NOVA	NORFORK, VA	36.54	76.12	CHARLOTTE	WASHINGTON, DC
WINC	WILLMINGTON, NC	34.16	77.55	CHARLOTTE	ATLANTIC OCEAN

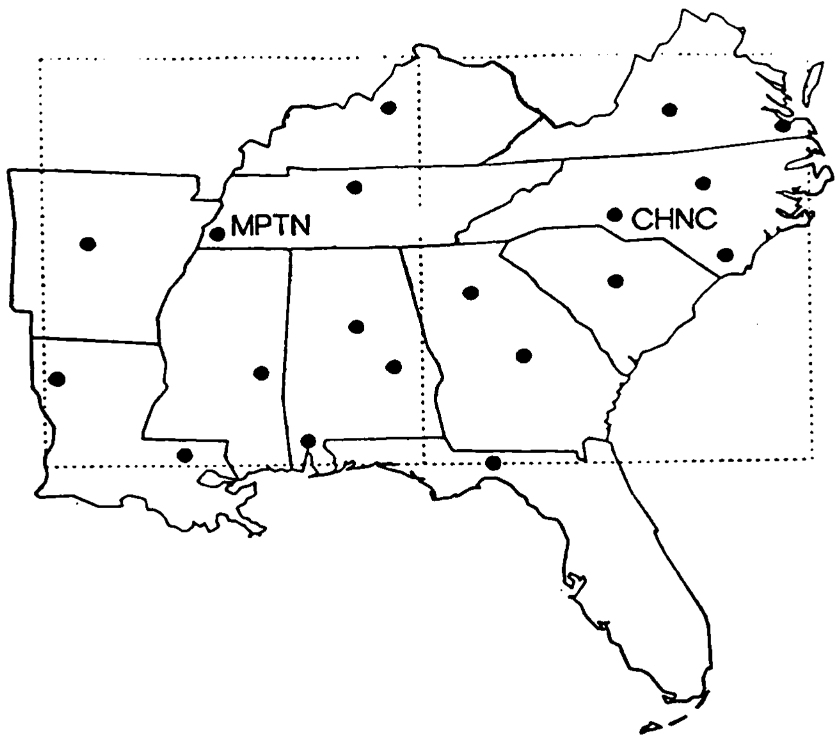

Figure 6. GISS grid boxes and mid points (near Memphis, TN, and Charlotte, NC) and weather data locations used in this study.

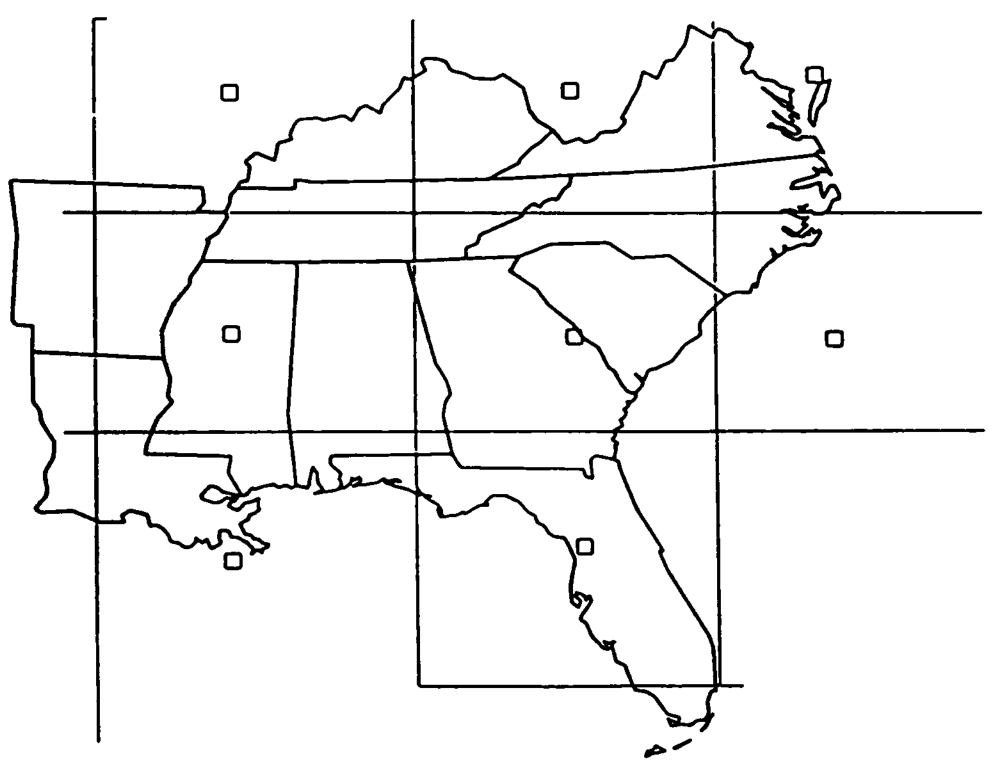

Figure 7. GFDL grid boxes and mid points (near St. Louis, MO; Huntington, WV; Washington, DC; Greenville, MS; Augusta, GA; New Orleans, LA; Gainesville, FL; and in the Atlantic Ocean off the Virginia coast).

answer to this question could completely change the results of this study in terms of rainfed yields if it suggested that the change was in terms of events rather than amounts. The assumption we made for runs reported was that the amount of rainfall was changed but the number of events was not.

The importance of using daily rainfall data as we did in this study is emphasized in a 4-year study of turfgrass water requirements at Fort Lauderdale, FL. Allen et al. (1978) showed that on a whole-year basis, annual rainfall exceeded annual evapotranspiration by 198 to 561 mm. However, on a monthly water-budget basis, irrigation requirements computed for the whole year ranged from 142 to 356 mm. Furthermore, irrigation requirements for daily water budgets were much higher, 569 to 589 mm, for very shallow-rooted turfgrass on droughty soil with available water of 20 mm in the top 300 mm of soil. For a soil holding 71 mm of available water in the rooting zone, the calculated annual irrigation requirements ranged from 213 to 427 mm. Therefore, crops are likely to have more serious water stress periods under actual daily conditions than would appear when the rainfall is averaged across each month.

ii) Variability of the precipitation ratios. The variability of the precipitation ratios from month to month for both GISS and GFDL is much greater than the variability of the temperature and solar radiation ratios. This variability is of particular concern when dealing with crops such as soybeans and corn where timing of morphologic development related to soil moisture stress greatly affects final yield. This large variability of precipitation makes the meaningfulness of the results open to question.

In Table 6, for example, note the variations in monthly Columbia, SC, precipitation for July, August, and September under the three scenarios:

	Base (actual 30-yr. ave.)	GISS	GFDL
July	136 mm	192 mm	88 mm
August	140 mm	173 mm	60 mm
September	107 mm	86 mm	87 mm

August is a critical month for reproductive fruit growth.

iii) Representative plant temperature. Based on the information provided by NCAR, the air temperature is calculated by the GCMs at some elevation considerably above the crop. The ratio of this temperature with and without double CO_2 when applied to the 1.5 m air temperature from the historic data base may not represent the actual air temperature above the plant canopy. A second assumption is that the air temperature at 1.5 m (such as measured and reported to NCDC) is the plant temperature in the models. Since temperature has major influences on most crop growth processes, a major limitation is the assumption that the historic air temperature as modified by the GCM scenarios is the plant temperature. Plant temperatures are often different from air temperatures and are influenced by vapor pressure deficit of the air. Thus, errors in computing air temperature at 1.5 m and errors in assuming that plant temperature is the same as air temperature may result in errors in the predictions of the impact of climate and CO_2 enrichment effects. The magnitude of these errors is not known at present, but future work should investigate this limitation.

iv) The monthly time step of the ratios provided by the GLM scenarios may be too large for accurate results from the plant models because a month is a very long time when calculating the timing of the physiological events in the plant life cycle, such as flowering, fruit set, and maturity.

v) Sites for which data were provided do not correspond very well with major growing areas in the region.

CROP MANAGEMENT

No attempt was made to evaluate the effects of crop management on the results of the study of doubled CO_2 effects on crop yield due to the time and resources constraints of the project.

Table 6. Summary of Weather Data, 30-year Averages (1951-80) of Three Sites in the Delta (Memphis), Uplands (Charlotte), and Coastal Plains (Columbia) (PREC. = mm, TMAX and TMIN = °C)

COLUMBIA, SC		STD			GISS			GFDL	
MONTH	PREC.	TMAX	TMIN	PREC.	TMAX	TMIN	PREC.	TMAX	TMIN
Jan.	111.25	13.45	0.67	120.93	15.75	2.97	85.55	15.57	2.79
Feb.	101.35	15.28	1.47	126.07	17.42	3.60	106.82	17.60	3.78
Mar.	131.06	19.47	5.51	162.13	23.48	9.52	150.33	22.20	8.24
Apr.	91.19	24.99	10.26	107.42	27.05	12.32	104.77	28.36	13.63
May	97.28	28.78	15.04	110.80	31.65	17.91	80.55	31.27	17.53
June	112.52	31.76	18.93	147.63	34.29	21.47	49.62	35.85	23.03
July	135.89	33.27	21.17	192.01	35.23	23.14	88.46	38.19	26.09
Aug.	140.21	32.77	20.80	172.60	34.14	22.17	59.73	35.71	23.74
Sept.	107.44	29.74	17.74	85.63	33.02	21.02	86.81	33.80	21.80
Oct.	65.28	24.72	10.16	63.32	28.08	13.53	44.00	27.71	13.15
Nov.	63.75	19.53	4.77	47.56	21.89	7.13	68.73	22.98	8.22
Dec.	88.90	14.86	1.49	81.52	16.64	3.27	114.77	18.24	4.87
MEAN	103.84	24.05	10.67	118.14	26.55	13.17	86.68	27.29	13.91

AVG. YR. SOLAR RADIATION

STD	GISS	GFDL
383.60	392.87	387.28

MEMPHIS, TN		STD			GISS			GFDL	
MONTH	PREC.	TMAX	TMIN	PREC.	TMAX	TMIN	PRC.	TMAX	TMIN
Jan.	117.09	9.05	-0.59	78.34	12.00	2.37	91.10	11.31	1.67
Feb.	109.98	11.65	1.14	185.32	14.64	4.13	123.51	13.59	3.07
Mar.	138.18	16.33	5.49	85.67	20.66	9.82	198.97	19.04	8.20
Apr.	146.56	22.70	11.24	116.95	26.24	14.79	84.86	25.68	14.23
May	128.52	27.21	16.06	183.28	29.51	18.36	104.10	30.46	19.31
June	90.93	31.35	20.48	110.12	33.89	23.02	61.47	33.89	23.02
July	102.36	33.07	22.56	153.85	35.44	24.93	43.20	36.03	25.52
Aug.	95.00	32.36	21.58	83.79	34.92	24.13	75.33	34.33	23.54
Sept.	91.95	29.04	17.83	100.13	33.68	22.46	180.31	32.32	21.11
Oct.	60.20	23.60	10.73	36.54	26.77	13.91	42.44	26.40	13.53
Nov.	105.92	16.33	5.06	90.03	21.73	10.47	106.24	19.57	8.31
Dec.	123.1[illegible]	11.26	1.[illegible]	90.30	15.13	5.15	196.00	14.78	4.79
MEAN	109.16	22.00	11.07	109.53	25.38	14.46	108.96	24.78	13.86

AVG. YR. SOLAR RADIATION

STD	GISS	GFDL
383.90	390.11	385.76

CHARLOTTE, NC		STD			GISS			GFDL	
MONTH	PREC.	TMAX	TMIN	PREC.	TMAX	TMIN	PREC.	TMAX	TMIN
Jan.	96.5	10.26	-0.71	104.92	12.53	1.55	74.22	12.35	1.38
Feb.	96.8	12.12	0.03	120.39	14.22	2.13	102.00	14.40	2.31
Mar.	122.7	16.56	3.92	151.76	20.52	7.88	140.72	19.26	6.62
Apr.	83.1	22.45	9.12	97.84	24.49	11.16	95.43	25.79	12.46
May	92.5	26.41	14.01	105.31	29.25	16.86	76.55	28.87	16.48
June	90.7	29.76	18.11	118.97	32.28	20.63	39.99	33.82	22.17
July	99.1	31.47	20.33	139.97	33.43	22.29	64.49	36.36	25.22
Aug.	95.3	31.12	20.05	117.25	32.48	21.42	40.58	34.04	22.98
Sept.	91.2	27.83	16.78	72.68	31.09	20.04	73.68	31.86	20.81
Oct.	69.1	22.21	9.76	67.02	25.54	13.09	46.57	25.17	12.72
Nov.	72.4	16.61	4.29	54.00	18.95	6.63	78.04	20.03	7.71
Dec.	86.4	11.58	0.44	79.19	13.33	2.20	111.49	14.91	3.78
MEAN	91.3	21.53	9.68	102.44	24.01	12.16	78.65	24.74	12.89

AVG. YRLY. SOLAR RADIATION

STD	GISS	GFDL
389.20	398.61	392.93

A review of the results would suggest that adaptation to changing climate by changing cultivars could possibly compensate for some of the negative responses to climate change. The extent of this is unknown and needs further investigation. For both corn and soybean, varieties are available and the models could be used to make an evaluation of this management practice. Earlier planting probably would be adopted by farmers as weather becomes warmer in the early spring, and the impact of this practice could be evaluated using the models.

Double cropping is a management practice that could be applied in areas where the changing climate provided a longer growing season. The limitation would be the availability of adequate soil moisture at planting time for the second crop as well as for the growth and development of the second crop. This practice could also be evaluated for both corn and soybeans using the modeling.

SIMULATION EXPERIMENTS

Extension specialists or researchers in each of the 11 southeastern states were contacted to get current recommended varieties, soil types, planting dates, and area planted in soybeans, as well as the same information for corn. Table 1 presents the locations of the 19 weather sites, soil types, and cultivars used.

A set of correction parameters from the GISS and the GFDL data was applied to each weather site. Two grid points from GISS and eight grid points from GFDL data were used, and the parameters applied for each month to the appropriate weather site data without geographic interpolation. WGEN was used to generate solar radiation data for each of the 19 weather sites using the temperature and precipitation data from the weather data provided by NCAR.

Based on information obtained from personal contacts in each of the southeastern states, we chose a soil type from a generic soil base list that most closely characterized a typical field soil in the vicinity of each of the 19 sites. Note that this generic soil list was the same overall list as used by Ritchie of Michigan State University for the study of corn and soybeans in the Great Lakes region and by Rosenzweig for wheat in the Great Plains region. Runs of 30-year simulations for particular locations were made and the growing season dynamics plotted.

Runs were made for rainfed and irrigated management. For the irrigated management, when the available moisture dropped to 40% in the upper 0.5 m of the profile, water was applied to fill the soil profile to field capacity. An application efficiency of 75% was used.

As one looks over the results for the many runs of SOYGRO for various years and locations and weather scenarios, it is obvious that it would be valuable to be able to compare this data with data from runs in which a weather scenario was used that assumed a doubling of the atmospheric CO_2 level, but without the accompanying climate change suggested by the GISS and GFDL scenarios. This study would be a top priority for further work, if and when additional resources are available.

CHAPTER 3

RESULTS

RELATIVE CONTRIBUTIONS BY EACH CLIMATE VARIABLE

For a detailed study of the individual effects of the various weather factors, simulations were done for the 1951 weather data for Memphis, TN, and for the same data with the GISS doubled CO_2 factors applied. The SOYGRO model that responds to climate effects and direct effects of CO_2 was used. Precipitation, temperature, solar radiation, and carbon dioxide levels were changed individually between the standard or base data and the GISS $2xCO_2$ data to produce results for each of the above factors alone.

Figures 8 and 9 show the changes in precipitation, and maximum daily temperature over the season, indicating about a 20% increase in rainfall over the season and 4-6°C increase in temperature. Solar radiation changed very little (not shown). The simulated crop growing season length changed very little for any of the cases. Leaf area index (LAI) increased significantly under elevated CO_2 conditions (Figure 10), but much less under any of the other cases. The 33% increase in LAI under double CO_2 conditions is similar to the data reported by Baker et al. (1988) for soybean.

Seed yield was affected by temperature and precipitation (Figure 11). A water stress in the selected year occurred during the middle of the seed filling period. Increased rainfall for case P reduced the magnitude of the stress and caused about a 24% yield increase. Temperature increases of 4-6° during the season resulted in a 68% decrease in yield. This large decrease is due to the direct effect of high temperature on growth processes in SOYGRO and to increased evapotranspiration demand, which increased the length and severity of the drought. The direct effect of CO_2 acting alone caused about a 58% increase in seed yield, due to both increases in photosynthesis and reduced water stress (lower seasonal evapotranspiration (Figure 12).

Summaries of biomass, seed yield, and seasonal evapotranspiration are presented in Table 7. In general, temperature increases proposed by the GISS model caused considerable decreases in biomass and seed yield. Although increased precipitation at this site and double CO_2 increased yield when acting alone, their combined effect was not enough to overcome the temperature-induced yield loss, and a net loss of 11.5% occurred. It was interesting to note that seasonal ET decreased by 2% under direct CO_2 effects alone, but when all effects were included, ET increased by almost 11% primarily due to increased temperatures. Results from the GFDL scenarios would probably be more severe because of the lower amounts of precipitation simulated by that model.

SUMMARY OF YIELD RESULTS FOR ALL LOCATIONS

Simulations were run for all 19 locations, rainfed and irrigated, three weather scenarios (base, GISS $2xCO_2$ and GFDL $2xCO_2$) with SOYGRO and CERES-Maize models with climate effects alone. The same set of conditions was used for runs of SOYGRO modified for the combined climatic and direct effects. For CERES-Maize, four locations were run with the model modified for combined climatic and direct effects. These results were obtained for some 315 sets of 30-year runs, each requiring 1/2 to 2 hours of run time on microcomputers.

Table 8 is an example of the summary spreadsheets that were obtained for each combination. These spreadsheets calculated means, standard deviations, percentage differences, uncertainties, and yields in metric and English units. Spreadsheet input data was taken from output data of the simulations. Length of the time from planting to crop maturity, total evapotranspiration during that period, rainfall, total irrigation water applied, and seed weight are shown for each year's run.

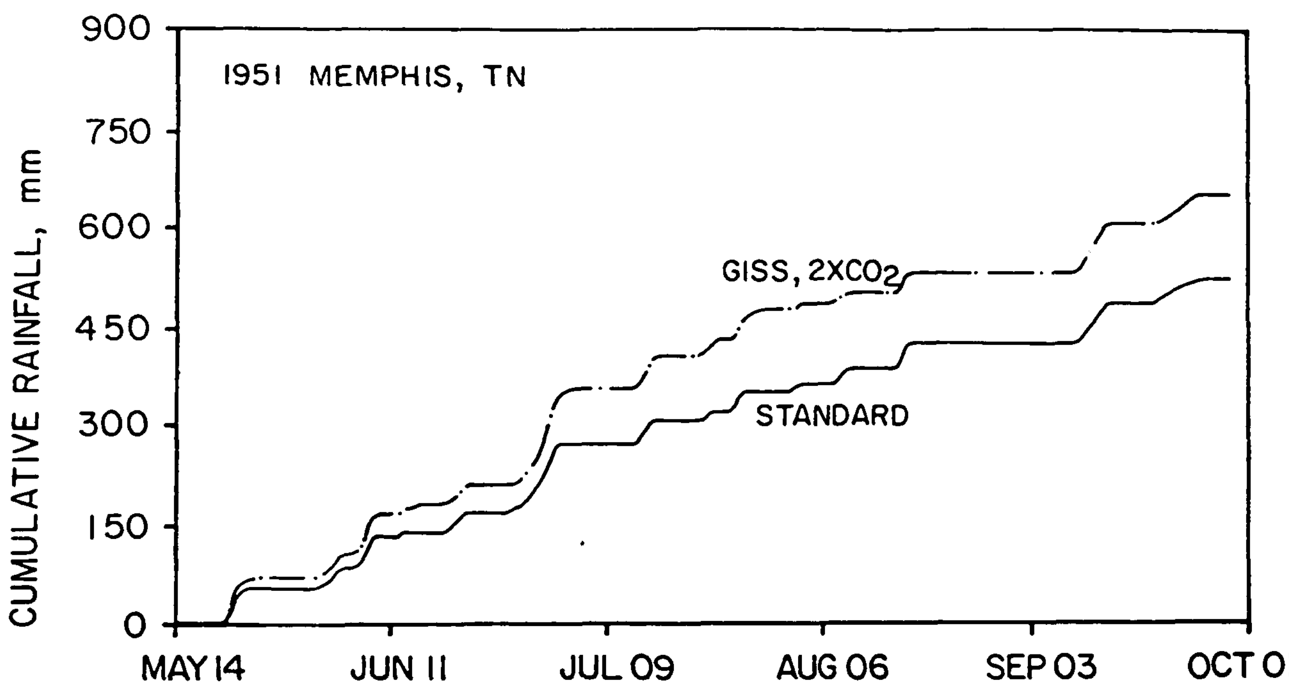

Figure 8. Cumulative rainfall as a function of time of year, based on SOYGRO runs for both GISS and STANDARD weather sets for Memphis, TN. 1951. The version of SOYGRO used had been modified to include combined climatic and the direct effects of $2xCO_2$ on photosynthesis and transpiration.

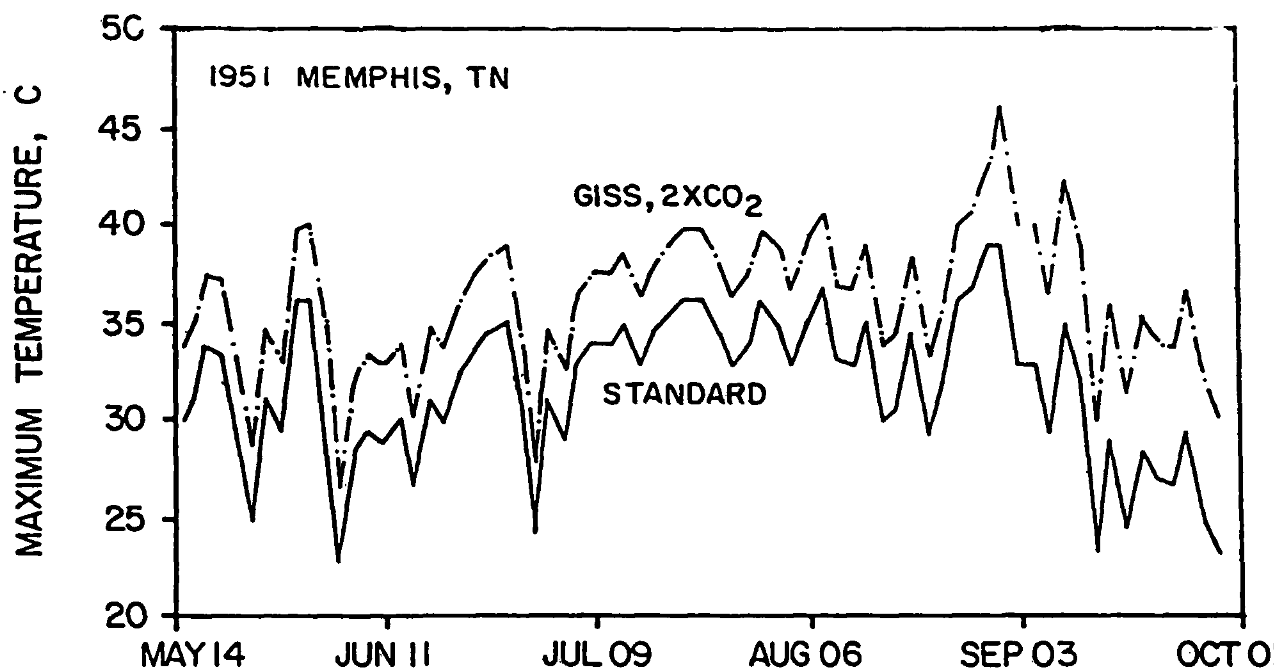

Figure 9. Maximum daily air temperatures as a function of time of year for the same conditions as Figure 8.

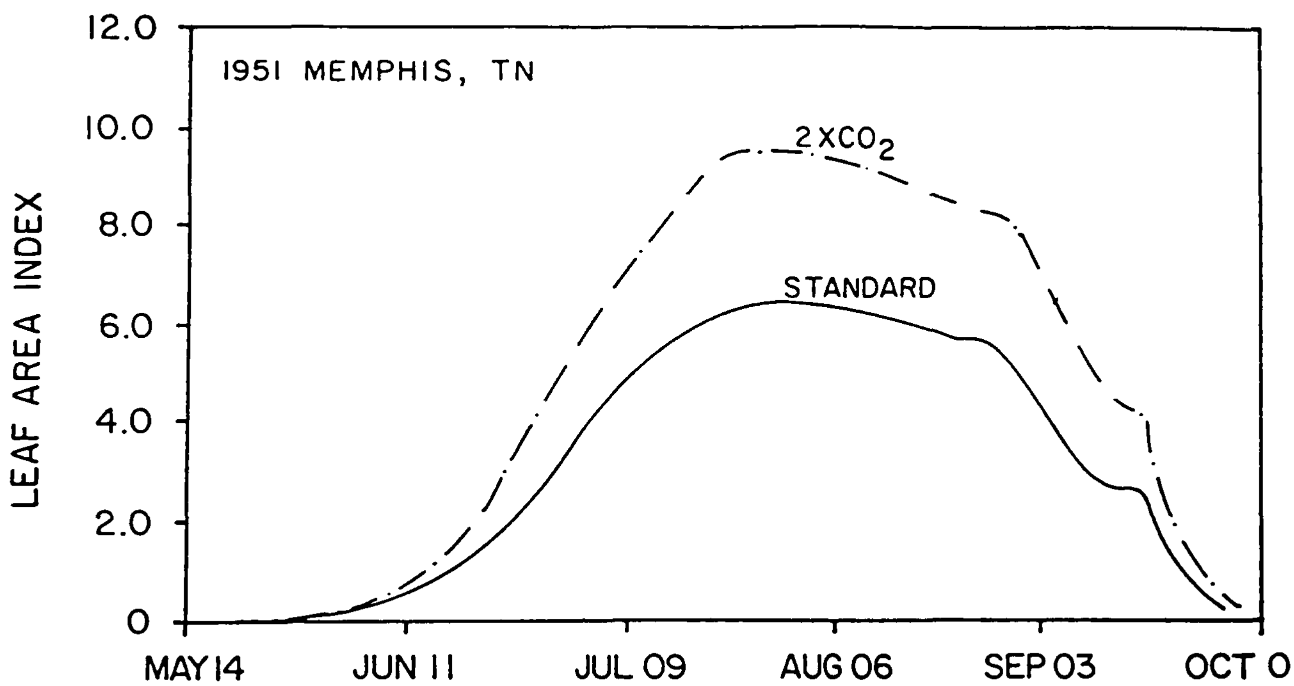

Figure 10. Simulated leaf area index as a function of time of year for the case where direct effects of 2xCO_2 (GISS) alone are included for the 1951 year of weather data from Memphis, TN. The standard curve represents the effect of normal ambient CO_2.

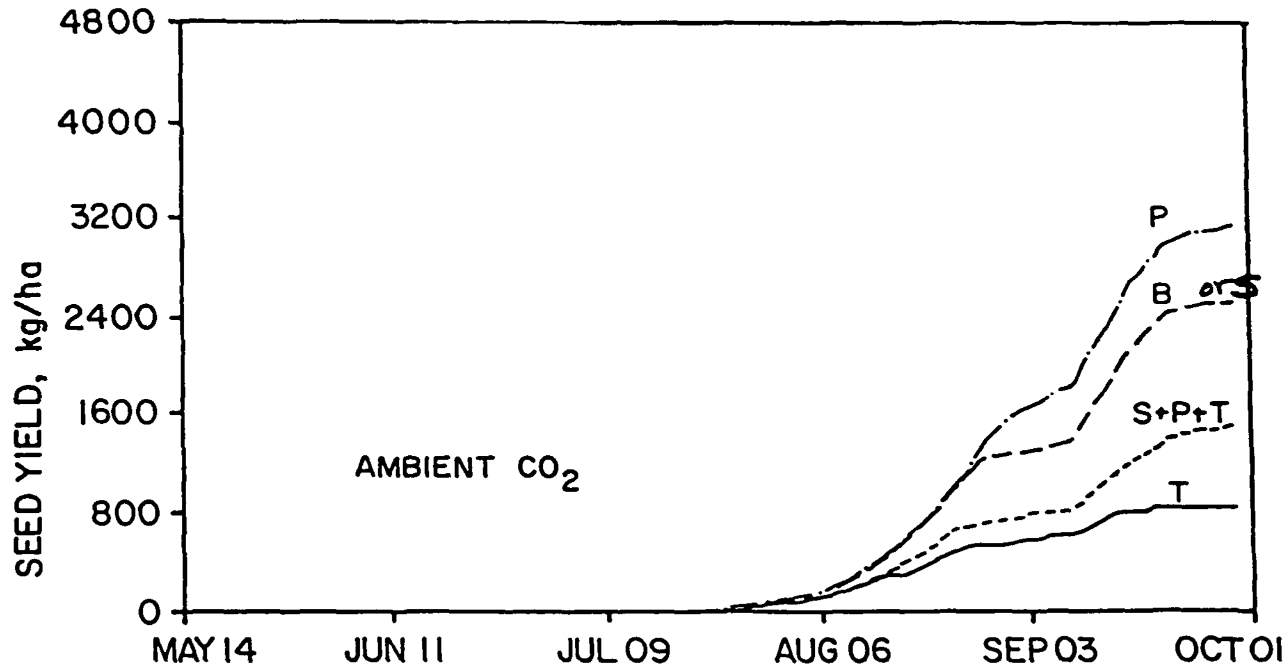

Figure 11. Simulated seed yield vs time of year using the 1951 Memphis, TN weather data except the standard weather was modified by the GISS climate model parameters for precipitation alone (P), solar radiation alone, (S) temperature alone (T), and combined (S+P+T).

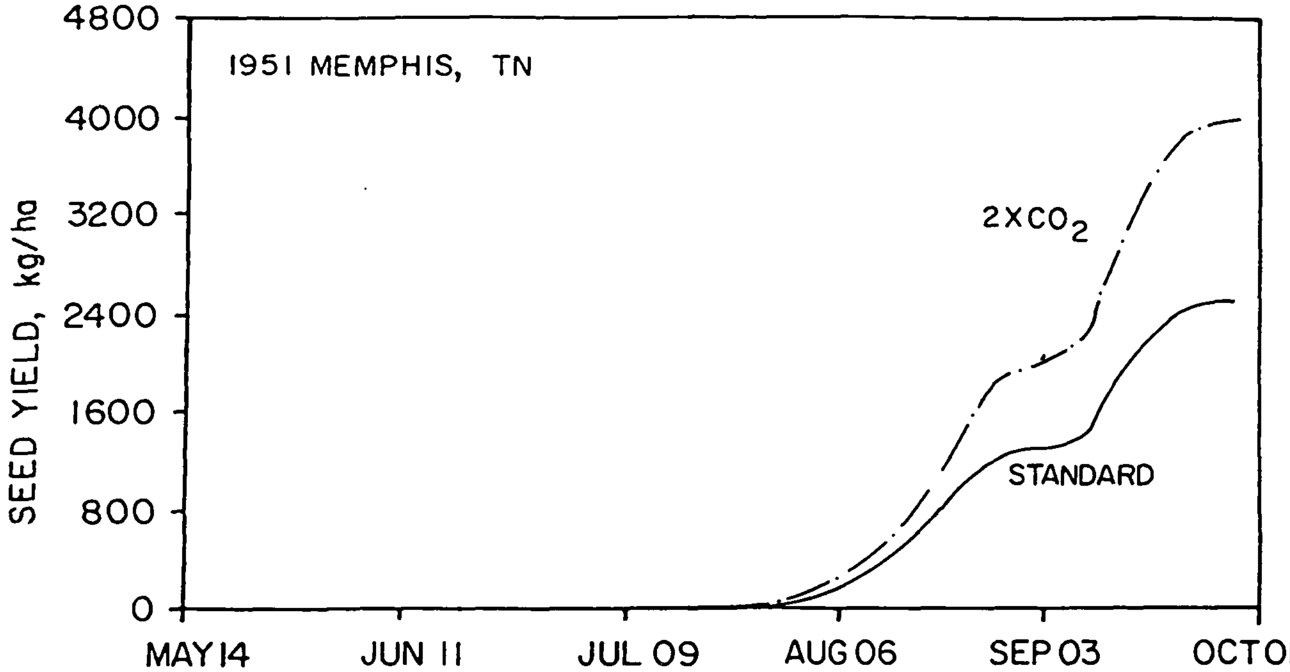

Figure 12. Simulated seed yield versus time of year comparing the results for the combined climate and direct effects of $2xCO_2$ (GISS) with those of the standard weather data.

Table 7. Sensitivity of Simulated Yields to Each Climate Change Factor Alone, Based on the GISS Climate Change Scenario and Double CO_2, and to Combinations for the Memphis, TN Site Using 1951 Weather Data

Factor	Biomass kg/ha	Seed Yield kg/ha	Evapotranspiration mm
Standard Run	6690	2520	617
	Percentage Change		
Solar Radiation (S)	-0.6	-0.8	-0.2
Precipitation (P)	+15.5	+23.8	+5.0
Temperature (T)	-44.1	-68.3	+4.1
Carbon Dioxide (C)	+53.9	+57.9	-2.0
S+P+T	-29.4	-41.3	+12.3
S+P+T+C	+7.8	-11.5	+10.9

Table 8. SOYGRO, Modified for Direct CO2, GISS Weather, RAINFED
University of Florida, EPA Global Climate Change Project, 1988

	MP,TN 2CO2 RAINFED	SOYGRO-2 GISS				Planting Date: 135 STD RAINFED					
Yr	Length	CET	IR	Rain	SdWtco	Length	CET	IR	Rain	SdWt	Diff
51	125	684	0	647	223	125	620	0	523	252	-29
52	126	491	0	328	29	125	449	0	274	47	-18
53	125	390	0	398	38	124	357	0	277	36	2
54	130	414	0	252	2	126	385	0	218	14	-12
55	125	658	0	664	219	125	593	0	517	257	-38
56	125	543	0	417	90	125	489	0	330	76	14
57	123	698	0	857	417	124	633	0	706	388	29
58	125	652	0	626	312	125	577	0	526	335	-23
59	125	706	0	703	441	125	610	0	560	431	10
60	126	661	0	580	134	125	588	0	526	160	-26
61	127	486	0	305	107	128	428	0	254	74	33
62	125	644	0	589	215	123	558	0	502	225	-10
63	126	593	0	531	295	126	528	0	416	277	18
64	125	629	0	524	292	125	558	0	437	332	-40
65	125	518	0	624	68	124	483	0	519	97	-29
66	126	464	0	408	90	127	443	0	346	84	6
67	124	612	0	533	473	127	561	0	433	414	59
68	125	530	0	512	84	126	486	0	419	130	-46
69	126	484	0	312	90	125	442	0	292	86	4
70	127	651	0	553	293	125	573	0	443	306	-13
71	126	619	0	498	340	125	566	0	438	334	6
72	125	585	0	556	192	125	532	0	440	189	3
73	127	587	0	537	266	124	526	0	447	319	-53
74	124	647	0	881	324	126	598	0	700	316	8
75	125	513	0	430	127	124	466	0	343	126	1
76	125	599	0	558	177	127	532	0	443	168	9
77	129	531	0	463	101	123	455	0	367	134	-33
78	127	671	0	614	329	123	571	0	544	355	-26
79	126	613	0	621	349	125	536	0	534	348	1
80	134	520	0	634	20	126	468	0	504	79	-59

SUMMARY, Univ. of Florida | EPA Project, 1988

	MP,TN 2CO2 RAINFED	SOYGRO GISS				Planting Date: STD RAINFED					
	Length	CET	IR	Rain	SdWtco	Length	CET	IR	Rain	SdWt	Diff
Mean	126.0	579.8	.0	538.5	204.6	125.1	520.4	.0	442.6	213.0	-8.4
SDV	2.02	83.3	.0	143.6	131.7	1.19	69.9	.0	117.0	124.6	26.5
SDVS	.37	15.2	.0	26.2	24.0	.22	12.8	.0	21.4	22.7	

Yield Analysis Summary Report:

Means:	g/m2	Bu/acre
Base Yld, muA:	213	31.7
2CO2 Yld, muB:	204.6	30.4
Diff. (muC):	-8.4	-1.2
Diff,sigma muC:	33	4.9
% Diff,muC/muA:	-3.9%	
sigma muC/muA, Uncertnty: +,-	15.5%	

Definitions:

Length (days)=Growing Season
CET (mm)= Evapotranspiration
IR (mm)=Cumulative Irrigation
Rain (mm) = Cumulative Rain
SdWtco (g/sq.m)=Yield, GISS, 2CO2
SdWt (g/sq.m)= Base Yield

R. M. Peart, Agr. Eng. Dept. 4/28/88

Uncertainty percentages are shown in some tables, and they were calculated as follows:

$$\text{The uncertainty of \% change} = \frac{\mu_c}{\mu_a} \pm \frac{{}^{\sigma}\mu_c}{\mu_a} \times 100$$

where μ_c = difference between mean of standard yield and the mean of yield as a result of modified climate.

μ_a = mean of standard yield

$${}^{\sigma}\mu_c = \left(\sigma^2_{\mu_a} + \sigma^2_{\mu_b} \right)^{1/2}$$

where ${}^{\sigma}\mu_a$ and ${}^{\sigma}\mu_b$ are the standard deviations of the appropriate yields.

In this discussion, we will focus more on rainfed than irrigated cases, since the great majority of these crops are not irrigated in the Southeast. We discuss the results first with the original SOYGRO and CERES-MAIZE models, which are sensitive to weather variables, but assume current concentrations of CO_2 in the ambient air. Table 9 shows the rainfed and irrigated results for all locations. Figures 13 and 14 show the 30-year average rainfed and irrigated soybean results for all locations and for both the climate alone (GISS-N and GFDL-N) scenarios and the climate and direct CO_2 effects (GISS-D and GFDL-D) scenarios. The combined (-D) scenarios account for carbon dioxide enrichment, or the direct effects.

Annual Variability. Most results shown in this report are 30-year averages for actual 1951-1980 weather at a given location or for weather data modified by the GISS or GFDL weather models. The following figure was included to emphasize the year to year variability at a sample site. A shorter period of 10 years (1951-60) was chosen for these examples. Figure 15 shows 10 years of yearly results at Memphis, TN, 1951-60, and the variability is striking. Three of the years would be considered crop failures, when value of the yield hardly covered harvesting costs, while three other years produced outstanding yields. Figure 15 results include the modified SOYGRO results, which account for carbon dioxide enrichment. GISS results show slightly higher than base yields for only 2 of the 10 years at Memphis, and GFDL results are lower in all years, and drastically lower in most of the 10 years. Variability between years is even greater with the GISS weather than the base weather. Since the GFDL yields were so much lower, variability was less.

Soybean Simulations for Climate Effect Only. For climate effect alone the discussion in this section will refer only to the models of climate alone (-N). The results, therefore, are only influenced by the change in weather variables and not by any direct influence of CO_2 on photosynthesis and transpiration.

In the Delta area, where normal yields are lower, the climate predicted by carbon dioxide doubling ($2xCO_2$) cuts yields almost in half for GISS and reduces the yields to near crop failure for the GFDL case. For commercial and economic reference, 1800 kg/ha is a little less than 30 bushels per acre, a typical yield, and soybean prices have been the $6-$8/bushel range. Thus the Delta GFDL-N results would mean a gross income of about $30-$40 per acre, not enough to pay land capital costs.

The Coastal Plains locations had better base yields and reductions of about 20% due to the GISS weather and 70% due to the GFDL weather. The GFDL results were more variable in their effect among locations, with reductions of 78% to 90% for Columbia, Macon, Meridian, Montgomery, and Norfolk, which means 30 years of mostly crop failures. The other three locations, Mobile, Tallahassee, and Wilmington, all coastal areas, were reduced less.

Table 9. SOYGRO Results, Kg/ha, Southeastern USA, 30-yr Average

N - Doubled CO_2 , weather effects only.
D - Doubled CO_2, weather and direct effects.

SOYGRO Rainfed Yields, Kg/ha, 30-Yr. Ave.

Location	Climate Alone,N		Comb. Climate & Direct,D		
	BASE	GISS-N	GFDL-N	GISS-D	GFDL-D
DELTA:	1701	982	309	1451	572
COASTAL PL:	2698	2067	817	2978	1358
UPLANDS:	2724	2313	878	3313	1393
AVERAGE:	2495	1929	733	2777	1205

SOYGRO, Irrigated Yields, Kg/ha, 30-yr Average

DELTA:	3948	2814	3120	3931	4425
COASTAL PL:	3770	3144	3097	4265	4381
UPLANDS:	3852	3370	3070	4686	4388
AVERAGE:	3837	3158	3092	4347	4390

DELTA - Baton Rouge, LA, Little Rock, AR, Memphis, TN, Shreveport, LA.

COASTAL PL - Columbia, SC, Mobile, AL, Macon, GA, Meridian, MS, Montgomery, AL, Norfolk, VA, Tallahassee, FL, Wilmington, NC.

UPLANDS - Atlanta, GA, Birmingham, AL, Charlotte, NC, Lynchburg, VA, Louisville, KY, Nashville, TN, Raleigh, NC.

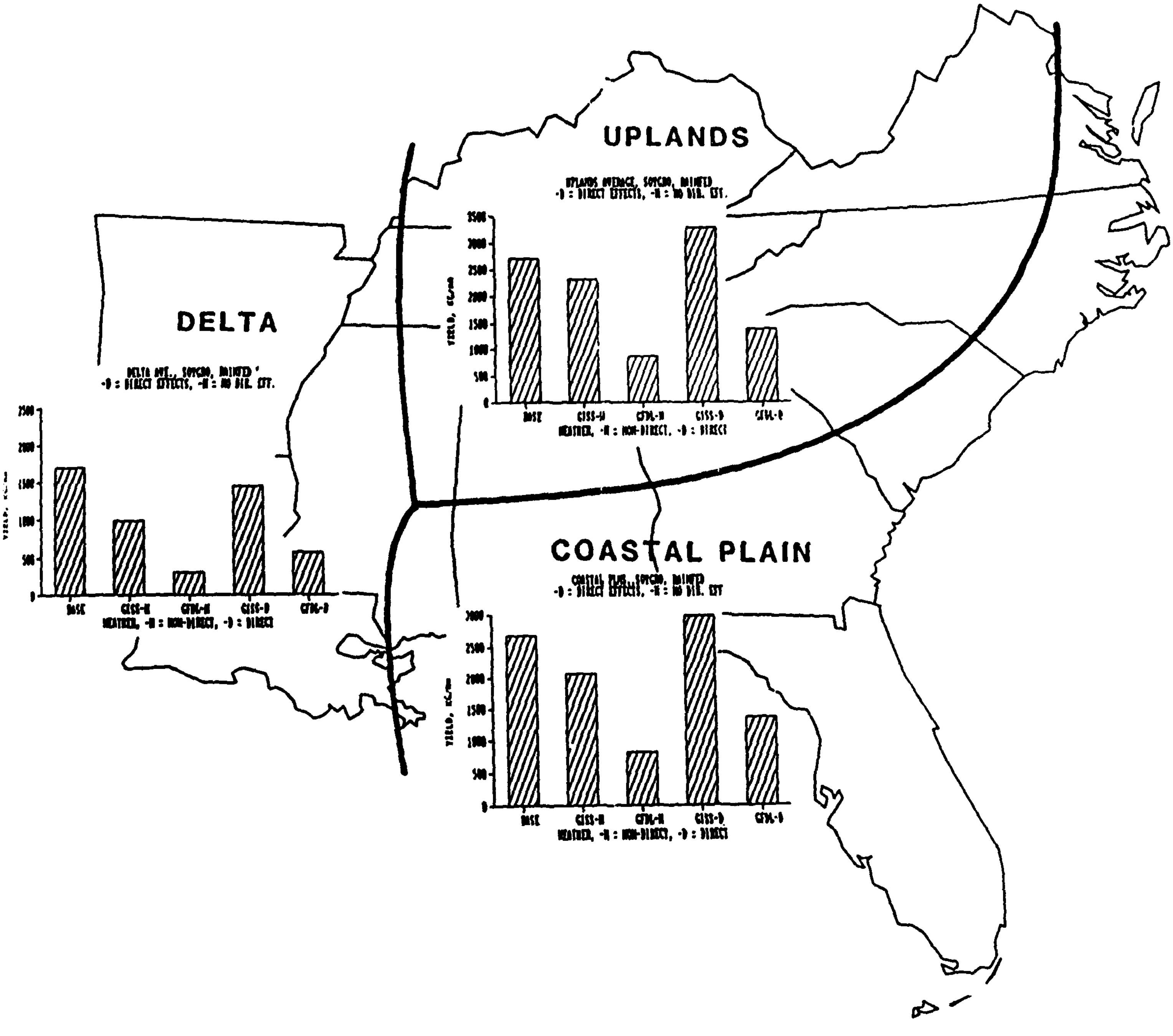

Figure 13. Summary of rainfed SOYGRO yield results for GISS & GFDL scenarios. Includes both the climatic effects (N) and the combined climatic and direct CO_2 effect (D) on the plant of $2xCO_2$. Yield in Kg/Ha.

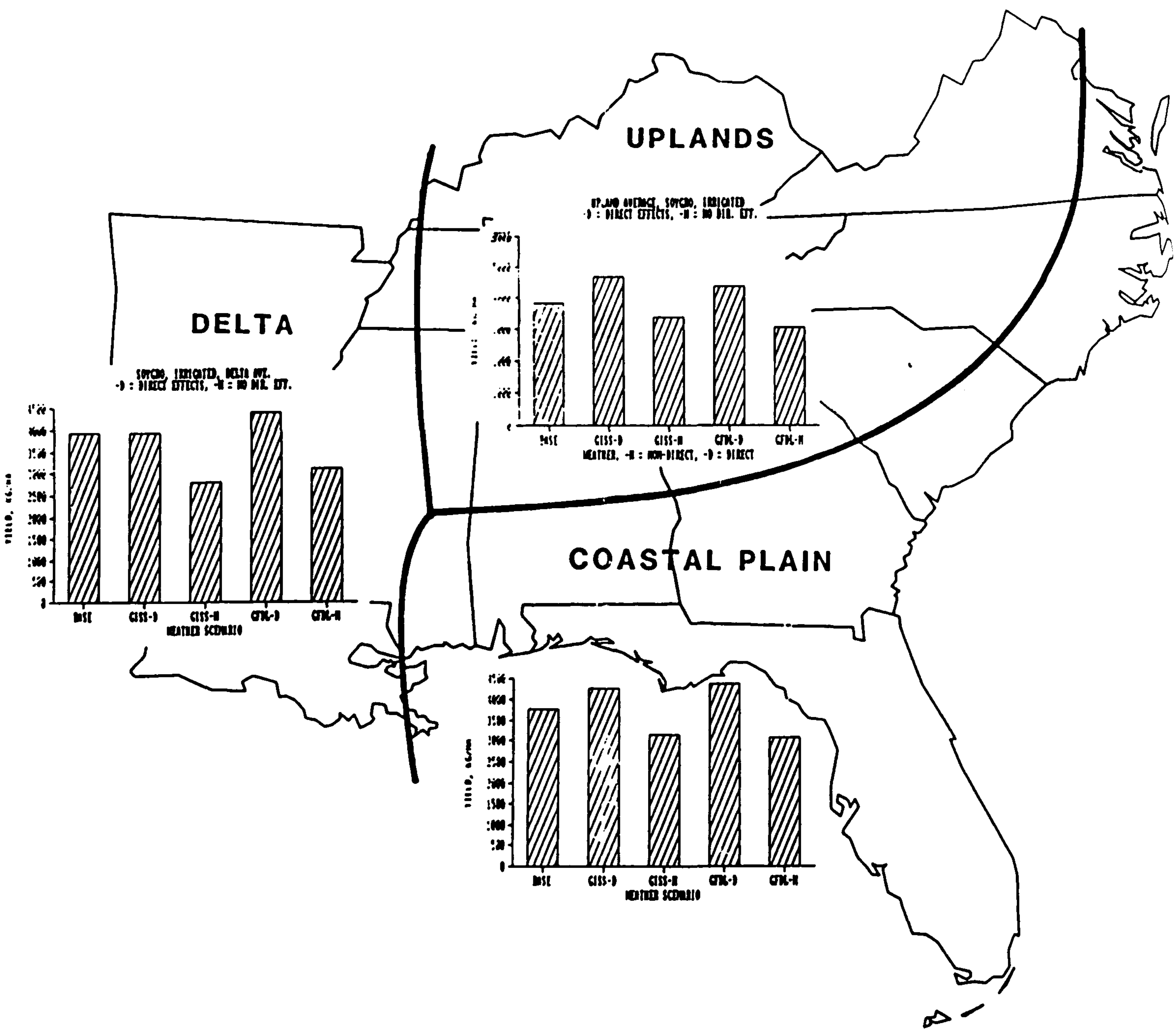

Figure 14. Summary of irrigated SOYGRO yield results for GISS & GFDL scenarios. Includes both the climatic effects (N) and the combined climatic and direct CO_2 effects on plant of $2xCO_2$. Yield in Kg/Ha.

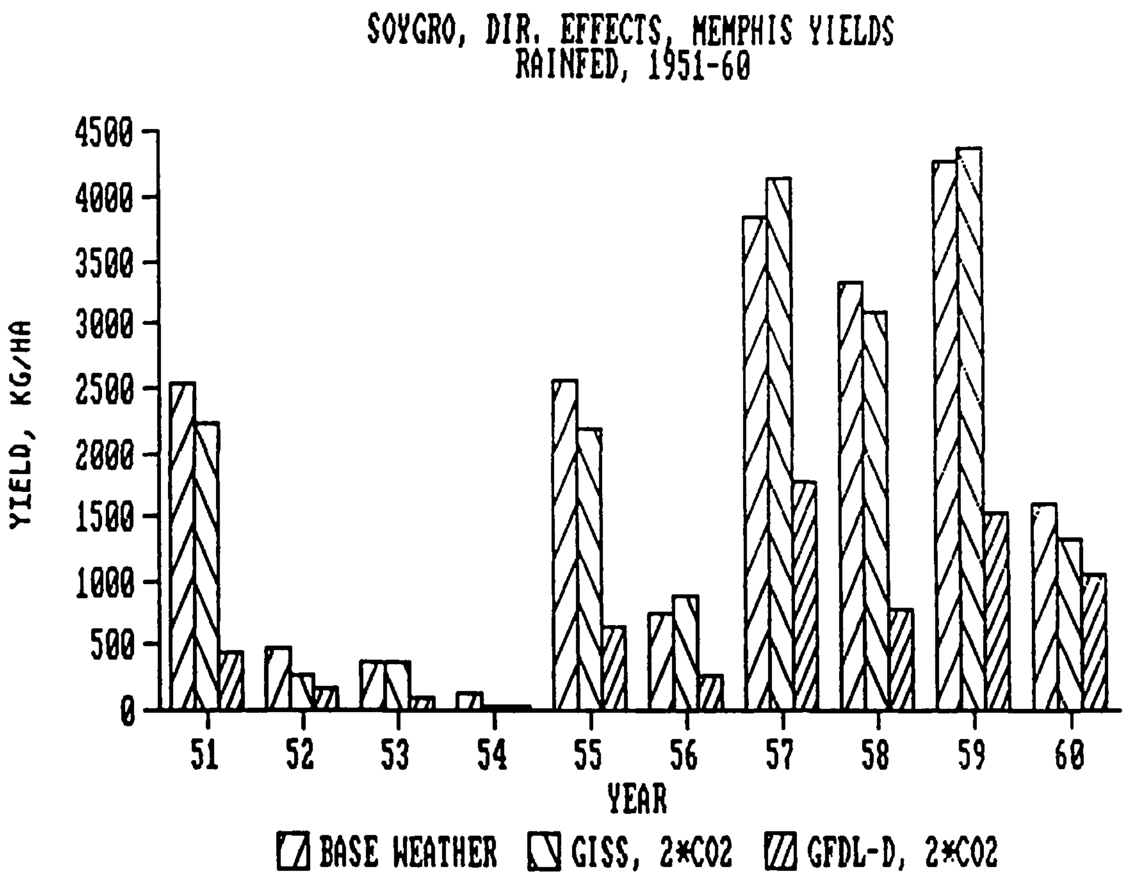

Figure 15. Typical annual yield variations, 1951-60.

Most of the Upland locations had more moderate reductions for the GISS weather, but drastic reductions for GFDL. Lynchburg, VA, had a peculiar tiny increase with GISS, probably due to more rainfall at some times and more moderate temperatures.

In summary, the rainfed climate-effect-only SOYGRO model used with the GISS weather scenario shows serious yield reductions, from 20% to almost 50% for 13 of the 19 locations, and less serious reductions for the other 6 locations. Used with the GFDL weather scenario, the model showed very serious yield reductions of not less than 37% and averaging 72.7% for all locations.

The irrigated results are shown in Tables 10 and 11, and naturally show less drastic effects, since the irrigation cancels any lowered rainfall effects of the doubled carbon dioxide weather scenarios. However, the average effects show similar reductions of 17.5% for the GISS scenario and 19.2% for GFDL. Comparing the GFDL results for rainfed and irrigated implies that rainfall reductions were a major factor in the GFDL model results for climate effects alone.

Maize Simulations for Climate Effect Only. Table 12 summarizes the Maize model results, nonmodified for direct effects. Rainfed GISS reductions from the base runs are much less drastic at Baton Rouge, Little Rock, Montgomery, and Shreveport than for soybeans. These four locations account for most of the change in the percent difference between soybeans and maize for rainfed GISS results. The lower sensitivity to temperature effects in this range probably account for the difference between soybeans and maize at the four locations. GFDL rainfed results were drastically reduced, averaging 64.6%.

Irrigated maize showed results similar to soybeans, with average reductions of 18.2% for GISS and 27.6% for GFDL doubled carbon dioxide scenarios compared to the base weather. These reductions were more uniform among locations than was the case for soybeans.

Soybean Simulations for Combined Climate and Direct Effects. As described earlier in this report, SOYGRO was modified with a set of constants to increase the photosynthetic rate and increase the stomatal resistance to transpiration for the doubled carbon dioxide. This effect is often called "carbon dioxide enrichment," and is carried on in some commercial greenhouses to increase the rate of growth of plants. This effect has led some writers to assume that doubling the carbon dioxide in the atmosphere would increase crop production, but the answer is not that simple.

The simulation process, where all the effects of the different environmental conditions, rainfall, solar radiation, temperature, carbon dioxide concentration, and others are integrated on a daily basis, is necessary to estimate the overall effects of such a change. These results are based on quickly made modifications to the models, and more detailed work on the models and in growth chambers are needed, but they give the best estimates we can now make of the results of the doubled carbon dioxide scenarios.

Table 11 gives, by areas of the southeastern U.S.A., yield results for the modified SOYGRO under rainfed conditions for the GISS and GFDL weather scenarios. Under the GISS conditions, 7 of the 19 locations had yield reductions, and the average change was an increase of 9.1%. Under the GFDL conditions, all but two locations were drastically reduced in yields, with an average reduction of 54.6%. For the GISS data, the Delta area had reductions of about 15%, the Coastal Plains increased in yield by about 10%, and the Upland area had an increase of about 20%. For the GFDL weather, all areas suffered about equally.

Table 10. SOYGRO Simulation, Univ. of Florida, 30-yr Averages
Non-Modified for CO2 Effect on P-Syn., 3-18-88

Location	Yld, Base	GISS Kg/ha 2*CO2	GISS Diff., Pct.	GISS Uncrty, +,-,%	GDFL Kg/ha 2*CO2	GDFL Diff, Pct.	GDFL Uncrty, +,-,%
NON-IRRIGATED (RAINFED)							
AT,GA	3618	3235	-10.6%	5.0%	807	-77.7%	4.4%
BI,AL	3477	2394	-31.0%	4.7%	1614	-53.5%	5.1%
BR,LA	1775	915	-48.4%	12.1%	437	-75.2%	11.7%
CH,NC	2408	2239	-7.1%	12.7%	188	-92.1%	9.6%
CL,SC	2603	2085	-20.0%	11.5%	565	-78.2%	9.6%
LB,VA	2529	2562	1.5%	11.1%	646	-74.3%	8.8%
LR,AR	1641	982	-40.3%	15.7%	276	-83.0%	13.2%
LU,KY	2448	1903	-22.1%	11.2%	1533	-37.4%	10.6%
MB,AL	3450	2286	-33.8%	5.9%	1957	-43.3%	6.7%
MC,GA	1890	1426	-24.5%	12.4%	161	-91.4%	9.6%
ME,MS	2374	1500	-36.9%	11.9%	518	-78.1%	10.2%
MG,AL	2051	1244	-39.3%	14.5%	330	-83.8%	11.6%
MP,TN	2132	1325	-37.9%	13.3%	377	-82.5%	11.0%
NO,VA	2999	2771	-7.7%	7.7%	276	-90.8%	5.9%
NS,TN	2226	1567	-29.6%	12.4%	1063	-52.2%	11.0%
RA,NC	2360	2293	-2.8%	10.8%	296	-87.6%	7.9%
SH,LA	1258	706	-43.5%	15.8%	148	-88.2%	13.3%
TL,FL	3147	2508	-20.3%	4.4%	1553	-50.7%	5.0%
WI,NC	3067	2717	-11.4%	5.4%	1177	-61.6%	6.5%
AVE.:	2497	1929	-24.5%	10.4%	733	-72.7%	9.0%

Location	Yld, Base	GISS Kg/ha 2*CO2	GISS Diff., Pct.	GISS Uncrty, +,-,%	GFDL Kg/ha 2*CO2	GFDL Diff, Pct.	GFDL Uncrty, +,-,%
IRRIGATED							
AT,GA	4270	3800	-10.9%	1.6%	3120	-26.9%	2.2%
BI,AL	3961	3013	-23.9%	1.8%	3188	-19.5%	1.8%
BR,LA	3618	2710	-25.1%	2.9%	3208	-11.3%	2.8%
CH,NC	4048	3578	-11.5%	1.5%	3020	-25.4%	1.8%
CL,SC	3948	3537	-10.5%	2.6%	3362	-14.9%	2.8%
LB,VA	3712	3658	-1.3%	1.9%	3060	-17.6%	1.9%
LR,AR	4008	2878	-28.1%	2.3%	3114	-22.4%	2.1%
LU,KY	3685	3194	-13.3%	2.2%	3120	-15.3%	2.2%
MB,AL	3753	2804	-25.4%	3.0%	3376	-10.1%	2.6%
MC,GA	3934	3396	-13.8%	2.8%	3208	-18.6%	2.9%
ME,MS	3961	2932	-26.1%	2.3%	3046	-23.2%	2.2%
MG,AL	4001	3067	-23.3%	2.5%	3181	-20.5%	2.6%
MP,TN	4048	2952	-27.1%	2.2%	3181	-21.3%	2.0%
NO,VA	3806	3457	-9.2%	1.6%	2885	-24.2%	1.8%
NS,TN	3887	3093	-20.5%	1.9%	2919	-25.0%	-2.0%
RA,NC	3396	3255	-4.1%	2.3%	3067	-9.7%	2.4%
SH,LA	4116	2717	-34.1%	2.7%	2979	-27.6%	2.6%
TL,FL	3369	2892	-14.2%	3.3%	2730	-19.0%	3.4%
WI,NC	3389	3067	-9.6%	2.4%	2986	-12.0%	2.4%
AVE.:	3837	3158	-17.5%	2.3%	3092	-19.2%	2.1%

Table 11. EPA Climate Change Project, 6/6/88,
SOYGRO, Modified for Direct CO_2 Effects, 30-yr. ave. Results

Loc.	Base Wthr kg/ha	GISS-D kg/ha	Diff. %	Uncrty, %	GFDL-D kg/ha	Diff. %	Uncrty, %
			RAINFED SOYGRO				
AT,GA	3618	4587	26.8%	6.0	1197	-66.9%	5.1
BI,AL	3470	3470	.0%	5.6	2482	-28.5%	6.4
BR,LA	1775	1480	-16.7%	13.6	935	-47.3%	14.2
CH,NC	2408	3181	32.1%	14.8	282	-88.3%	9.8
CL,SC	2603	3060	17.6%	13.6	982	-62.3%	11.2
LB,VA	2529	3692	46.0%	13.0	1130	-55.3%	10.4
LR,AR	1641	1439	-12.3%	18.0	464	-71.7%	14.0
LU,KY	2441	2663	9.1%	13.4	2340	-4.1%	12.7
MB,AL	3450	3174	-8.0%	6.7	3174	-8.0%	7.8
MC,GA	1890	2105	11.4%	14.0	343	-81.9%	10.0
MP,TN	2132	1849	-13.2%	15.1	652	-69.4%	11.8
ME,MS	2374	2179	-8.2%	13.7	854	-64.0%	11.2
MG,AL	2051	1843	-10.2%	16.6	659	-67.9%	12.8
NS,TN	2226	2320	4.2%	14.6	1762	-20.8%	12.9
NO,VA	2999	4008	33.6%	8.7	437	-85.4%	6.3
RA,NC	2361	3275	38.7%	12.6	558	-76.4%	8.7
SH,LA	1251	1036	-17.2%	18.5	235	-81.2%	13.6
TL,FL	3147	3632	15.4%	5.3	2616	-16.9%	6.0
WI,NC	3067	3820	24.6%	6.2	1802	-41.2%	8.2
Ave.	2496	2780	9.1%		1206	-54.6%	
Std. Dev	639	969			871		

IRRIGATED

Location	Base kg/ha	GISS-D kg/ha	Diff. %	Uncrty,: %	GFDL-D kg/ha	Diff. %	Uncrty, %
AT,GA	4270	5219	22.2%	2.1	4513	5.7%	2.5
BI,AL	3961	4203	6.1%	2.2	4519	14.1%	2.1
BR,LA	3618	3719	2.8%	3.7	4439	22.7%	3.5
CH,NC	4049	4956	22.4%	1.8	4311	6.5%	2.0
CL,SC	3948	4734	19.9%	3.3	4687	18.7%	3.5
LB,VA	3712	5077	36.8%	2.3	4365	17.6%	2.4
LR,AR	4008	4042	.8%	2.9	4439	10.7%	2.7
LU,KY	3685	4519	22.6%	2.6	4459	21.0%	2.7
MB,AL	3753	3685	-1.8%	3.8	4492	19.7%	3.3
MC,GA	3934	4580	16.4%	3.6	4459	13.3%	3.9
MP,TN	4042	4116	1.8%	2.9	4526	12.0%	2.5
ME,MS	3961	4049	2.2%	2.8	4358	10.0%	2.6
MG,AL	4001	4075	1.8%	3.2	4513	12.8%	3.2
NS,TN	3887	4358	12.1%	2.4	4284	10.2%	2.4
NO,VA	3806	4829	26.9%	1.9	4176	9.7%	2.5
RA,NC	3396	4468	31.6%	2.9	4264	25.5%	2.8
SH,LA	4116	3847	-6.5%	3.5	4297	4.4%	3.1
TL,FL	3369	3995	18.6%	4.3	4223	25.3%	4.2
WI,NC	3389	4176	23.2%	3.2	4143	22.2%	3.0
AVE:	3837	4350	13.7%	2.9%	4393	14.9%	2.9%
STD.DEV	248	442			137		

Table 12. CERES-MAIZE Simulation, 30-yr Averages, Univ. of Florida
Non-Modified for CO2 Effect on P-Syn., 3-18-88

RAINFED Location	BASE Yld, Kg/ha	GISS : Yld, Kg/ha	GISS Diff., Pct.	GISS Uncrty, +,-,%	GDFL : Yld, Kg/ha	GDFL Diff, Pct.	GDFL Uncrty, +,-,%
AT,GA	13236	11874	-10.3%	5.2%	5714	-56.8%	4.7%
BI,AL	12609	9951	-21.1%	4.3%	6622	-47.5%	4.7%
BR,LA	3206	2940	-8.4%	24.2%	1578	-50.7%	21.5%
CH,NC	8906	8855	-.5%	10.6%	2133	-76.1%	8.7%
CL,SC	8718	7602	-12.8%	11.5%	2356	-73.0%	10.3%
LB,VA	10196	9864	-3.3%	11.1%	3062	-70.0%	
LR,AR	6593	6999	+6.2%	14.0%	2313	-64.9%	10.9%
LU,KY	9706	8877	-8.6%	11.5%	6845	-29.5%	11.1%
MB,AL	10390	8135	-21.7%	8.1%	5548	-46.6%	8.3%
MC,GA	8459	8264	-2.4%	9.5%	1491	-82.4%	8.2%
ME,MS	8358	7040	-15.8%	10.2%	2543	-69.6%	9.8%
MG,AL	7962	7803	-2.0%	9.5%	1477	-81.4%	8.0%
MP,TN	8149	7544	-7.4%	13.0%	2990	-63.4%	11.7%
NO,VA	10390	9561	-7.9%	8.8%	3278	-68.4%	8.5%
NS,TN	8610	8142	-5.5%	11.1%	5181	-39.9%	10.9%
RA,NC	9597	9561	-.4%	9.7%	2313	-75.9%	8.3%
SH,LA	5281	6326	+19.7%	18.8%	2147	-59.4%	14.3%
TL,FL							
WI,NC	12033	10304	-14.4%	5.9%	6939	-42.3%	6.4%
AVE.:	9022	8313	-7.9%	10.9%	3585	-64.6%	9.8%

IRRIGATED Location	BASE Yld, Kg/ha	: Yld, Kg/ha	Diff., Pct.	Uncrty, +,-,%	GDFL : Yld, Kg/ha	GDFL Diff, Pct.	GDFL Uncrty, +,-,%
AT,GA	15210	12761	-16.1%	3.5%	10239	-32.7%	3.2%
BI,AL	13351	10866	-18.6%	3.7%	10714	-19.8%	3.9%
BR,LA	14627	12307	-15.9%	3.1%	11312	-22.7%	3.2%
CH,NC	14591	12674	-13.1%	2.6%	10376	-28.9%	2.3%
CL,SC	13777	11211	-18.6%	3.4%	9115	-33.8%	3.1%
LB,VA	15880	13560	-14.6%	4.7%	11067	-30.3%	4.5%
LR,AR	14115	11384	-19.3%	2.9%	10938	-22.5%	3.0%
LU,KY	15758	12544	-20.4%	3.9%	11010	-30.1%	3.5%
MB,AL	14122	11507	-18.5%	3.5%	10613	-24.9%	3.5%
MC,GA	13582	11024	-18.8%	3.1%	8790	-35.2%	3.1%
ME,MS	13532	10794	-20.2%	3.4%	10779	-20.3%	3.4%
MG,AL	13697	10858	-20.7%	2.6%	8762	-36.1%	2.6%
MP,TN	13892	11327	-18.5%	3.3%	11082	-20.2%	3.3%
NO,VA	14915	11644	-21.9%	3.6%	9670	-35.1%	3.2%
NS,TN	14202	12141	-14.5%	3.3%	10642	-25.1%	3.4%
RA,NC	14461	12271	-15.1%	3.9%	10275	-29.0%	3.8%
SH,LA	14396	11183	-22.3%	2.2%	10938	-24.0%	2.2%
TL,FL							
WI,NC	14007	11175	-20.2%	3.2%	10440	-25.5%	3.1%
AVE:	14340	11735	-18.2%	3.3%	10376	-27.6%	3.2%

For irrigated soybeans, under GISS, about half the locations had significant increases in yield, while the rest had insignificant changes compared to the base case. The average increase in yield for all locations was 13.7%. For the GFDL weather, results were about the same, with an average increase of 14.9%.

Maize Simulations for Combined Climate and Direct Effects. Time constraints prevented running Maize for all locations, but rainfed results from four locations, Charlotte, NC, Macon, GA, Meridian, MS, and Memphis, TN, are shown in Table 13. Modification of MAIZE for carbon dioxide enrichment did not have as great an effect on yields because the physiological effects are less, and this is seen in Figure 15, which shows results for modified and nonmodified MAIZE for both GISS and GFDL weather scenarios. Briefly, under GISS weather, insignificant yield changes occurred, but under GFDL weather, drastic yield reductions occurred in the range of 75%.

WATER-USE RESULTS

Soybean Water-Use Results for Combined Climate and Direct Effects. Since the modification for carbon dioxide enrichment affected transpiration of water from the plant leaves to the air, we are interested in how the combined effect and climate-alone models compared in water use efficiencies. Figure 17 shows these results for three rainfed locations for SOYGRO. We defined water-use efficiency as the seed yield divided by the total evapotranspiration during the growing season. Study of the SOYGRO yield results in Figure 16 along with the water-use efficiencies shown in Figure 17 show a very close relationship of water-use efficiency to yield. Allen et al. (1985) and Jones et al. (1985a) pointed out that changes in WUE were strongly related to changes in photosynthetic rates and only weakly related to changes in transpiration rates under various CO_2 treatments at constant temperatures. However, Jones et al. (1985b) showed that temperature increases from 28°C to 35°C with other factors constant reduced soybean WUE about 26%. Allen et al. (1985) and Jones et al. (1985a) also showed that increasing crop leaf area index from 3.3 to 6.0 decreased WUE about 17%. Evapotranspiration is a function of air temperature and relative humidity, crop leaf area, soil water potential, and leaf water potential among other factors, so the weather, as well as the crop, has a strong effect on it.

Comparing water-use efficiencies for the combined-effect SOYGRO to those of the climate-alone model, the direct effect significantly increases water-use efficiency. This is because it increases yields somewhat and reduces evapotranspiration somewhat. The GFDL scenario reduces yields drastically, and therefore also reduces water-use efficiency in the same way.

Maize Water-Use Results for Combined Climate and Direct Effects. Figures 18 and 19 show yields and water-use efficiencies, respectively, for MAIZE and the several scenarios. Since yields change less between the modified and nonmodified model, water-use efficiencies are not affected much by the carbon dioxide direct effect. The GFDL scenario shows drastic yield and water-use efficiency reductions, whereas the GISS weather shows little change from the base weather.

Irrigation Requirements - Soybeans. As a basis for an estimate of the potential increase in the demand on water resources in the southeastern region, a summary of average rainfall, evapotranspiration, and irrigation amount was extracted from the simulation runs. The numbers represent averages of 19 locations x 30 years of weather data. For the base (standard) weather case, the average rainfall was 508 mm, average ET 590 mm, average irrigation requirement 224 mm. For runs made using the climate scenarios incorporating the combined climatic effect and the direct CO_2 effects on the plant, the GISS scenario would increase the potential irrigation demand on the average 33%, while the GFDL scenario would increase the demand by 133%.

Table 13. CERES Maize, Combined Climate and Direct Effects on Yields Charlotte, Macon, Meridian and Memphis

Loc.	BASE kg/ha	GISS-D kg/ha	Diff, % %	Uncrty, %	GFDL-D kg/ha	Diff., %	Uncrty, %
				RAINFED			
CH,NC	9020	8995	-.3%	10.7%	2172	-75.9%	8.8%
MC,GA	8580	8386	-2.3%	9.6%	1488	-82.7%	8.3%
ME,MS	8455	7156	-15.4%	10.4%	2599	-69.3%	9.9%
MP,TN	8254	8009	-3.0%	13.1%	2636	-68.1%	10.7%
				IRRIGATED			
CH,NC	14845	12811	-13.7%	2.5%	10558	-28.9%	2.3%
MC,GA	13344	10834	-18.8%	3.1%	8624	-35.4%	3.1%
ME,MS	13778	10991	-20.2%	3.5%	10953	-20.5%	3.5%
MP,TN	14242	11543	-19.0%	3.3%	11317	-20.5%	3.2%

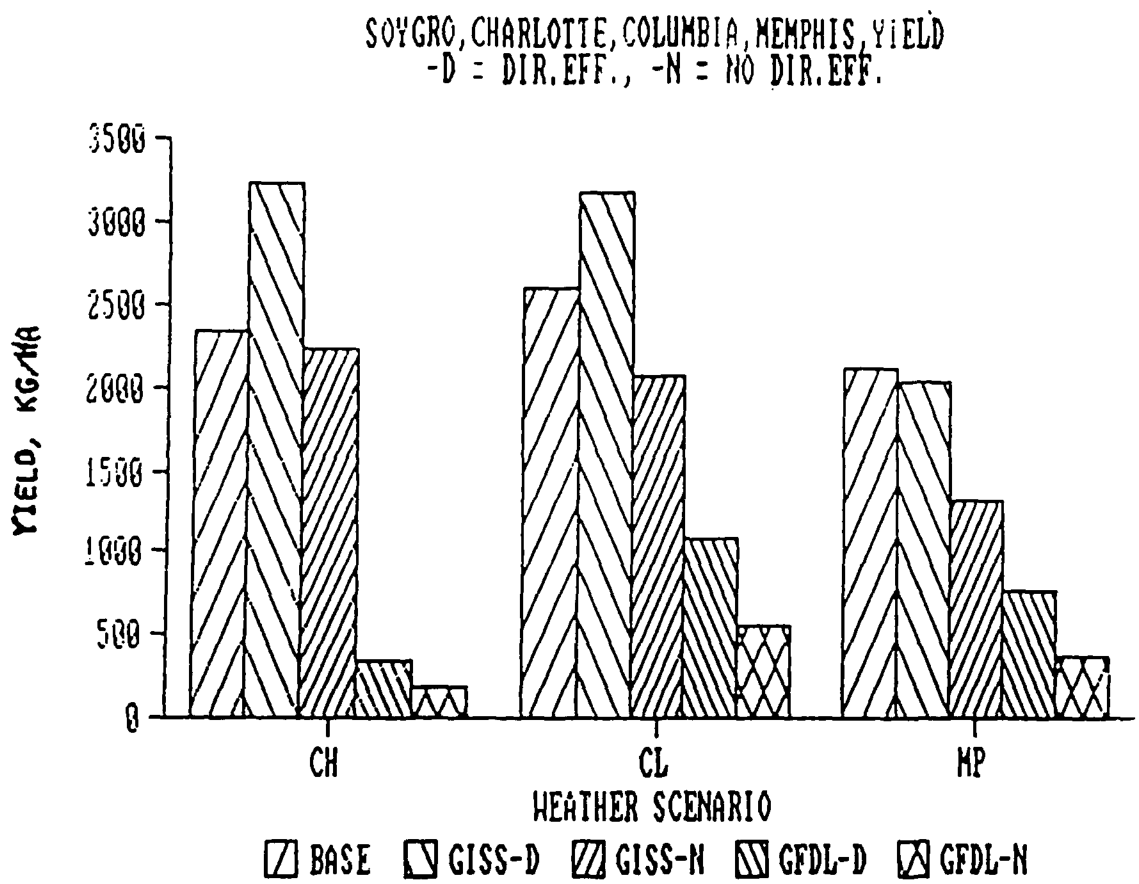

Figure 16. Rainfed yields for soybeans for Charlotte, NC, Columbia, SC, and Memphis, TN based runs with SOYGRO modified to include both climatic and direct CO_2 effects.

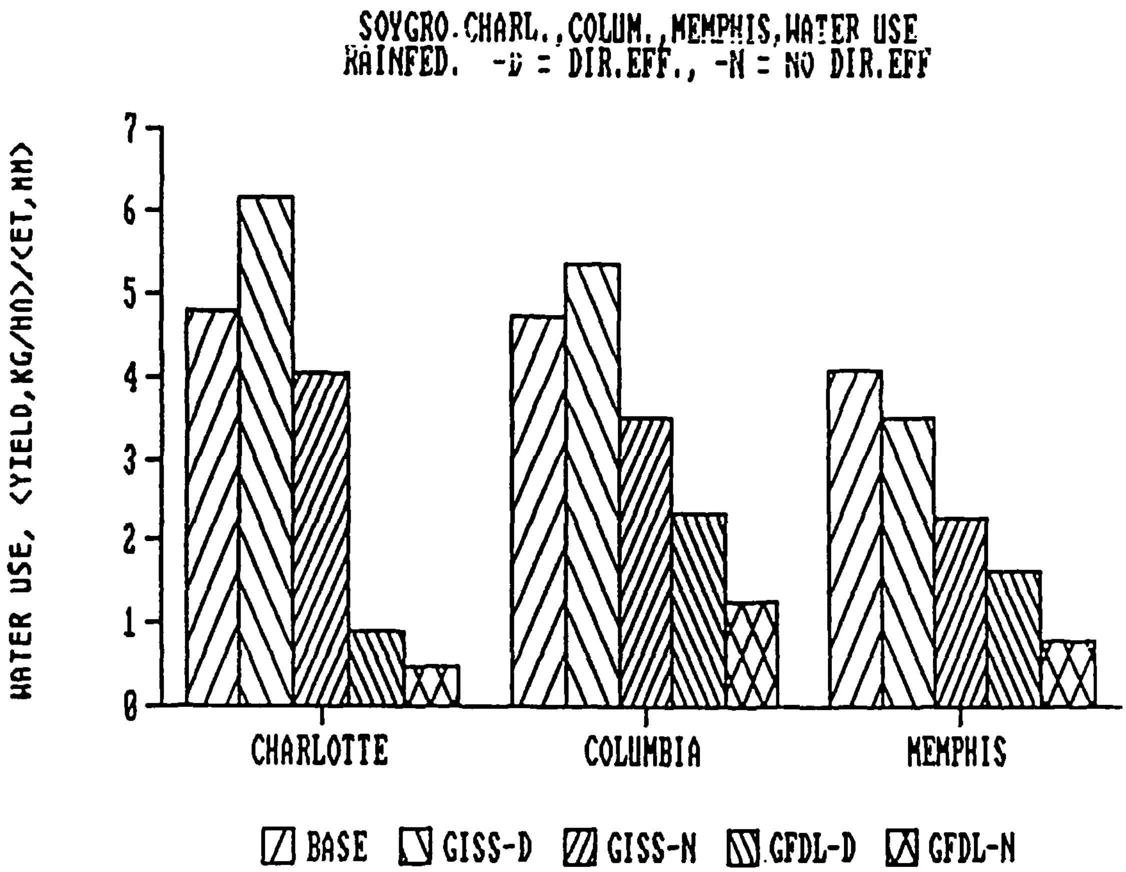

Figure 17. Water used for soybeans for the same three locations and data used in Figure 16.

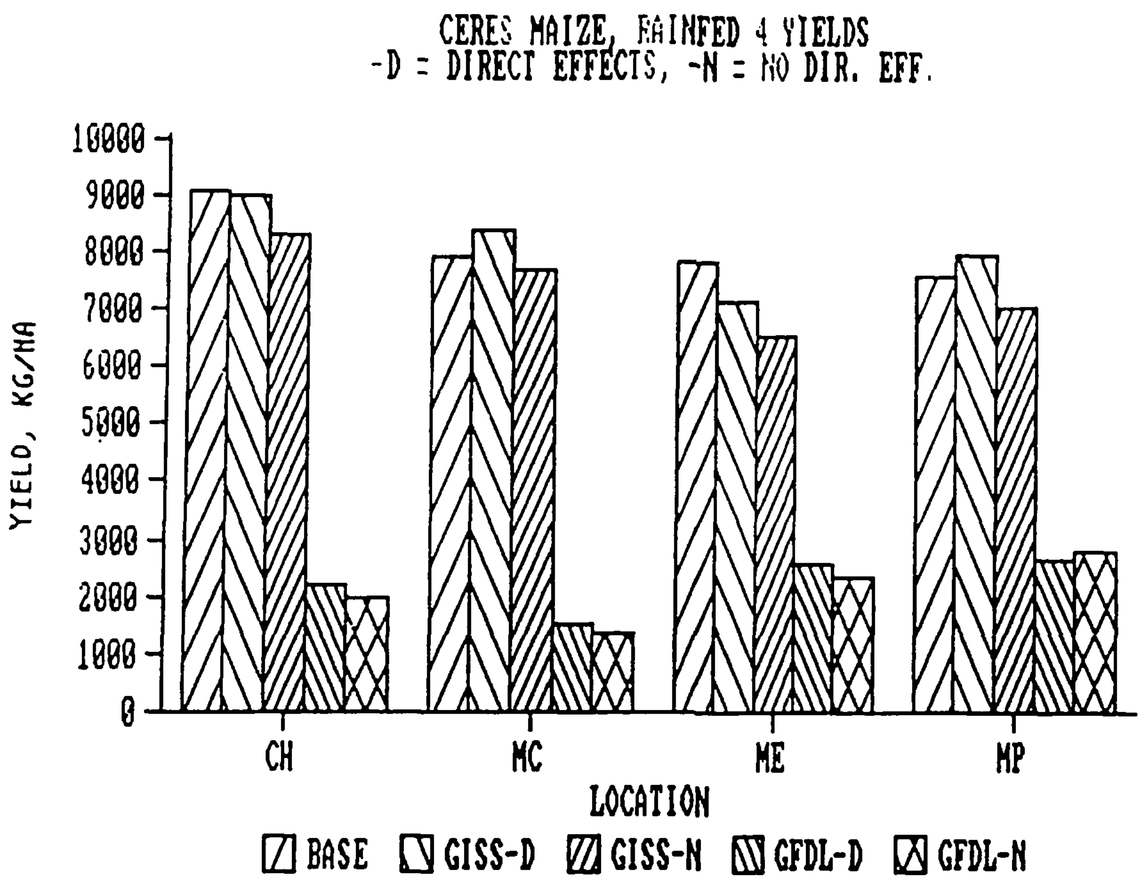

Figure 18. Rainfed yields for maize for CH-Charlotte, NC; MC-Macon, GA; ME-Meridan, MS; and MP-Memphis, TN.

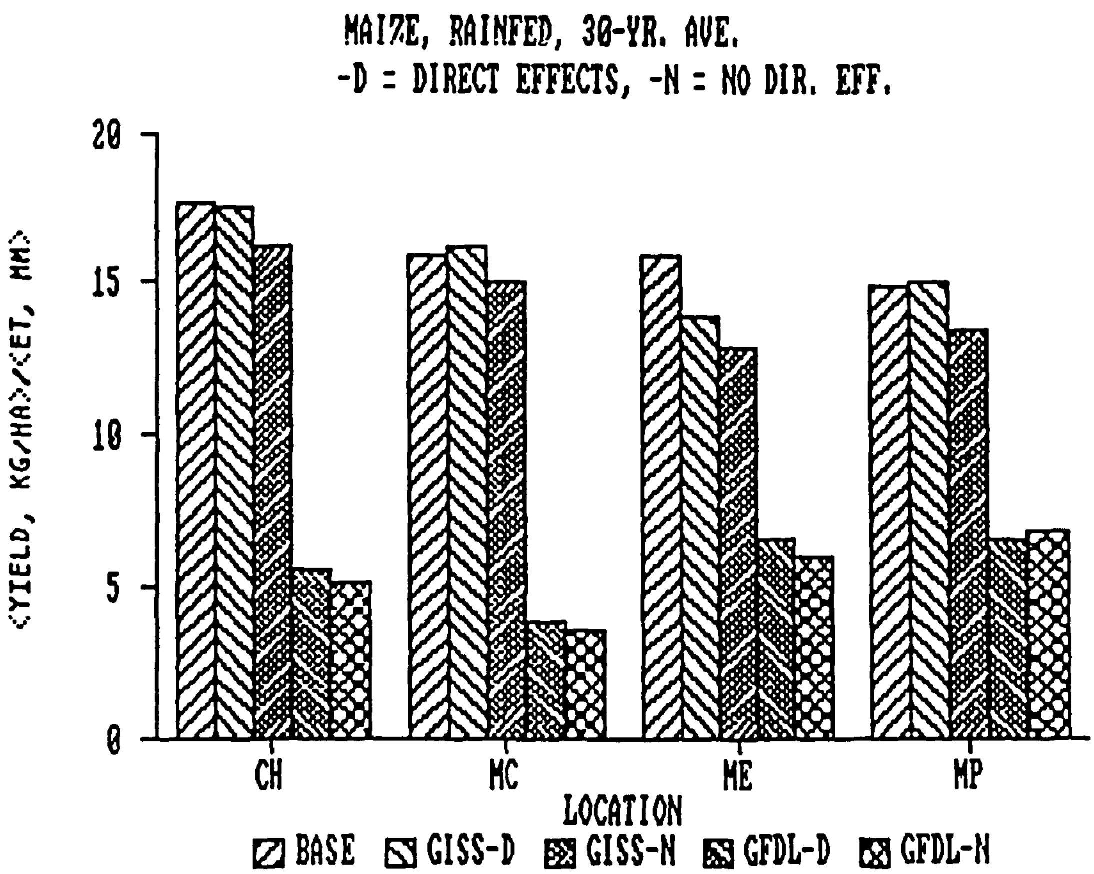

Figure 19. Water efficiency for maize.

CHAPTER 4

IMPLICATIONS OF RESULTS

ENVIRONMENTAL IMPLICATIONS

Two important environmental implications are noticeable with only a cursory look at results. The first is the greatly increased demand for irrigation likely to be caused by these changes over time. This demand has implications both for water resource availability and water quality. The second is the likely increase in soil erosion caused by the increased rainfall during some periods.

Even in the most drastic case shown by the GFDL weather data, the crop failure results with rainfed soybeans can be converted to increased yields with the addition of irrigation. With these changes occurring slowly over many years, farmers are likely to slowly increase irrigation, as, indeed, they are currently doing in the Southeast, as insurance against the crop failures. Gradually, the irrigation water demand for previously installed systems would increase, and concurrently, more systems would be installed.

SOCIOECONOMIC IMPLICATIONS

The changes shown in this report would have very drastic and important socioeconomic implications. Soybeans could be dropped as an economic crop over wide areas of the Southeast, including at least the southern part of the important Mississippi delta area. Corn would be affected less, but it is less important in the region than is the soybean. These suggested implications are based on the assumption of current prices and costs and assume no shifting of cultivars or changes in other management practices. Further research is required to evaluate the effects of changes in management as climate changes occur.

Other socioeconomic implications include (1) competition for water resources between the potential increased agricultural use and nonagricultural demands, (2) increased fertilizer use could increase if other high-value, nonlegume crops replaced soybeans, (3) effect of changing growing seasons on the supply of inputs such as fertilizers, labor, etc. Many of these implications will become defined clearly based on the work of Dr. Rich Adams, Washington State University, in a companion project.

POLICY IMPLICATIONS

For agricultural production program policies, implications depend on effects on other important crops of the region, notably cotton and peanuts. A combination of increased soybean irrigation by some farmers and reduced acreage by others might maintain overall total production while seriously reducing income of those forced by the weather to drop soybean production. If peanut yield were adversely affected, the production control and price support program might be unnecessary. Similarly, cotton might also be a candidate for deregulation if the new weather caused cotton yield reductions.

Irrigation water demand seems very likely to increase substantially over time, and state and regional water policies will need modification.

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POTENTIAL EFFECTS OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTION IN THE GREAT PLAINS A SIMULATION STUDY

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CONTENTS

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FINDINGS[1]

This study is a first step in linking models of climate change to models of crop growth. The results should be regarded as indications of the sensitivity of wheat and corn production in the central and southern Great Plains to projected climatic changes, rather than as predictions. The uncertainties in the study lie primarily in the following areas:

The global climate models were not designed for regional studies and their results are often on too large a spatial scale to project effects on crop production realistically. The crop models, while among the best now available for large-area studies, are semi-empirical, and may not provide accurate estimates for the extreme climatic conditions implied in the scenarios. The physiological (or "direct") effects of CO_2 on crop growth and water use are only approximated in the crop models. Accurate prediction of these effects awaits further, specially designed experiments and continuing model development. The range of possible alternative cropping strategies was not fully explored, such as substitution of different crop species and double-cropping.

The following specific results are found in the modeling study:

1. Projected climate changes cause simulated wheat and corn yields to decrease in the southern and central Great Plains. Decreases in modeled grain yields are caused primarily by increases in temperature which shorten the duration of crop life cycle, thus curtailing the production of harvestable biomass.

2. When the direct effects of increased concentrations of CO_2 on crop growth and water use are combined with the effects of climate change in simulations, an enhancement of modeled crop yields compensated for the negative effects of climate change in some cases, but not in others. The more severe the climate change scenario, the less compensation the physiological effects of CO_2 provide, especially in dryland simulations.

3. In climate change simulations, the amount of water needed for automatic irrigation increases in areas where precipitation decreases and irrigated yields are higher and less variable year-to-year compared to dryland yields. These results suggest a potential for increased demand for irrigation in the region.

4. Adjusting the planting dates of wheat and corn does not significantly ameliorate the effects of one climate change scenario on modeled yields. Changing wheat cultivars to ones with lower vernalization requirements, lower photoperiod sensitivity, and longer grain-filling periods, in addition to delaying planting dates, overcomes yield decreases at some sites, but not at others.

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CHAPTER I

INTRODUCTION

The objective of this study is to characterize the direction, magnitude, and uncertainty of potential climate change-induced alterations in wheat and corn yield in the central and southern Great Plains region. The climate change is that predicted to arise as a result of increasing carbon dioxide (CO_2) and other radiatively active trace gases in the earth's atmosphere. Climate change simulation experiments are designed for both dryland and irrigated conditions in order to estimate relative changes in crop yield, evapotranspiration, water applied for irrigation, and duration of crop growth. Potential production management adjustments to climate change, such as farmer responses to changes in length of growing season and climate regime, are included in some model runs as shifts in planting date and substitution of more climatically appropriate cultivars.

The effects of increasing atmospheric CO_2 on photosynthesis and transpiration are also approximated in some model runs, based on results from published reports of controlled environment experiments. The simulations involving climate change effects alone provide an "extreme case" scenario, while the simulations with combined climatic and physiological effects of CO_2 represent a more moderate impact.

Description of the Agricultural System

There are nearly 100,000 farms in Nebraska, Kansas, Oklahoma and Texas, occupying over 111 million acres. Farmers in these states grow a third of the nation's wheat and a seventh of the nation's corn, primarily on deep prairie soils. The importance of this abundant grain crop production to both the U.S. and international grain supply justifies an analysis of the potential effects of climate change on agriculture in these states.

National attention has also recently focused on the water resources in the region, especially on overuse of the Ogallala Aquifer (High Plains Associates, 1982). An evaluation of how changes in demand for water for irrigation could exacerbate or alleviate water scarcity in the areas fed by this and other aquifers will be useful to federal, state, and local decision-makers responsible for acceptable water supply and quality.

Although irrigation is important in certain areas, agriculture in the Great Plains region is primarily dryland farming, i.e., without irrigation. This causes agriculture to be vulnerable to climatic stresses, particularly to recurring drought episodes, such as the severe droughts of the 1930s (Worster, 1979; Hurt, 1981). In the Dust Bowl period, crop failure and economic depression led to farm abandonment and to migration away from the region.

If global climate change brings increased frequency of high temperature extremes and droughts in the Great Plains, regional agriculture could again be negatively affected. Farm acreage and field size have both expanded recently in the region. Despite the adoption of conservation tillage techniques, drought-resistant cultivars, and risk management programs, some analysts argue that the region remains particularly vulnerable to climate-induced reductions in crop yields and may be one of the first U.S. agricultural regions to exhibit impacts of climate change (Warrick, 1984). Some global climate models project pronounced reductions in soil moisture in mid-continental areas in summer, a prediction which implies potentially severe impacts on dryland farming and increased demand for irrigation in the Great Plains.

Literature Review

There have been several systematic modeling studies of climate change impacts on agriculture in the Great Plains. Warrick (1984), in a historical approach, analyzed the vulnerability of the region to a possible recurrence of the 1930s drought by running a dryland crop yield statistical model tuned to 1975 technology with 1934 and 1936 temperature and precipitation conditions. He found the recurrence of 1930s conditions in the region would result in wheat yield reductions of over 50%. Others have used an agroclimatic zone approach (Rosenzweig,

1985) or a basic parametric crop yield model (Terjung et al., 1984; Liverman et al., 1986) to study potential changes in crop location, yield, evapotranspiration, and irrigation requirements with climate change estimates alone.

Terjung et al. (1984) used a crop water demand and yield model to investigate irrigated corn production sensitivity to differing temperature, precipitation, and solar radiation fluctuations. They found that in the central Great Plains, evapotranspiration and total water applied for irrigation were very sensitive to climate variations. Liverman et al. (1986) continued this modeling and found that the lowest irrigated yields occurred under cloudy, hot, and very dry climate scenarios. Under dryland cropping, minimum yields occurred under sunny-hot and sunny-warm scenarios with very dry conditions.

Using an agroclimatic approach, Rosenzweig (1985) found that lack of cold winter temperatures in the southern Great Plains may necessitate a change from winter to spring wheat cultivars with climate change projected for a doubling of CO_2. Changes in temperature, precipitation, and solar radiation were considered. The study found that decreased water availability may also increase demand for irrigation.

Few studies simultaneously consider both the climatic and physiological effects of increased CO_2. Experiments in field chambers and controlled environments have shown that increased atmospheric CO_2 concentration increases photosynthesis and yield and improves water-use efficiency (Kimball, 1983; Acock and Allen, 1985; Cure, 1985). Kimball (1983) estimated an increase in crop yields due to a doubling of carbon dioxide of about 33% +/- 6%. However, the relative effects of climate changes, particularly the increased temperatures predicted by global climate models (GCMs), and physiological changes on crop production in the field are still very much in question.

Robertson et al. (1987) estimated the impact of climate change on yields and erosion using the Erosion Productivity Impact Calculator (EPIC) in Bell County, Texas, with increased energy/biomass conversion efficiencies to estimate the effects of doubling current levels of carbon dioxide on plant growth and yields. Results showed that modeled wheat yields in Texas decreased and modeled corn yields increased only marginally owing to moisture stress.

The CERES-Wheat model has been used to estimate yield changes with combined CO_2 and climate effects for the southern Great Plains (Rosenzweig, 1987). In this study, the direct effects of elevated CO_2 (increased photosynthesis and improved water use) compensated for the negative effects of climate change (temperature, precipitation, and solar radiation changes) in years with adequate rainfall, but did not reduce crop failures in dry years. The CERES-Maize model has been used to project an increase in corn production in Illinois with the physiological effects of CO_2, but not the climate effects (Decker and Achutuni, 1987).

Potential effects of predicted climate change (Williams et al., 1988) and combined climatic and physiological CO_2 effects (Stewart, 1986) on spring wheat production in Saskatchewan, Canada, have been estimated. The results of the Williams et al. (1988) study, which used both historic and climate change scenarios, agroclimatic indices, and a crop growth model, suggest that a shift to a warmer long-term climate, even if precipitation increases, would reduce spring wheat yields, decrease wind erosion potential, enhance average potential biomass productivity, and increase frequency and severity of droughts. Stewart (1986), with similar methodology, found that spring wheat production in Saskatchewan would fall with climate change scenarios, both with and without the direct effects of CO_2, and that any decrease in precipitation from current levels would significantly reduce yields and production.

Organization of This Report

The remainder of this report consists of three sections. The next section describes the methods and limitations of the analysis. The following section describes and interprets the results of the set of crop modeling experiments with two GCM-derived scenarios of climate change induced by a doubling of CO_2 concentration. The environmental and socioeconomic implications of these results are set forth in the final section, along with some policy considerations and suggestions for future research. Tabulated site and soil characteristics, statistical methods, and model results are included as appendices.

CHAPTER 2

METHODS

Crop Models

Potential changes in crop production in the Great Plains were modeled with CERES-Wheat (Ritchie and Otter, 1985) and CERES-Maize* (Jones and Kiniry, 1986). The CERES models were chosen because they simulate crop responses to the major factors which affect crop yields, i.e., climate, soils, and management, and because they have been widely validated. Management practices which may be varied in the models include cultivar, planting date, plant population, row spacing, and sowing depth. The presence of these variables permits experiments that simulate management adjustments by farmers to climate change.

The CERES models were developed with experimental data from many locations over a period of time. They have been validated over a wide range of environments (Otter-Nacke et al., 1986) and are not specific to any particular location or soil type. Thus they are suitable for use in a study in which the baseline (present-day) climate ranges from semi-tropical conditions in southern Texas to mid-continental conditions in Nebraska. The validation of the CERES crop models over different environments also serves to enhance predictive capability for the climate change scenarios.

The CERES models were designed to predict the growth and yields of wheat and corn varieties in different types of environments where the crops are generally grown. The models employ simplified functions to predict crop growth and yield as influenced by plant genetics, weather (daily solar radiation, maximum and minimum temperatures, and precipitation), soil, and management factors. Modeled processes include phenological development, i.e., duration of growth stages, growth of vegetative and reproductive plant parts, extension growth of leaves and stems, senescence (aging) of leaves, biomass production and partitioning among plant parts, and root system dynamics. The CERES models also simulate the effects of soil-water deficit and nitrogen deficiency on photosynthesis and pathways of carbohydrate movement in the plant. The nitrogen portions of the models were not used in this study; thus nitrogen fertilizer is assumed to be nonlimiting.

Input variables are the daily solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperatures (°C), and precipitation (mm day^{-1}). The user specifies the beginning day of the simulation, plant population (plants m^{-2}), row spacing (m), depth of sowing (cm), and irrigation regime. Also needed are the latitude of the production area, soil characteristics and initial conditions of the soil profile, and genetic coefficients of the crop variety.

The soil characteristics are soil albedo, upper limit of Stage 1 soil evaporation (mm), soil-water drainage constant, and the USDA Soil Conservation Service curve number, which is used to calculate runoff. For each soil layer, parameters describe the lower limit of plant-extractable soil water (volume fraction), the drained upper limit water content (volume fraction), the saturated water content (volume fraction), a weighting factor for new root growth distribution, the bulk density, and the initial soil water content (volume fraction).

The genetic coefficients for CERES-Wheat relate to photoperiod sensitivity, duration of grain filling, conversion of biomass to grain number and grain filling, vernalization, stem size, tillering habit, and cold hardiness. For CERES-Maize, the genetic coefficients are the thermal time required from emergence to end of juvenile stage, rate of photo-induction (degree-days per hour), thermal time required for grain filling, potential kernel number, and maximum daily rate of kernel fill (mg per kernel).

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*CERES-Maize simulates the growth and development of Zea mays L., known in the United States as corn.

Modifications of the CERES Models for CO_2 Enrichment

A method was developed to give an approximation of the changes in photosynthesis and evapotranspiration caused by a doubling of CO_2 from 330 to 660 ppm (Peart et al., 1988). The approach was to compute ratios of daily photosynthesis and evapotranspiration rates for a canopy exposed to elevated CO_2 to those rates of the same canopy exposed to ambient CO_2 conditions. These ratios were then applied to the model-calculated rates of photosynthesis and evapotranspiration for current CO_2 concentrations.

Photosynthesis. Experimental results were reviewed to obtain estimates of increases in canopy photosynthesis for both corn and wheat. Plants with a C3 carbon fixation pathway are more responsive to increases in atmospheric CO_2 than plants with C4 pathways (Acock and Allen, 1985). Peart et al. (1988) conducted an evaluation of corn (C4) canopy photosynthesis and selected a value of 15% for the increase in instantaneous rate. This value was reduced by 33% to 10% for the daily integrated increase in canopy photosynthesis, accounting for lower light intensities in the morning and evening. This value is consistent with values of plant light-use efficiency at normal and high CO_2 concentrations given by Charles-Edwards (1982). Wheat has a C3 carbon fixation pathway and appears to lie between soybean (35% as used by Peart et al., 1988) and corn in its photosynthetic response to increases in atmospheric CO_2 (Cure, 1985).
Therefore, a value of 25% was chosen for increase in daily canopy photosynthesis for wheat under doubled CO_2 conditions.

In the crop models, the photosynthesis rates for current CO_2 concentrations for wheat and corn were thus multiplied by factors of 1.25 and 1.10, respectively, to simulate conditions in the doubled CO_2 environment. It is assumed that the relative increase in photosynthesis was independent of other factors, so that no interactions with water stress, temperature, and leaf area were included, other than those already in the models. Changes in respiration were not taken into account.

Evapotranspiration. Increased CO_2 concentration increases leaf stomatal resistance, resulting in lowered transpiration rates per unit leaf area (Acock and Allen, 1985). However, this decrease in water use is offset by the photosynthetically enhanced production of greater leaf area; thus the total canopy transpiration rate under elevated CO_2 is higher than is accounted for by increased stomatal resistance alone.

In the CERES models, potential plant transpiration was changed under elevated CO_2 conditions due to increased stomatal closure and changes in the partitioning of energy captured by the canopy with increased leaf area index (LAI). The Penman-Monteith equation was used to develop a ratio of transpiration under elevated CO_2 conditions to that under ambient conditions (Peart et al., 1988):

$$\lambda E = \frac{s\, R_n + c_p\, \rho\, (p_s(T_a) - p_a)\, g_a}{s + \gamma(1 + g_a/g_c)} \qquad (1)$$

where λE is evapotranspiration rate in energy units, s is the slope of the saturated vapor pressure-temperature curve, γ is the psychometric constant, R_n is net radiation, c_p is specific heat of the air at constant pressure, ρ is the density of air, $(p_s(T_a) - p_a)$ is the vapor pressure deficit of the air, g_a is the boundary layer conductance between the canopy and the bulk air, and g_c is the canopy conductance to water vapor.

To derive this method, Peart et al. applied the Penman-Monteith equation to the same canopy and environment, except for differing CO_2 concentrations. The only variable which changes in the two cases is the canopy conductance to vapor transport. Therefore, a ratio of evapotranspiration rates under elevated and ambient CO_2 concentrations is obtained:

$$\text{RATIO} = \frac{\lambda E^c}{\lambda E} = \frac{s + \gamma\,(1+g_a/g_c)}{s + \gamma\,(1+g_a/g_c^c)} \tag{2}$$

where g_c^c is the canopy conductance to water vapor under elevated CO_2 conditions.

The canopy resistance is computed by

$$R_c = (r_L + r_b)/LAI \tag{3}$$

where r_L is the leaf stomatal resistance (s m^{-1}), LAI is the leaf area index, and r_b is the leaf boundary layer resistance.

Then, the canopy conductances for ambient and elevated CO_2 (g_c and g_c) are computed by:

$$g_c = 1/R_c$$
$$g_c = 1/R_c \tag{4}$$

To calculate the evapotranspiration ratio in CERES-Wheat, stomatal resistance values for well-watered (0.48 and 0.63 s cm^{-1}) and drought-stressed (0.78 and 0.75 s cm^{-1}) winter wheat under 330 and 660 ppm from Chaudhuri et al. (1986) were used for irrigated and dryland runs, respectively. These experimental results show that elevated CO_2 increased stomatal resistance of well-watered wheat plants, while a slight decrease in stomatal resistance was observed under drought conditions. For corn, leaf resistance was computed as a function of CO_2 concentration using the equation developed by Rogers et al. (1983).

Temperature, windspeed, LAI and CO_2 concentration are needed to calculate RATIO. Average daily temperature is computed from maximum and minimum temperatures which are inputs to the CERES models; windspeed is set at 2.0 m s^{-1}. LAI is specified directly as calculated in models. The ratio procedure results in a lower transpiration rate for higher CO_2 levels on a daily basis, but may or may not change seasonal evapotranspiration by the same proportion because of the increased LAI in increased CO_2 conditions. Differences in canopy temperature, canopy height, and leaf vapor pressure with increased CO_2 are not taken into account.

Limitations Resulting from the Crop Models

The CERES models contain many simple, empirically derived relationships. For example, the use of a thermal time scale, (i.e., growing degree days) may not accurately represent the behavior of different crop cultivars in different environments, and the absence of vapor pressure deficit in the evaporation equations means that important advection effects are not considered. The photosynthesis equations do not explicitly include maintenance respiration, which responds quite differently to temperature than photosynthesis. Some of the assumptions of the modeling study are listed in Table 1.

Also, the relationships in the models may or may not hold under differing climatic conditions. Most of the data used to derive the relationships in the crop models were obtained with temperatures below 35°C, whereas the projected temperatures for doubled CO_2 are often above 35 or even 40°C during the growing period. While the models do simulate temperature effects on photosynthesis, leaf extension, vernalization, and winterkill, they do not include a temperature effect on pollination and its viability. Technology and climatic tolerances of crop cultivars are held constant, even though both are likely to adapt to changing climate.

Table 1. Assumptions and Limitations of Crop Models

1. Thermal time scale for phenological stages.
2. Absence of vapor pressure deficit in evaporation.
3. Lack of maintenance respiration in carbohydrate production.
4. Behavior of crops in high temperature not well defined.
5. Lack of temperature effect on pollination and pollen viability.
6. Beneficial physiological effects of CO_2 may be overestimated.
7. Higher leaf temperatures due to increased CO_2 not modeled.
8. Interactions of increased CO_2 with high-temperature and water stress not simulated.
9. Yields not limited by pests and lack of nutrients.
10. Technology and climatic tolerances of cultivars held constant.

The modifications of the models for the direct effects of CO_2 engender uncertainties as well. In particular, they do not consider the interactions of increased CO_2 with higher temperatures or water stress, which could result in either higher or lower photosynthesis rates (Rose, 1988). Nor were changes in plant temperature due to stomatal closure under high CO_2 explicitly modeled. The Penman-Monteith model is not appropriate for incomplete canopies.

Some other assumptions of the modeling study are that all nutrients are nonlimiting; weeds, diseases, and insect pests are controlled; there are no problem soil conditions such as high salinity, acidity, or heavy compaction; and there are no catastrophic weather events such as hail, tornadoes, floods, high winds, or heavy storms. All these assumptions tend to bias simulated yields upwards. The CERES models do not simulate windspeed, thereby ignoring changes in evapotranspiration driven by changes in windspeed. Technology and climatic tolerances of crop cultivars are held constant, even though both are likely to adapt to changing climate.

The direct effects of CO_2 in the crop modeling study may be overestimated for two reasons. First, experimental results from controlled environments, used to derive the crop model simulation of increasing CO_2 effects, may not replicate variable, windy, and pest-infested (e.g., weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases besides CO_2, such as methane (CH_4), are also increasing, the equivalent warming of a doubled CO_2 climate will occur before actual doubling of atmospheric CO_2. A level of 660 ppm CO_2 concentration was assumed for the crop modeling experiments, while the CO_2 concentration in 2060, when the equivalent warming of doubled CO_2 occurs in the GISS GCM transient run, is estimated to be 555 ppm (Hansen et al., 1988).

Climate Change Scenarios

CERES-Wheat and CERES-Maize were run at 14 locations in Nebraska, Kansas, Oklahoma, and Texas with baseline observed climate (1951-1980) and climate change scenarios developed on the basis of estimates from the global climate models of the Goddard Institute for Space Studies (GISS) and Geophysical Fluid Dynamics Laboratory (GFDL). Availability of daily climate data from 1951 to 1980 and geographical distribution determined choice of locations. The climate models produce climate change results in distinct latitude by longitude grids. Climate stations and the GISS and GFDL gridboxes in the central and southern Great Plains are shown in Figure 1.

The climate change scenarios were developed from average monthly changes in temperature, precipitation, and solar radiation calculated for each GCM gridbox for current and doubled CO_2 conditions (Smith and Tirpak, 1988). Observed daily climate variables were multiplied by monthly ratios of climate variables from the GCM doubled CO_2 runs over the variables simulated for current conditions from the appropriate gridbox. No interpolations were made between gridboxes. Seasonally and annually averaged temperature and precipitation changes from the climate change scenarios are shown in Table 2 and Figure 2 for the study area.

The magnitudes of climate changes from the GFDL scenario and the climate of the 1930s drought in Nebraska and Kansas are compared in Figure 3. While the climate change scenario decreases in precipitation are about the same as those during the most severe drought years (1934 and 1936) in the area, the climate change scenario temperatures are about 3°C higher than the Dust Bowl temperatures.

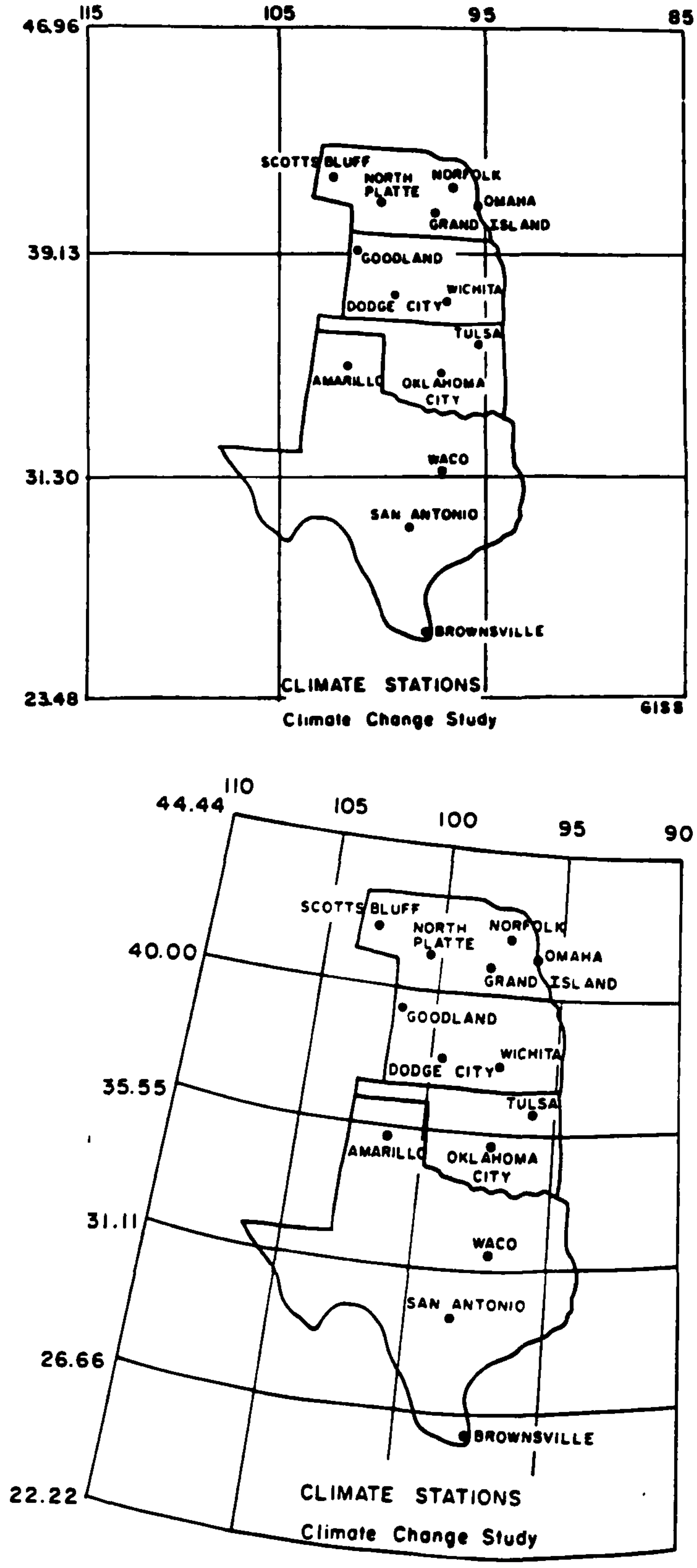

Figure 1. Climate stations and GCM gridboxes used in crop modeling study; a) GISS GCM, b) GFDL GCM.

Table 2. Temperature (°C) and Precipitation (mm/month) Changes* in the Great Plains, GISS and GFDL Climate Change Scenarios

GISS

Latitude	39.13-46.96°N		31.30-39.13°N		23.48-31.30°N	
	Temp	Precip	Temp	Precip	Temp	Precip
D,J,F	5.8	5.1	4.9	-5.4	4.7	-16.5
M,A,M	4.8	20.7	4.3	-18.9	3.7	9.0
J,J,A	3.8	0.6	4.1	-6.6	4.5	-10.2
S,O,N	5.2	-6.0	5.0	0.0	4.1	-12.0
Annual	14.9	5.1	4.6	-7.7	4.3	-7.4

GFDL

Latitude	40.00-44.44°N		35.55-40.00°N		31.11-35.55°N		26.66-31.11°N	
	Temp	Precip	Temp	Precip	Temp	Precip	Temp	Precip
D,J,F	5.0	4.2	5.1	3.9	4.8	3.6	4.2	-7.4
M,A,M	4.8	7.7	5.2	9.0	5.1	-7.8	4.5	-7.9
J,J,A	7.7	-28.2	5.9	-30.1	3.4	11.8	3.2	66.4
S,O,N	5.5	1.9	4.8	3.6	4.6	-9.7	4.6	3.2
Annual	5.8	-3.6	5.3	-3.4	4.5	-0.5	4.1	13.6

*Values from study sites are averaged latitudinally.

a)

b)

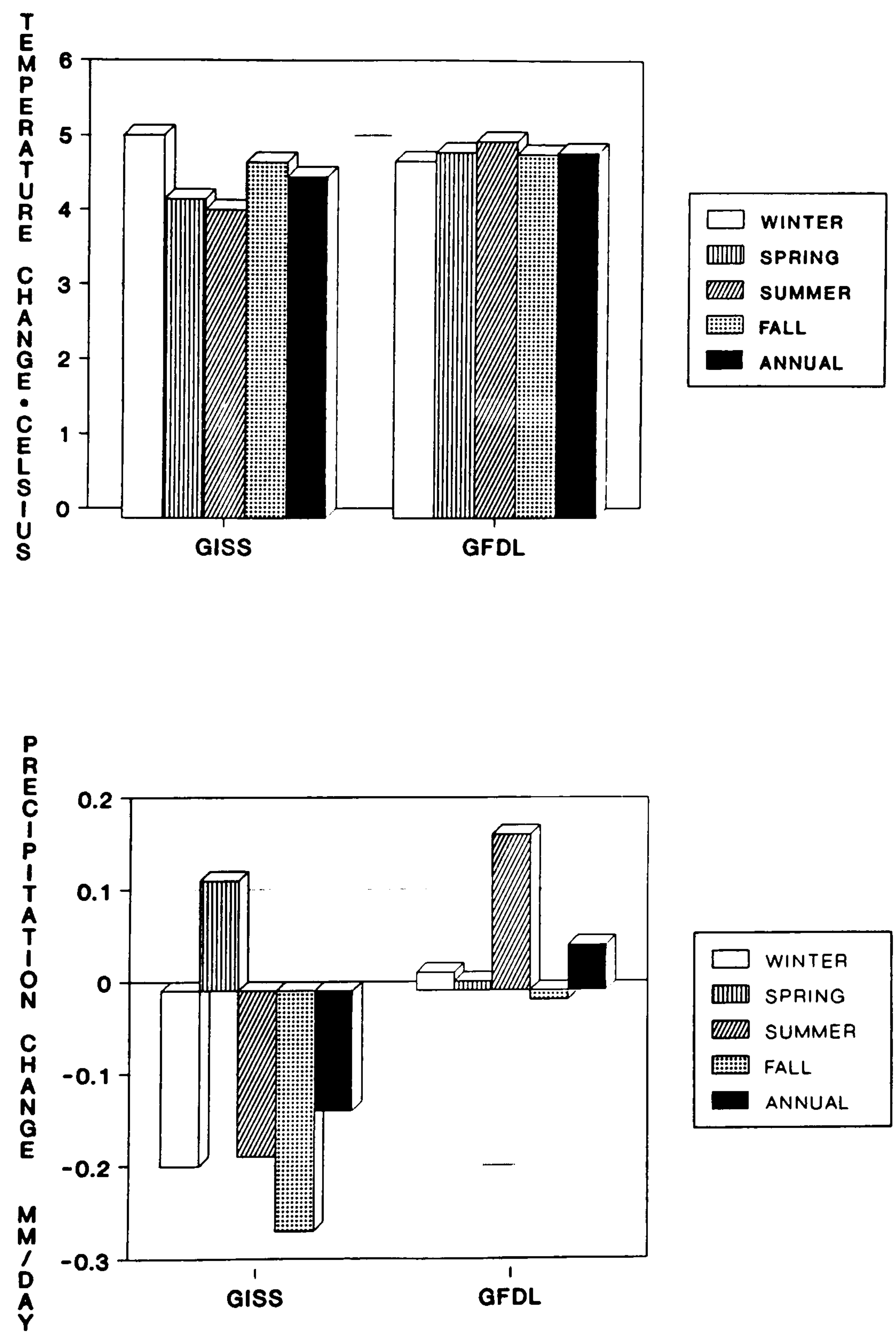

Figure 2. Average change in (a) temperature and (b) precipitation over Great Plains study sites for GISS and GFDL climate change scenarios.

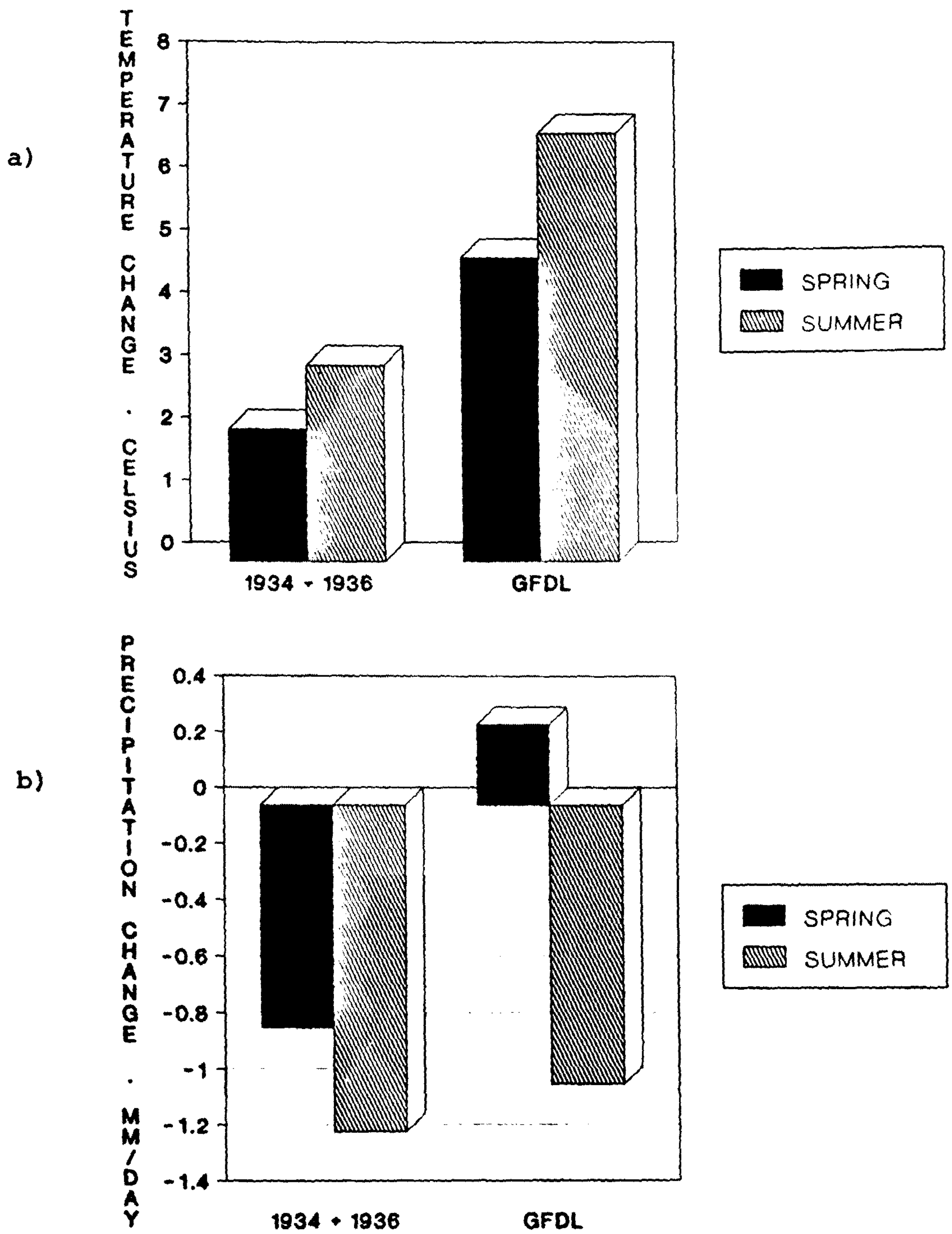

Figure 3. Comparisons of observed climate (mean of 1934 and 1936) and GFDL climate change scenario at study sites in Nebraska and Kansas; (a) temperature, and (b) precipitation.

The use of observed climate as a baseline is advantageous because it can be related directly to observed crop yields in the recent past. Changes occurring under scenario conditions can be assessed relative to both actual climate and to simulated, yet validated yields. This make the study results more relevant to current agricultural production.

Limitations Resulting from the Climate Scenarios

Current climate models oversimplify certain aspects of the climate system, such as ocean, cloud, and land-surface processes. In particular, precipitation and the hydrological cycle are often poorly simulated by GCMs. The GCMs were not specifically designed for regional studies, and regional representation of current climate is often inaccurate. Thus, the use of GCM-generated scenarios for the regional case studies for the U.S. EPA Report to Congress must be approached with caution. In addition, since atmospheric trace gases are increasing gradually without a predicted artificial plateau at 600 ppm CO_2, the $2xCO_2$ climate change scenario represents an unrealistic step change to a different climate equilibrium that will probably never be realized.

This work uses predicted changes in mean climate variables from the GCMs and does not consider alterations in interannual climate variability. For example, the number of days of precipitation remains the same in the baseline and climate change scenarios, while the amount of precipitation on each of those days is adjusted by the GCM ratio. The frequency of extremes such as maximum temperatures changes in the climate change scenarios, but the patterns of the extreme episodes are determined by the observed climate. The lack of changes in the patterns of extreme events is particularly important, because runs of climate extremes (e.g., prolonged hot spells during grain filling and drought) can decrease crop productivity (Mearns et al., 1984). For dryland crops, yields may change considerably depending on whether a change in precipitation is caused by more or fewer events or by higher or lower precipitation per event.

Climate Data

Observed daily maximum and minimum temperatures and daily total precipitation from the National Climate Data Center, Asheville, NC, were provided by Dr. Roy Jenne of the National Center for Atmospheric Research, with interpolation of missing data by Dr. Amos Eddy, of the Oklahoma Climatological Survey. Observed daily solar radiation, another CERES input, is lacking in consistent length of record, sites, and calibration. Therefore, daily solar radiation was simulated for each site according to the method of Richardson and Wright (1984) as modified by Hodges et al. (1985). In this method, daily solar radiation is estimated based on correlations between departures of observed daily solar radiation from long-term daily means and departures of daily maximum and minimum temperatures from long-term daily means stratified according to wet and dry days. The correlations at sites for which long-term daily means are available have been computed (Richardson and Wright (1984); these were interpolated to estimate daily solar radiation for the study sites.

Soils

The CERES models were run for three agricultural soils at each study site. The three soils were chosen from the description of the Major Land Resource Area of each location to represent low, medium, and high productive capacity (Appendix 1) (USDA, 1981). Soil characteristics for these representative soils were specified by twelve generic soil types by Drs. Joe T. Ritchie and J. W. Jones (Appendix 2).

Management Variables

For CERES-Wheat, cultivar, plant population, row spacing, sowing depth, and planting date windows (periods when planting normally occurs) were specified for each location according to information on current practices provided by local county extension agents. For CERES-Maize, cultivars were specified according to Jones and Kiniry (1986), and other variables were specified as suggested by county agents for Nebraska sites.

Simulations

CERES-Wheat and CERES-Maize were run for 30 years of baseline climate under dryland and irrigated conditions at the study sites. In the irrigated simulations, the soil moisture profile was automatically filled to the drained upper limit when the soil water in the top meter of soil was less than 80% of that amount; the efficiency of irrigation was assumed to be 100%, that is, all water applied was available for crop use. The irrigated simulations are unrealistic since few farmers fully irrigate wheat, but they were done in order to study relative changes in applied irrigation water and the stability of yields under irrigated conditions.

Reported and modeled baseline yields for wheat and corn are shown in Tables 3 and 4. County wheat yields reported from 1985 are generally lower than yields simulated at the study sites; modeled dryland corn yields are both above and below reported yields, depending on location. Modeled irrigated yields of both corn and wheat are consistently higher than observed yields because of the automatic filling of the model soil water profile.

The crop models were run again with the GISS and GFDL climate change scenarios; percent change and standard deviations of percent change (see Appendix 3) were calculated for differences in crop yields, evapotranspiration, and water applied for automatic irrigation. Changes in maturity date were also computed. Another set of simulations was executed with the crop models modified for the direct effects of CO_2, using the GISS and GFDL scenarios at all study sites.

Adjustment experiments were carried out with the CERES models and the GISS climate change scenario. These simulation experiments show how farmers might adjust management variables to mitigate the negative effects or to take advantage of possible beneficial effects of the projected climate changes. In one adjustment experiment, planting date was shifted by the average number of days that the first frost in the fall changed (this was later at all locations in the GISS climate change scenario). Infestations of the Hessian fly (Phytophaga destructor), which damages wheat sown too early in the fall in some parts of the Great Plains, were not considered. In another adjustment experiment, planting dates of CERES-Maize were advanced between 20 and 30 days, according to earlier last spring frosts in the GISS climate change scenario.

Another adjustment farmers may make to climate change is to plant cultivars adapted to the new climate regime. To test the effect of such an adjustment on modeled crop yields, new cultivars chosen on the basis of vernalization requirement and photoperiod sensitivity were used in CERES-Wheat. Since winter wheat cultivars with high vernalization requirements need cold temperatures to induce reproductive growth (Evans et al., 1975), warmer temperatures in the winter in the GISS climate change scenario allow shifts to cultivars with intermediate or no vernalization requirements (i.e., spring-type wheat cultivars). Wheat cultivars also vary in photoperiod sensitivity, i.e., need for long hours of daylight to flower (Evans et al., 1975). The warmer temperatures of the GISS $2xCO_2$ climate change scenario hasten green-up in the spring during a period with short days. Thus, cultivars with less photoperiod sensitivity are required.

Simulations were done using a new cultivar with either an intermediate vernalization requirement or no vernalization requirement at all, in addition to the changed planting date. Cultivars were also selected with low sensitivity to photoperiod in order to avoid negative photoperiod effects caused by delayed flowering during short days.

Table 3. Observed and Modeled Baseline Wheat Yields

State	County	Dryland*	CERES** Dryland	SD	Irrig.*	CERES** Irrig.	SD
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Nebraska							
	Douglas	2 898	4 325	717	2 965	5 000	470
	Hall	2 359	3 593	732	3 100	5 035	369
	Lincoln	1 820	2 465	811	3 774	4 982	649
	Madison	2 426	3 300	682	2 763	4 828	395
	Scotts Bluff	2 763	1 634	618	3 774	5 282	370
Kansas							
	Ford	1 530	1 794	792	3 188	5 926	427
	Sherman	3 417	1 381	649	3 868	6 043	370
	Sedgwick	1 961	3 885	1 039	2 648	5 704	434
Oklahoma							
	Oklahoma	1 833	3 553	865	3 659	4 767	366
	Tulsa	1 611	6 273	705	- ***	6 579	551
Texas							
	Potter	1 483	1 186	657	3 727	6 431	405
	Cameron	0	2 379	423	0	2 583	355

*Observed 1985.
**Mean of modeled yields on 3 representative generic soils, 1951-1980.
***Not available

Sources: 67th Annual Report and Farm Facts, Kansas State Board of Agriculture; 1986 Nebraska Agricultural Statistics, Nebraska Dept. of Agriculture; Oklahoma Agricultural Statistics 1985, Oklahoma Agricultural Statistics Service; 1985 Texas Field Crop Statistics, Texas Dept. of Agriculture.

Table 4. Observed and Modeled Baseline Maize Yields

State	County	Dryland*	CERES** Dryland	SD	Irrig.	CERES** Irrig.	SD
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Nebraska							
	Hall	7 607	5 573	1 621	8 676	9 730	664
	Madison	5 030	7 064	2 248	8 928	11 802	682
	Lincoln	3 898	3 194	1 691	8 613	9 281	1 080
	Douglas	6 790	8 643	1 121	8 865	9 572	652
	Scotts Bluff	2 200	1 194	1 206	7 859	11 289	1 468
Kansas							
	Ford	9 915	2 635	1 583	0	11 178	753
	Sherman	3 646	1 588	1 434	8 443	10 238	634
	Sedgwick	3 772	6 891	2 138	9 242	10 515	736
Oklahoma							
	Tulsa	-**	10 333	1 580	-	12 064	961
	Oklahoma	-	8 244	1 711	-	12 265	1 302
Texas							
	Bexar	4 583	4 096	1 235	5 639	6 396	550
	McLennon	4 885	8 515	2 122	0	12 412	640

*Observed 1985
**Mean of yields on 3 representative generic soils, 1951-1980
***Not available

Sources: 1985 Kansas Farm Facts, Kansas State Board of Agriculture; 1986 Nebraska Agricultural Statistics, Nebraska Dept. of Agriculture; Oklahoma Agricultural Statistics 1985, Oklahoma Agricultural Statistics Service; 1985 Texas Field Crop Statistics, Texas Dept. of Agriculture.

CHAPTER 3

RESULTS AND DISCUSSION

Climate Change Alone

Wheat. Under the GISS climate change scenario without the physiological effects of CO_2, modeled dryland wheat yields decrease in every location, with larger decreases toward lower latitudes (Table 5a). Yield decreases range from 10 to 55%; mean decrease was about 30%, assuming equal area at each site. The yield decreases are driven primarily by the increased temperatures in the climate change scenario, which cause the duration of crop growth stages, particularly grain fill, to be shortened. Shortening of the grain filling period reduces the amount of carbohydrates available for grain formation and harvestable yield. Maturity dates of wheat occur, on average, about three weeks earlier in the GISS climate change scenario (see Appendix 4).

Total dryland crop evapotranspiration (ET) also decreases at every site (Table 5a). Although the higher temperatures of the climate change scenario cause daily rate of ET to increase, total crop ET decreases due to the significant shortening of the crop growing season.

Results with the GFDL climate change scenario are similar to those with the GISS scenario. Dryland CERES wheat yields decrease everywhere, with reductions ranging from 12 to 55%; mean decrease is about 33%, again assuming equal area at each site (Table 6a). Large decreases occur at both higher and lower latitudes. Total crop also is reduced everywhere, again due to shortening of the crop growing season. Maturity dates of modeled dryland wheat advance by up to four weeks in the GFDL scenario (see Appendix 5).

In the automatic irrigation simulations with both GISS and GFDL scenarios, modeled wheat yields and crop ET generally decrease, but not as much as in the dryland cases (Tables 5b and 6b). Standard deviations of the percent changes are also lower. Dryland and irrigation yields for the entire 30 years of simulation are shown in Figure 4 for Amarillo, Texas. The high temperatures of climate change scenarios have a negative effect on crop growth, even when adequate water is Table 5.available, by shortening crop duration: maturity dates occur about three weeks earlier in the irrigated as well as the dryland simulations for both GISS and GFDL climate change scenarios (Appendices 4 and 5).

Even though total crop ET generally decreases, water applied for irrigation at most study sites either remains the same or increases with the modeled climate change (Tables 5b and 6b). This is because water applied for irrigation depends on modeled soil moisture which in turn depends on precipitation as well as evaporation. Increases in water applications range from about 10 to 50%. With the GISS climate change scenario, water applied for irrigation remains almost the same in the northern gridbox where precipitation increases, and increases at most sites in the central and southern gridboxes where precipitation decreases (see Table 2). With the GFDL scenario, significant increases in irrigation occur at half of the study sites, especially in the northern gridboxes where precipitation decreases greatly during the growing season (see Table 2).

Planting winter wheat too early in the fall can decrease yields because of excessive growth before the onset of cold weather. If global warming extends the period between last frost in the spring and first frost in the fall, farmers may adjust planting date of winter wheat accordingly. When planting date windows are delayed in dryland and irrigated CERES-Wheat simulations with the GISS $2xCO_2$ climate change scenario, yields improve over those for the original planting date under this scenario in only a few cases (Table 7). This shows that the modeled yield decreases in the climate change scenario are not caused primarily by too early fall planting.

Results of the adjustment experiment with cultivars better adapted to the changed climate show that a change in cultivar brings wheat yields back up to or improves on baseline levels at two-thirds of the dryland sites (Table 7). In the irrigated runs, yields equal to or higher than baseline yields occur at more than half of

Table 5. CERES-Wheat Percent Changes in Yield, Evapotranspiration, and Water Applied for Irrigation With GISS Climate Change Scenario; a) Dryland and b) Irrigated

a) DRYLAND CERES-WHEAT GISS $2xCO_2$ EXPERIMENT

Site	YIELD %Δ	YIELD SD %Δ	ET %Δ	ET SD %Δ
NEBRASKA				
Norfolk	-10.5	6.0	-12.7 *	2.6
Grand Island	-17.1 *	6.0	-13.2 *	2.6
Scotts Bluff	-25.9 *	9.6	-17.7 *	2.8
Omaha	-13.9 *	4.3	-11.2 *	2.3
North Platte	-27.7 *	8.4	-14.2 *	2.8
KANSAS				
Goodland	-10.5	16.1	-15.4 *	4.1
Dodge City	-38.7 *	11.7	-16.7 *	3.6
Wichita	-33.6 *	6.9	-14.3 *	3.4
OKLAHOMA				
Tulsa	-33.9 *	3.3	-5.8 *	1.6
Okla. City	-45.4 *	5.9	-11.6 *	2.4
TEXAS				
Amarillo	-55.4 *	12.3	-11.8 *	4.3
Brownsville	-45.3 *	4.1	-19.0 *	3.0

b) IRRIGATED CERES-WHEAT GISS $2xCO_2$ EXPERIMENT

Site	YIELD %Δ	YIELD SD %Δ	ET SD %Δ	ET SD %Δ	IRRIG %Δ	IRRIG SD %Δ
NEBRASKA						
Norfolk	-3.2	2.4	-9.9 *	1.2	-2.5	3.9
Grand Island	-3.7	2.0	-8.4 *	1.5	2.0	4.2
Scotts Bluff	6.1 *	1.8	-8.7 *	1.3	3.2	3.4
Omaha	-11.6 *	2.4	-10.5 *	1.3	-6.8	5.2
North Platte	6.5 *	2.8	-3.0 *	1.4	9.4 *	3.7
KANSAS						
Goodland	0.8	1.9	-8.3 *	1.2	-0.8	3.3
Dodge City	-6.9 *	2.0	-0.3 *	1.2	16.5 *	2.6
Wichita	-10.7 *	2.0	-2.5 *	1.2	20.0 *	5.1
OKLAHOMA						
Tulsa	-21.5 *	2.0	2.7	1.4	49.2 *	8.1
Okla. City	-19.6 *	2.1	3.1 *	1.2	31.8 *	5.2
TEXAS						
Amarillo	-18.3 *	1.8	3.8 *	1.4	17.9 *	3.3
Brownsville	-48.3 *	3.3	-11.2 *	2.3	-4.1	4.1

*Greater than 2x SD %' change.

Table 6. CERES-Wheat Percent Changes in Yield, Evapotranspiration, and Water Applied for Irrigation With GFDL Climate Change Scenario; a) Dryland and b) Irrigated

a) DRYLAND CERES-WHEAT GFDL 2xCO_2 EXPERIMENT

Site	YIELD %	YIELD SD %	ET %	ET SD %
NEBRASKA				
Norfolk	-30.1 *	5.6	-19.2 *	2.7
Grand Island	-26.0 *	5.9	-15.7 *	2.8
Scotts Bluff	-45.3 *	9.1	-17.7 *	2.9
Omaha	-20.1 *	4.1	-11.8 *	2.4
North Platte	-40.4 *	8.3	-19.2 *	3.0
KANSAS				
Goodland	-46.9 *	11.7	-23.5 *	3.7
Dodge City	-12.3	13.2	-10.1 *	4.0
Wichita	-18.8 *	6.8	-7.7 *	3.4
OKLAHOMA				
Tulsa	-20.4 *	3.3	-4.3 *	1.4
Okla. City	-26.9 *	6.2	-8.8 *	2.5
TEXAS				
Amarillo	-55.1 *	13.0	-27.5 *	4.2
Brownsville	-40.4 *	3.9	-13.3 *	2.9

b) IRRIGATED CERES-WHEAT GFDL 2xCO_2 EXPERIMENT

Site	YIELD %	YIELD SD %	ET SD %	ET SD %	IRRIG %	IRRIG SD %
NEBRASKA						
Norfolk	-9.9 *	2.3	-2.2	1.4	14.6 *	4.2
Grand Island	-9.2 *	1.9	-1.0	1.6	13.6 *	4.3
Scotts Bluff	-2.2	1.9	3.3 *	1.3	21.2 *	3.6
Omaha	-16.3 *	2.3	-3.8 *	1.3	2.8	5.2
North Platte	0.2	2.8	4.8 *	1.5	22.8 *	3.9
KANSAS						
Goodland	-14.8 *	3.1	1.8	1.2	17.4 *	3.2
Dodge City	-15.6 *	1.9	-1.4	1.3	5.9	3.4
Wichita	-17.9 *	2.0	-4.0 *	1.3	-2.3	5.3
OKLAHOMA						
Tulsa	-19.4 *	2.4	-11.6 *	1.4	-2.3	7.4
Okla. City	-20.8 *	2.1	-1.5	1.2	12.4 *	5.2
TEXAS						
Amarillo	-17.3 *	1.9	-0.9	1.6	13.2 *	3.4
Brownsville	-42.7 *	3.1	-8.0 *	2.1	-3.4	4.1

*Greater than 2x SD % change.

Table 7. **CERES-Wheat Yield GISS 2xCO$_2$ Adjustment Experient for Planting Date and Combined Planting Date and Change in Cultivar; a) Dryland and b) Irrigated**

a) DRYLAND CERES-WHEAT YIELD GISS 2xCO2 ADJUSTMENT EXPERIMENT

Site	CC % CHANGE	CC SD % CHANGE	CC+PD % CHANGE	CC+PD SD % CHANGE	CC+PD+C % CHANGE	CC+PD+C SD% CHANGE
NEBRASKA						
Norfolk	-10.5	6.0	-33.4 *	3.1	-13.8 *	3.7
Grand Island	-17.1 *	6.0	-38.7 *	3.2	-19.4 *	4.0
Scotts Bluff	-25.9 *	9.6	-15.3	9.4	13.6	10.6
Omaha	-13.9 *	4.3	-11.8 *	4.2	6.7	5.5
North Platte	-27.7 *	8.4	-7.1	8.6	27.2 *	9.8
KANSAS						
Goodland	-10.5	16.1	-2.0	16.6	20.9	19.0
Dodge City	-38.7 *	11.7	-37.8 *	11.6	25.4	14.4
Wichita	-33.6 *	6.9	-28.6 *	6.7	9.1	6.7
OKLAHOMA						
Tulsa	-33.9 *	3.3	-32.4 *	3.2	18.8 *	4.0
Okla. City	-45.4 *	5.9	-45.9 *	5.9	2.1	7.6
TEXAS						
Amarillo	-55.4 *	12.3	-50.8 *	12.3	152.7 *	20.8
Brownsville	-45.3 *	4.1	-48.4 *	3.9	-30.2 *	4.4

b) IRRIGATED CERES-WHEAT YIELD GISS 2xCO2 ADJUSTMENT EXPERIMENT

Site	CC % CHANGE	CC SD % CHANGE	CC+PD % CHANGE	CC+PD SD % CHANGE	CC+PD+C % CHANGE	CC+PD+C SD% CHANGE
NEBRASKA						
Norfolk	-3.2	2.4	25.9 *	4.5	56.6 *	4.8
Grand Island	-3.7	2.0	42.1 *	9.5	257.2 *	11.3
Scotts Bluff	6.1 *	1.8	1.5	1.8	10.4 *	3.0
Omaha	-11.6 *	2.4	-13.7 *	2.4	5.6	3.9
North Platte	6.5 *	2.8	2.7	2.9	19.7 *	3.5
KANSAS						
Goodland	0.8	1.9	-0.6	1.9	18.5 *	3.3
Dodge City	-6.9 *	2.0	-8.7 *	2.0	-18.3 *	2.2
Wichita	-10.7 *	2.0	-12.8 *	2.0	-8.6 *	2.4
OKLAHOMA						
Tulsa	-21.5 *	2.0	-21.8 *	2.0	31.3 *	2.5
Okla. City	-19.6 *	2.1	-19.6 *	2.1	34.5 *	2.7
TEXAS						
Amarillo	-18.3 *	1.8	-19.3 *	1.8	-30.0 *	1.8
Brownsville	-48.3 *	3.3	-50.4 *	3.2	-33.6 *	3.8

*Greater than 2 x SD % change.

CC = Climate change alone
CC+PD = Climate change plus change in planting date
CC+PD+C = Climate change plus change in planting date plus change in cultivar

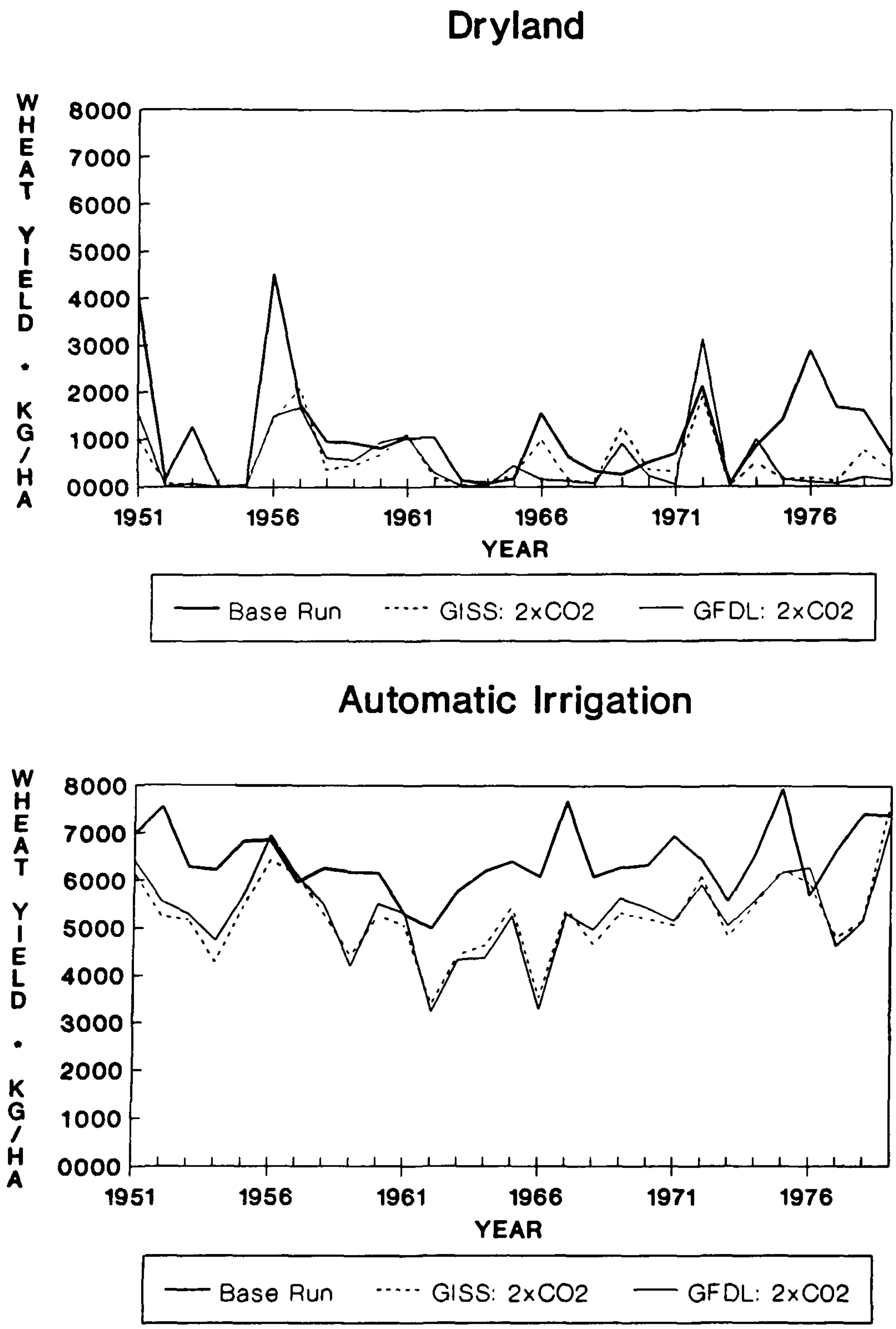

Figure 4. CERES-Wheat yields for Amarillo, Texas with GISS and GFDL Climate Change Scenarios; a) Dryland and b) Irrigated

the locations. At two sites, Amarillo (dryland) and Grand Island (irrigated), the change in cultivar results in very large increases in yields, although this may be caused by poorly specified cultivars in the baseline simulation.

Corn. Modeled corn yields are less negatively affected by the GISS climate change scenario than modeled wheat yields. While dryland CERES-Maize yields do decrease everywhere, the decreases are significant in only 7 out of 14 locations (Table 8a). Yield decreases range from 4 to 43%; the mean decrease is 17%, assuming equal area. Corn yield decreases are somewhat lower at lower latitudes, perhaps due to the use of cultivars already adapted to high temperatures at the southern study sites in the baseline simulation. Total crop ET decreases, but not significantly, with the GISS climate change scenario, implying that the increased daily evapotranspiration is approximately offset by the shortened season (Table 8a). Maturity dates of corn advance significantly (11 to 30 days) in the dryland case.

Dryland corn yield decreases are very large in the hotter and drier GFDL scenario, particularly at higher latitudes (Table 9a). Decreases range from 9 to 90%; mean decrease is about 50%. The yield decreases, especially those at higher latitudes, are caused by the combined effects of high temperatures shortening the grain filling period and increased moisture stress. The GFDL scenario has pronounced reductions of about 30 mm per month in summer precipitation (see Table 2) in the two northern gridboxes of the study area, which occur during critical growth stages of corn, i.e., flowering and grain filling (Doorenbos and Kassam, 1979). Total crop ET decreases everywhere and maturity dates are advanced by an average of three weeks in the GFDL scenario.

Irrigated corn yields decrease significantly at all locations in both the GISS and GFDL scenarios (Tables 8b and 9b). Even with irrigation, yields decreases from 9 to 21% occur in the GISS scenario and from 13 to 37% in the GFDL scenario. Compared to the less severe GISS case, where water applied for irrigation increases significantly at only about half the study sites, the more severe GFDL climate change scenario causes water applied for irrigation to increase everywhere, in one location by over 100%. Maturity dates advance by about two and one-half and three weeks in the GISS and GFDL scenarios respectively.

To simulate farmer adjustment to a longer growing season, the planting date window in CERES-Maize was set earlier according to changes in last spring frost in the GISS scenario. This results in some amelioration in dryland yield decreases, but declines are still large (up to 32%) in most locations (Table 10).

Combined Climatic and Direct Effects of CO_2

Wheat. The direct effects of CO_2 are able to mitigate the decreased wheat yields in the dryland case in some but not all locations, in both the GISS and GFDL scenarios. Yield values for latitudinal bands are shown in Figure 5 for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2. Sites at more southern latitudes show less compensation by the direct effects. With the GISS dryland scenario, 6 of the 12 locations have yield reductions; with the GFDL dryland scenario, 7 of the 12 locations have yield reductions. When automatic irrigation is applied, wheat yields improve over the baseline in almost all locations with combined climatic and direct effects of CO_2 in both the GISS and GFDL scenarios (Figure 5b). However, yields still decrease in all scenarios at the southernmost study sites.

Corn. Dryland corn yields increase under the less severe GISS climate scenario when combined with direct CO_2 effects, but decrease significantly in half of the locations with the more severe GFDL scenario (Figure 6a). An interesting result occurs with the irrigated corn runs in that yields decreased compared to baseline irrigated corn yields almost everywhere, despite the positive effects of increased photosynthesis and stomatal resistance (Figure 6b). As simulated in CERES-Maize, this is caused by the high temperature advancement of development stages, particularly grain filling, which cause yield decreases despite increased photosynthate and improved water use attributable to the direct effects of CO_2. The lower photosynthetic response to CO_2 of corn (10% increase) as compared to wheat (25%) also contributes to this result.

Table 8. CERES-Maize Percent Changes in Yield, Evapotranspiration, and Water Applied for Irrigation with GISS Climate Change Scenarios; a) Dryland and b) Irrigated

a) CERES-MAIZE YIELD GISS 2xCO2 EXPERIMENT

Dryland

Site	YIELD % CHANGE	YIELD SD% CHANGE	ET % CHANGE	ET SD % CHANGE
NEBRASKA				
Norfolk	-18.6 *	7.7	-3.2	-2.6
Grand Island	-19.8 *	7.2	-3.1	2.8
Scotts Bluff	-33.2	22.3	-1.6	5.3
Omaha	-24.5 *	3.1	-3.6 *	1.4
North Platte	-4.0	12.8	-3.3	3.8
KANSAS				
Goodland	-26.7	20.6	-1.3	5.2
Dodge City	-42.9 *	14.7	-5.5	4.8
Wichita	-26.6 *	7.4	-4.5	2.8
OKLAHOMA				
Tulsa	-10.5 *	3.7	-2.5	1.7
Okla. City	-12.6 *	5.3	-3.0	2.1
TEXAS				
Amarillo	-12.5	16.4	-1.2	5.3
Waco	-5.4	5.9	-4.4	2.3
San Antonio	-3.5	7.4	-4.1	3.6
Brownsville	-7.1	11.5	-2.2	5.2

b) Irrigated

Site	YIELD % CHANGE	YIELD SD% CHANGE	ET % CHANGE	ET SD % CHANGE	IRRIG % CHANGE	IRRIG SD% CHANGE
NEBRASKA						
Norfolk	-20.2 *	1.6	0.6	1.1	12.0 *	4.1
Grand Island	-18.9 *	1.6	1.7	1.0	7.1	3.6
Scotts Bluff	-12.3 *	2.6	3.9 *	1.9	6.9	3.7
Omaha	-22.6 *	1.7	1.6	1.2	14.2 *	4.8
North Platte	-12.5 *	2.6	1.6	1.5	7.6	4.5
KANSAS						
Goodland	-18.7 *	1.5	7.8 *	1.1	14.9 *	3.3
Dodge City	-21.4 *	1.8	12.8 *	1.3	28.1 *	4.6
Wichita	-17.5 *	2.0	9.4 *	1.9	29.4 *	6.7
OKLAHOMA						
Tulsa	-8.7 *	1.8	5.0 *	1.3	15.7 *	5.0
Okla. City	-10.5 *	2.3	8.0 *	1.9	20.5 *	5.2
TEXAS						
Amarillo	-17.1 *	1.3	11.6 *	1.2	28.1 *	3.7
Waco	-11.5 *	1.6	-1.9	1.3	4.0	4.1
San Antonio	-18.8 *	2.0	-2.4	1.6	-4.7	4.7
Brownsville	-19.4 *	3.1	-5.4 *	2.3	-3.6	3.6

* Greater than 2x SD % change

Table 9. CERES-Maize Percent Changes in Yield, Evapotranspiration, and Water Applied for Irrigation With GFDL Climate Change Scenario; a) Dryland and b) Irrigated

a) CERES-MAIZE GFDL 2xCO2 EXPERIMENT
Dryland

Site	YIELD % CHANGE	YIELD SD % CHANGE	ET % CHANGE	ET SD % CHANGE
NEBRASKA				
Norfolk	-76.0 *	6.4	-24.3 *	2.7
Grand Island	-74.5 *	5.9	-21.1 *	2.8
Scotts Bluff	-83.4 *	19.6	-25.6 *	4.9
Omaha	-63.4 *	3.2	-14.3 *	1.8
North Platte	-66.8 *	10.9	-28.2 *	3.9
KANSAS				
Goodland	-90.1 *	17.7	-38.8 *	4.6
Dodge City	-66.7 *	13.7	-15.8 *	4.5
Wichita	-42.2 *	7.2	-7.7 *	2.8
OKLAHOMA				
Tulsa	-23.5 *	3.5	-4.4 *	1.6
Okla. City	-8.2	5.5	-3.4	2.1
TEXAS				
Amarillo	-38.1 *	16.0	-14.7 *	5.4
Waco	-18.2 *	6.0	-7.4 *	2.5
San Antonio	-12.2	7.7	-8.3 *	3.4
Brownsville	8.8	10.6	-0.8	4.8

b) Irrigated

Site	YIELD % CHANGE	YIELD SD% CHANGE	ET % CHANGE	ET SD % CHANGE	IRRIG % CHANGE	IRRIG SD% CHANG
NEBRASKA						
Norfolk	-35.0 *	1.7	26.1 *	1.6	87.3 *	4.7
Grand Island	-33.3 *	1.9	30.6 *	1.6	78.9 *	4.6
Scotts Bluff	-22.7 *	2.7	36.4 *	2.1	73.0 *	4.1
Omaha	-37.3 *	1.7	32.4 *	1.7	107.2 *	5.8
North Platte	-26.4 *	2.6	23.2 *	1.9	64.8 *	5.3
KANSAS						
Goodland	-32.4 *	1.6	28.3 *	1.6	68.4 *	3.6
Dodge City	-25.3 *	1.8	20.9 *	1.6	47.9 *	4.8
Wichita	-21.0 *	2.1	16.4 *	2.1	51.9 *	6.6
OKLAHOMA						
Tulsa	-13.3 *	2.0	13.2 *	1.5	40.7 *	5.1
Okla. City	-10.9 *	2.3	3.7 *	1.8	10.7 *	5.1
TEXAS						
Amarillo	-24.5 *	1.5	23.6 *	1.5	48.8 *	4.3
Waco	-16.4 *	1.7	-0.6	1.3	8.1	4.2
San Antonio	-13.3 *	2.1	-1.6	1.5	7.8	4.8
Brownsville	-22.8 *	3.1	-1.6	2.3	6.7	3.6

* Greater than 2x SD % change

Table 10. Dryland CERES-Maize Yield GISS $2xCO_2$ Adjustment Experiment for Planting Date

DRYLAND

Site	CC % CHANGE IN YIELD	CC SD % CHANGE	CC+PD % CHANGE IN YIELD	SD % CHANGE
NEBRASKA				
Norfolk	-18.6 *	7.7	-15.2	7.8
Grand Island	-19.8 *	7.2	-11.0	7.4
Scotts Bluff	-33.2	22.3	-28.0	22.5
Omaha	-24.5 *	3.1	-18.9 *	3.5
North Platte	-4.0	12.8	-4.2	12.8
KANSAS				
Goodland	-26.7	20.6	-30.8	20.2
Dodge City	-42.9 *	14.7	-32.0 *	15.6
Wichita	-26.6 *	7.4	-20.0 *	7.4
OKLAHOMA				
Tulsa	-10.5 *	3.7	-7.4 *	3.6
Okla. City	-12.6 *	5.3	0.1	5.7
TEXAS				
Waco	-12.5	16.4	-4.5	5.9
San Antonio	-5.4	5.9	-4.7	7.8

*Greater than 2 x SD % change.

CC = Climate change alone
CC+PD = Climate change plus change in planting date

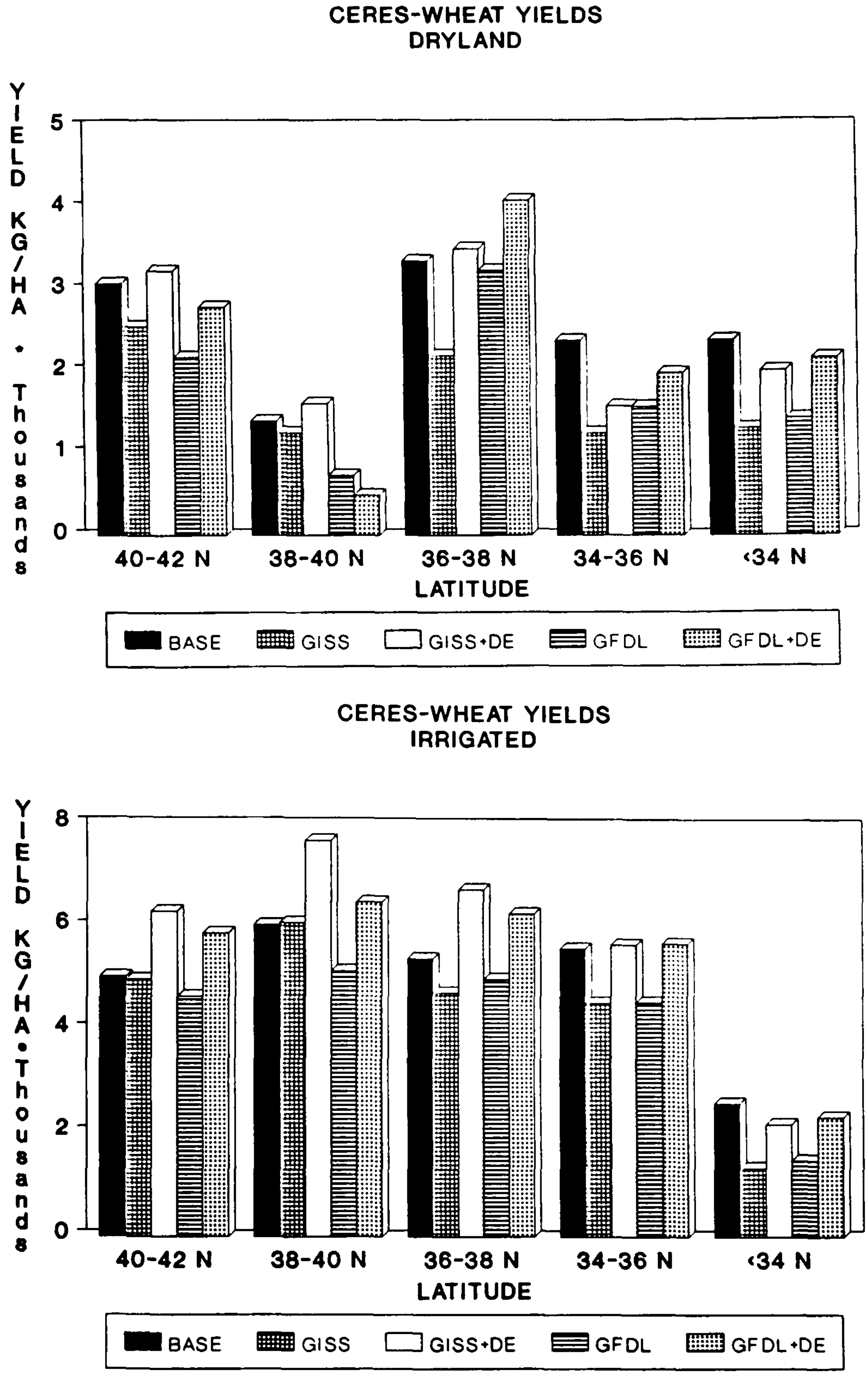

Figure 5. CERES-Wheat yields with GISS and GFDL climate change scenarios with and without the direct effects of CO_2: a) dryland and b) irrigated.

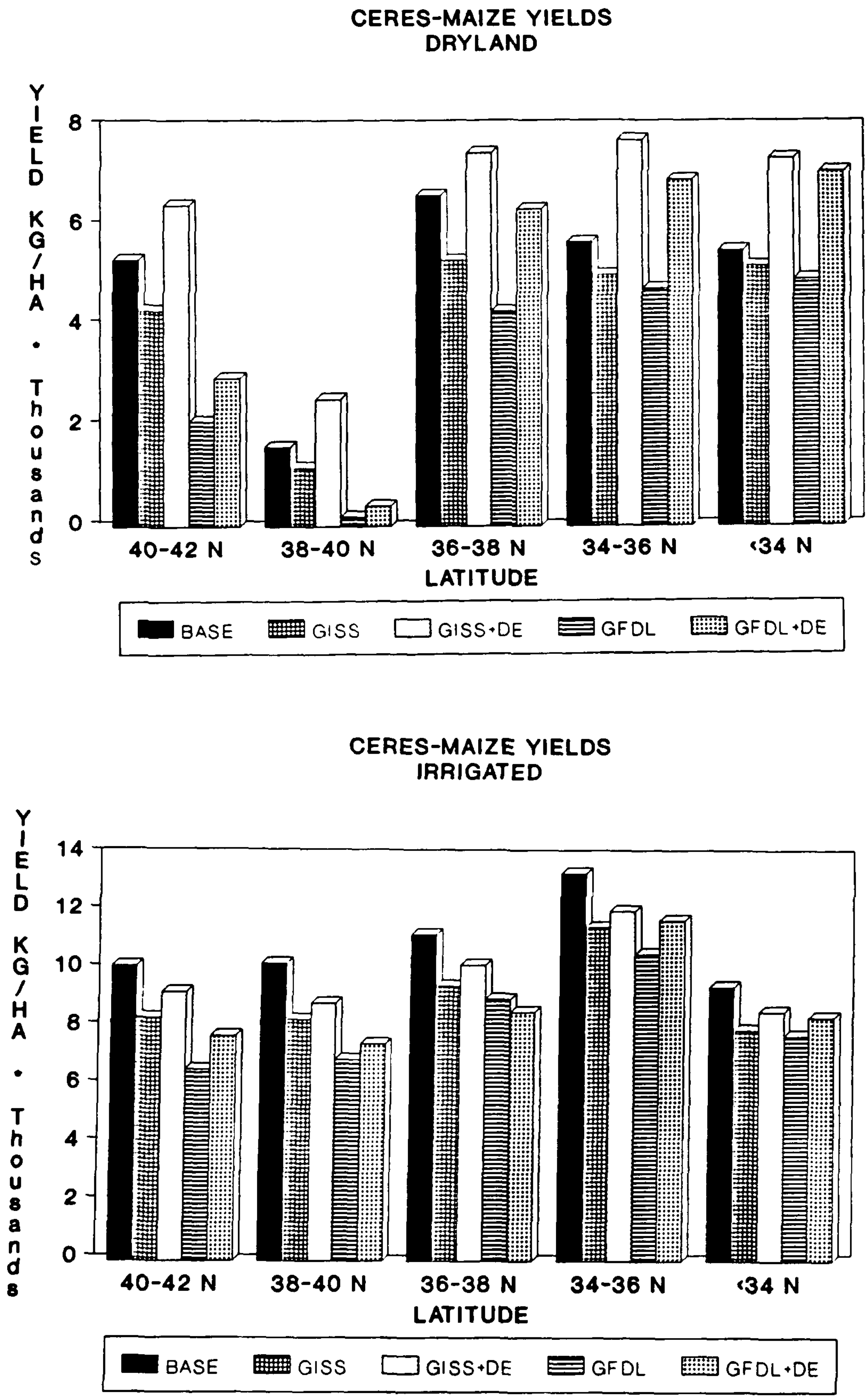

Figure 6. CERES-Maize yields with GISS and GFDL climate change scenarios with and without the direct effects of CO_2: a) dryland and b) irrigated.

Interpretation of Results

It should again be noted that many uncertainties are embedded in this study due to the assumptions and simplifications of the crop and climate models. Therefore, these results should be interpreted as the potential sensitivity of the modeled crops in the region to the range of climate change scenarios designed for the study.

Climate Change Alone. The results of the crop modeling studies with climate change scenarios alone show that increase in temperature is the major cause of modeled yield reductions in both wheat and corn in the southern and central Great Plains. In most cases, increases in temperature during the growing season cause a decrease in the duration of the crop life cycle, particularly the grain filling period. In general, the smaller temperature increases of the GISS scenario cause smaller yield reductions compared to the larger reductions occurring in the GFDL scenario.

Wheat yields decrease more at lower latitudes where wheat is close to its boundary of adaptation. These changes imply shifts in wheat production more northward in the region. Modeled yields of corn, a C4 crop more adapted to high temperatures, show an opposite effect in that larger decreases occur at higher latitudes. If climate changes occur at the level projected by the GISS scenario, corn cultivars already adapted to high temperatures may be available for growth in the region.

Changes in precipitation have a relatively minor effect on modeled wheat yields in the Great Plains, although they influence the amount of water applied in the irrigation simulations. Changes in precipitation do affect modeled corn yields in some locations. The largest yield reductions occur in corn with the GFDL climate scenario, which has very high temperatures and pronounced summer dryness to which corn is susceptible.

Combined Climate and Direct Effects of CO_2. The direct effects of CO_2, as modeled in this study, compensate for or even ameliorate, the climate change impacts in many locations, but not in all. Particularly with the hotter and drier GFDL scenario, modeled yield decreases of both corn and wheat are significant in the dryland case. Irrigated corn is more negatively affected than wheat in the combined scenarios because of the lower photosynthetic response of corn to CO_2. Because yield increases caused by higher levels of CO_2 do not overcome the negative effects of the predicted climate change in every location, even with the possibly overestimated direct effects as incorporated in the crop models, the results of this study suggest that the expectation that the direct CO_2 effects will compensate for climate change may be overly optimistic.

Irrigation. Irrigation partially mitigates the effects of climate change on both modeled corn and wheat yields in the climate change scenarios. Modeled irrigated yields are also more stable under climate change conditions. Modeled annual corn yields for dryland and irrigated corn in Grand Island, Nebraska, are shown in Figure 7. These results suggest that increased irrigation may be needed to fully counteract the negative effects of climate change in the Great Plains, and that regional demand for irrigation water would be likely to rise in response to the predicted changes. This would occur for two reasons: first, crops currently irrigated would require more water where precipitation decreases; and second, more acreage would be irrigated as high temperatures increase the variability of crop yields. Increased irrigation would thus be needed to ensure acceptable and stable yield levels.

Adjustments. Adjusting planting date of wheat to later in the fall does not significantly ameliorate the effects of the GISS climate change scenario on CERES-Wheat yields. Earlier corn planting dates slightly reduce yield decreases. Changing to more climatically adapted wheat cultivars with lower vernalization requirements and lower photoperiod sensitivity, in addition to delaying planting dates, overcomes yield decreases at some sites, but not in others. Thus, there appear to be some cultivars available for adaptation to the projected climate change, but these adaptations may not be efficacious at all locations. This suggests that development of heat- and drought-tolerant cultivars should be included in plant-breeding objectives for the region.

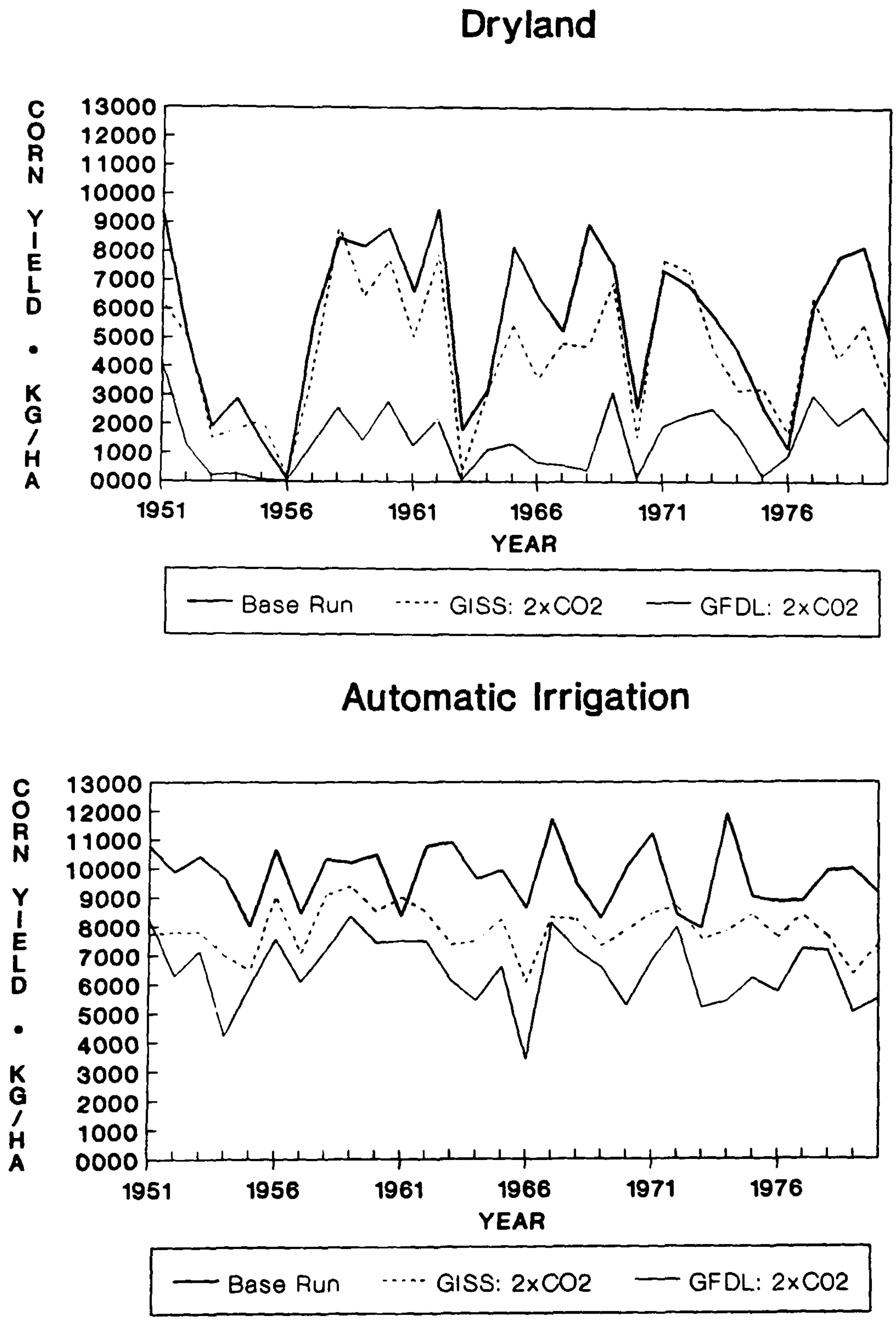

Figure 7. CERES-Maize yields for Grand Island, Nebraska with climate change scenarios alone; (a) dryland and (b) irrigated.

CHAPTER 4

IMPLICATIONS OF RESULTS

Given the projections of a virtually unidirectional warming trend driven by increasing concentrations of atmospheric trace gases and the potential for increased drought stress caused by higher temperatures and/or insufficient precipitation, agriculture as it is practiced now in the Great Plains may become more difficult to sustain in the future. If climate change occurs as predicted, agriculture may become more environmentally damaging and economically marginal in the region.

Environmental Implications

The primary environmental implication of the results is a probable increase in demand for irrigation in the region, particularly with more severe climate changes. Heightened demand for irrigation could place stress on the already depleted Ogalalla Aquifer and other water resources in the region. Many of the problems associated with intense groundwater use (for example, water depletion and soil erosion) could be exacerbated by global warming. However, availability of and competition for water supplies also may change with climate change, and defining the extent to which irrigation can provide an economic buffer against climate change requires further study.

Due to the potential for increased demand for water for irrigation, primary consideration should be given to sound environmental programs for managing water resources in terms of both quantity and quality. Competition for water resources between the potential increased agricultural use and nonagricultural demands may increase. This would imply that state and regional water policies would need modification in light of such potentialities.

Socioeconomic Implications

Yield decreases in dryland farming and need for increased irrigation may cause adverse economic consequences to farmers and rural communities in the region. Crop production may shift to the north, causing changes in production centers, markets, transportation, and storage. This is because the industry of agriculture is composed of many people besides farmers, such as farm equipment manufacturers, fertilizer and seed suppliers, and rural bankers. If climate change is extreme, climate change could cause dislocation of rural communities in the Great Plains through farm abandonment.

Further Research

Models of crop growth are needed which are both physiologically detailed and validated for wide areas. This is important both for simulation of agricultural yields under current climate and those projected for conditions of climate change and increased CO_2. In particular, crop models should include photosynthetic and transpiration processes responsive to concentration of CO_2. The method used in this study for simulating evapotranspiration does not include atmospheric vapor pressure or potential changes in plant temperatures due to stomatal closure. These should also be modeled more explicitly. Responses of all crop processes to combined high CO_2 levels and high temperatures need to be better understood.

The GISS GCM has been run with gradually increasing trace gases, and use of this "transient" climate change scenario will allow analysis of a more realistic trajectory of crop response to gradual warming. Running the crop models with observed climate for the Great Plains from the drought of the 1930s would provide a comparison of the crop responses to predicted future climate change with crop responses for an extreme climate event of the recent past. It would also help validate the crop models for climate change scenarios.

Extension of the study area to the Northern Great Plains, including North and South Dakota, would give a fuller picture of potential response of wheat to climate change over its entire range of production in the U.S.

Finally, further adjustment experiments with both wheat and corn under several climate change scenarios are also desirable, both with and without the physiological effects of CO_2, as are calculations of changes in agroclimatic indices such as thermal heat sums and drought indices for the region.

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APPENDIX 1. STUDY SITES

A. Climate station, tape ID#, latitude and longitude, county, Land Resource Region (LRR), Major Land Resource Area (MLRA), generic soil types* and soil ID numbers for sites used in Great Plains study.

1. Grand Island, NE	14935	40.58N 98.19W	Hall	H 71
H. deep silt loam, #6				
M. deep sandy loam, #9				
L. med. silt loam, #5				
2. Norfolk, NE	14941	41.59N 97.26W	Madison	M 102B
H. deep silty clay, #3				
M. deep silt loam, #6				
L. med. silt loam, #5				
3. N. Platte, NE	24023	41.08N 100.41W	Lincoln	G 65, H 72
H. deep silty clay, #3				
M. deep silt loam, #6				
L. deep sand, #12				
4. Omaha, NE	14942	41.18N 95.54W	Douglas	M 106,107
H. deep silty clay, #3				
M. deep silt loam, #6				
L. deep sandy loam, #9				
5. Scotts Bluff, NE	24028	41.52N 103.36W	S. Bluff	G 67
H. med. silty clay, #2				
M. deep silt loam, #6				
L. deep sandy loam, #9				
6. Dodge City, KS	13985	37.46N 99.58W	Ford	H 73
H. shallow silty clay, #1				
M. med. silt loam, #5				
L. deep sand, #12				
7. Goodland, KS	23065	39.22N 101.42W	Sherman	H 72
H. shallow silty clay, #1				
M. deep silt loam, #6				
L. deep sandy loam, #9				

* H = Generic soil with highest drained upper limit of plant extractable water of agricultural soils present in production area/or MLRA

M = Generic soil with medium water-holding capacity of agricultural soils present at site in production area/or MLRA.

L = Generic soil with lowest water-holding capacity of agricultural soils present in production area/or MLRA.

```
 8. Wichita, KS       3928   37.39N  97.25W    Sedgwick H 75,80A
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. med. silt loam, #5

 9. Okla. City, OK   13967   35.24N 97.36W     Oklahoma H 80A
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. deep sand, #12

10. Tulsa, OK        13968   36.12N 95.54W     Tulsa    M 112
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. med. silt loam, #5

11. Abilene, TX      13962   32.26N 99.41W     Taylor   H 78
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. deep sandy loam, #9

12. Amarillo, TX     23047   35.14N 101.42W    Potter   H 77
    H. deep silty clay, #3
    M. deep sandy loam, #9
    L. med. silt loam, #5

13. Brownsville, TX  12919   25.54N 97.26W     Cameron  I 83D
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. deep sandy loam, #9

14. El Paso, TX      23044   31.48N 106.24W    El Paso  D 42
    H. deep silty clay, #3
    M. deep sandy loam, #9
    L. deep sand, #12

15. Midland, TX      23023   31.56N 102.12W    Midland  H 77, I 81
    H. deep silty clay, #3
    M. deep silty loam, #9
    L. med. silt loam, #5

16. San Antonio, TX  12921  29.32N  98.28W   Bexar  I 81, J 86,87
    H. deep sandy loam, #9
    M. med. silt loam, #5
    L. med. sandy loam, #8

17. Waco, TX         13959   31.37N  97.13W McLennon   J 85,86
    H. deep silty clay, #3
    M. deep silt loam, #6
    L. deep sandy loam, #9
```

B. Land Resource Regions (LRR) and Major Land Resource Areas (MLRA) of sites in Great Plains study.

D Western Range and Irrigated Region

42 Southern Desertic Basins, Plains, and Mountains

G Western Great Plains Range and Irrigated Region

65 Nebraska Sand Hills
67 Central High Plains

H Central Great Plains Winter Wheat and Range Region

71 Central Nebraska Loess Hills
72 Central High Tableland
73 Rolling Plains and Breaks
75 Central Loess Plains
77 Southern High Plains
78 Central Rolling Red Plains
80A Central Rolling Red Prairies

I Southwest Plateaus and Plains Range and Cotton Region

81 Edwards Plateau
83D Lower Rio Grande Valley

J Southwestern Prairies Cotton and Forage Region

85 Grand Prairie
86 Texas Blackland Prairie
87 Texas Claypan Area

M Central Feed Grains and Livestock Region

102B Loess Uplands and Till Plains
106 Nebraska and Kansas Loess-Drift Hills
107 Iowa and Missouri Deep Loess Hills
112 Cherokee Prairies

Source: USDA, Soil Conservation Services, 1981: Land Resource Regions and Major Land Resource Areas of the United States. Agriculture Hand-book 296.

APPENDIX 2. GENERIC SOIL TYPES FOR USE IN CLIMATE CHANGE STUDY

```
Format line #1 of soil
        IDUMSL   1X,I2    # assigned to a soil type
        PEDON    1X,A12   SCS pedon number
        TAXON    1X,A60   Soil classification

Format line #2
        SALB     F6.2     Bare soil albedo
        U        1X,F5.2  Upper limit stage 1 evaporation, mm
        SWCON    1X,F6.2  Soil H2O drainage constant fraction drained per day
        CN2      1X,F6.2  SCS curve # used to calculate daily runoff
        TAV      1x,F5.1  Annual average ambient soil temperature, °C
        AMP      1X,F5.1  Annual average amplitude in mean monthly soil temp., °C
        DMOD     1X,F3.1  Soil mineralization factor (Default = 1)
        SWCON1   1X,E9.2  Coefficient in steady state solution (Default=.00267)
        SWCON2   1X,F6.1  Coefficient in steady state solution (Default=58)
        SWCON3   1X,F5.2  Coefficient in steady state solution (Default=6.68)
        RWUMX    1X,F5.2  Maximum daily root water uptake (Default=0.03)
        PHFAC3   1X,F4.2  Variable to reduce apparent photosynthesis (Default=1)

Format line #3
        DLAYR(L) F6.0    Thickness of soil layer L, cm
        LL(L)    1X,F6.3 Lower limit of plant-extractable H2O cm**3/cm**3
        DUL(L)   1x,F6.3 Drain upper limit soil H2O content for layer L
        SAT(L)   1X,F6.3 Saturated H2O content for layer L cm**3/cm**3
        SW(L)    1X,F6.3 Default soil H2O for layer L cm**3/cm**3
        WR(L)    1x,F6.3 Weighting factor for soil depth L to determine root
                         growth distribution, no units
        BD(L)    1X,F5.2 Moist bulk density of soil in layer L g/c**3
        OC(L)    1X,F5.2 Organic carbon concentration in layer L %
        NH4(L)   1X,F4.1 Default ammonium in layer L, mg elememtal N/kg soil
        NO3(L)   1X,F4.1 Default nitrate in layer L, mg elememtal N/kg soil
        PH(L)    1X,F4.1 Default pH in layer L in 1:1 soil: water slurry


 1               SHALLOW SILTY CLAY
  .11  6.00    .10  89.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.   .513   .680   .730   .680  1.000  1.35  1.74  2.5  3.3  6.5
  15.   .513   .679   .729   .679   .819  1.36  1.66  2.4  3.2  6.5
  15.   .514   .679   .729   .679   .607  1.36  1.45  2.2  3.0  6.5
  20.   .516   .677   .727   .677   .449  1.36  1.16  2.1  2.7  6.5
  -1.
 2               MEDIUM SILTY CLAY
  .11  6.00    .20  87.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.   .513   .680   .730   .680  1.000  1.35  1.74  2.5  3.3  6.5
  15.   .513   .679   .729   .679   .819  1.36  1.66  2.4  3.2  6.5
  20.   .514   .679   .729   .679   .607  1.36  1.45  2.2  3.0  6.5
  25.   .516   .677   .727   .677   .407  1.37  1.12  2.0  2.7  6.5
  30.   .518   .676   .726   .676   .247  1.37   .73  1.8  2.3  6.5
  30.   .520   .674   .724   .674   .135  1.38   .37  1.5  1.9  6.5
  -1.
```

```
3                  DEEP SILTY CLAY
 .11  6.00      .30   85.00    6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .513    .680    .730    .680  1.000  1.35  1.74   2.5   3.3   6.5
 15.    .513    .679    .729    .679    .819  1.36  1.66   2.4   3.2   6.5
 25.    .514    .679    .729    .679    .607  1.36  1.45   2.2   3.0   6.5
 30.    .516    .677    .727    .677    .368  1.37  1.09   2.0   2.6   6.5
 30.    .519    .675    .725    .675    .202  1.38   .65   1.7   2.2   6.5
 30.    .521    .674    .724    .674    .111  1.38   .29   1.4   1.8   6.5
 30.    .522    .673    .723    .673    .061  1.39   .09   1.1   1.3   6.5
 30.    .522    .673    .723    .673    .033  1.39   .01    .8    .9   6.5
 -1.
4                  SHALLOW SILT LOAM
 .12  6.00      .20  81.00     6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .106    .262    .312    .262  1.000  1.37  1.16   2.5   3.3   6.5
 15.    .106    .262    .312    .262    .819  1.37  1.10   2.4   3.2   6.5
 15.    .107    .262    .312    .262    .607  1.37   .97   2.2   3.0   6.5
 20.    .108    .261    .311    .261    .449  1.38   .77   2.1   2.7   6.5
 -1.
5                  MEDIUM SILT LOAM
 .12  6.00      .30  79.00     6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .106    .262    .312    .262  1.000  1.37  1.16   2.5   3.3   6.5
 15.    .106    .262    .312    .262    .819  1.37  1.10   2.4   3.2   6.5
 20.    .107    .262    .312    .262    .607  1.37   .97   2.2   3.0   6.5
 25.    .108    .261    .311    .261    .407  1.38   .75   2.0   2.7   6.5
 30.    .110    .260    .310    .260    .247  1.38   .49   1.8   2.3   6.5
 30.    .111    .259    .309    .259    .135  1.39   .24   1.5   1.9   6.5
 -1.
6                  DEEP SILT LOAM
 .12  6.00      .40  77.00     6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .106    .262    .312    .262  1.000  1.37  1.16   2.5   3.3   6.5
 15.    .106    .262    .312    .262    .819  1.37  1.10   2.4   3.2   6.5
 25.    .107    .262    .312    .262    .607  1.37   .97   2.2   3.0   6.5
 30.    .108    .261    .311    .261    .368  1.38   .72   2.0   2.6   6.5
 30.    .110    .260    .310    .260    .202  1.38   .43   1.7   2.2   6.5
 30.    .111    .259    .309    .259    .111  1.39   .20   1.4   1.8   6.5
 30.    .112    .258    .308    .258    .061  1.39   .06   1.1   1.3   6.5
 30.    .112    .258    .308    .258    .033  1.39   .01    .8    .9   6.5
 -1.
7                  SHALLOW SANDY LOAM
 .13  6.00      .40  74.00     6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .086    .220    .400    .220  1.000  1.61   .70   2.5   3.3   6.5
 15.    .086    .220    .400    .220    .819  1.61   .66   2.4   3.2   6.5
 15.    .086    .220    .400    .220    .607  1.61   .58   2.2   3.0   6.5
 20.    .087    .219    .400    .219    .449  1.61   .46   2.1   2.7   6.5
 -1.
8                  MEDIUM SANDY LOAM
 .13  6.00      .50  70.00     6.9  13.9 1.0    .27E-02    58.0  6.68   .03 1.00
 10.    .086    .220    .400    .220  1.000  1.61   .70   2.5   3.3   6.5
 15.    .086    .220    .400    .220    .819  1.61   .66   2.4   3.2   6.5
 20.    .086    .220    .400    .220    .607  1.61   .58   2.2   3.0   6.5
 25.    .087    .219    .400    .219    .407  1.61   .45   2.0   2.7   6.5
 30.    .088    .219    .400    .219    .247  1.62   .29   1.8   2.3   6.5
 30.    .089    .218    .400    .218    .135  1.62   .15   1.5   1.9   6.5
 -1
```

```
 9              DEEP SANDY LOAM
  .13  6.00      .50  68.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.    .086   .220    .400   .220  1.000  1.61    .70  2.5  3.3  6.5
  15.    .086   .220    .400   .220   .819  1.61    .66  2.4  3.2  6.5
  25.    .086   .220    .400   .220   .607  1.61    .58  2.2  3.0  6.5
  30.    .087   .219    .400   .219   .368  1.61    .43  2.0  2.6  6.5
  30.    .088   .218    .400   .218   .202  1.62    .26  1.7  2.2  6.5
  30.    .089   .218    .400   .218   .111  1.62    .12  1.4  1.8  6.5
  30.    .089   .218    .400   .218   .061  1.62    .04  1.1  1.3  6.5
  30.    .089   .217    .400   .217   .033  1.62    .01   .8   .9  6.5
  30.    .089   .217    .400   .217   .018  1.62    .00   .5   .5  6.5
  -1.
 10             SHALLOW SAND
  .15  4.00      .40  75.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.    .032   .107    .370   .107  1.000  1.66    .29  2.5  3.3  6.5
  15.    .032   .107    .370   .107   .819  1.66    .28  2.4  3.2  6.5
  15.    .032   .107    .370   .107   .607  1.66    .24  2.2  3.0  6.5
  20.    .032   .107    .370   .107   .449  1.66    .19  2.1  2.7  6.5
  -1.
 11             MEDIUM SAND
  .15  4.00      .50  70.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.    .032   .107    .370   .107  1.000  1.66    .29  2.5  3.3  6.5
  15.    .032   .107    .370   .107   .819  1.66    .28  2.4  3.2  6.5
  20.    .032   .107    .370   .107   .607  1.66    .24  2.2  3.0  6.5
  25.    .032   .107    .370   .107   .407  1.66    .19  2.0  2.7  6.5
  30.    .033   .106    .370   .106   .247  1.66    .12  1.8  2.3  6.5
  -1.
 12             DEEP SAND
  .15  4.00      .60  65.00   6.9  13.9 1.0    .27E-02    58.0  6.68    .03 1.00
  10.    .032   .107    .370   .107  1.000  1.66    .29  2.5  3.3  6.5
  15.    .032   .107    .370   .107   .819  1.66    .28  2.4  3.2  6.5
  25.    .032   .107    .370   .107   .607  1.66    .24  2.2  3.0  6.5
  30.    .032   .107    .370   .107   .368  1.66    .18  2.0  2.6  6.5
  30.    .033   .106    .370   .106   .202  1.66    .11  1.7  2.2  6.5
  30.    .033   .106    .370   .106   .111  1.66    .05  1.4  1.8  6.5
  30.    .033   .106    .370   .106   .061  1.66    .01  1.1  1.3  6.5
  30.    .033   .106    .370   .106   .033  1.66    .00   .8   .9  6.5
  -1.
```

1. Individual run

	BASELINE YIELD	$2xCO_2$ YIELD	YIELD DIFFERENCE $2xCO_2$-BASELINE
	1	1	1
	.	.	.
	.	.	.
	.	.	.
	n_a	n_b	n_c
Observed mean	μ_a	μ_b	μ_c
Observed standard deviation	σ_a	σ_b	

Standard deviation of observed mean

$$\sigma_{\mu a} = \frac{\sigma_a}{\sqrt{n_a}}, \quad \sigma_{\mu b} = \frac{\sigma_b}{\sqrt{n_b}}$$

Observed mean yield difference

$$\mu_c = \mu_b - \mu_a$$

Observed standard deviation of mean yield difference

$$\sigma_{\mu c} = \sqrt{\sigma^2_{\mu a} + \sigma^2_{\mu b}}$$

Mean and uncertainty of percent change

$$\left(\frac{\mu_c \pm \sigma_{\mu c}}{\mu_a} \right) \times 100$$

2. Summary of 3 soils at one site

Summary mean and uncertainty of change over all soils; L, M, H = low, medium, and high production capacity

$$\left[\frac{\mu_{cL} + \mu_{cM} + \mu_{cH} \pm \sqrt{\sigma^2_{\mu c} + \sigma^2_{\mu cM} + \sigma^2_{\mu cH}}}{\mu_{aL} + \mu_{aM} + \mu_{aH}} \right] \times 100$$

APPENDIX 4. CERES-WHEAT MATURITY DATE GISS $2xCO_2$ EXPERIMENT

a) DRYLAND

Site	MEAN DIFF	SD MEAN DIFF	%Δ	SD %Δ
NEBRASKA				
Norfolk	-25 *	0.9	-13.3 *	0.5
Grand Island	-25 *	1.0	-14.0 *	0.5
Scotts Bluff	-30 *	0.9	-16.0 *	0.5
Omaha	-24 *	0.9	-13.7 *	0.5
North Platte	-27 *	0.9	-14.7 *	0.5
KANSAS				
Goodland	-27 *	0.9	-15.2 *	0.5
Dodge City	-20 *	0.9	-12.3 *	0.6
Wichita	-20 *	0.8	-12.3 *	0.5
OKLAHOMA				
Tulsa	-8 *	0.9	-10.5 *	0.6
Okla. City	-17 *	0.9	-10.9 *	0.6
TEXAS				
Amarillo	-18 *	0.9	-11.6 *	0.6
Brownsville	-11 *	1.6	-13.7 *	2.2

b) IRRIGATED

Site	MEAN DIFF	SD MEAN DIFF	%Δ	SD %Δ
NEBRASKA				
Norfolk	-24 *	0.9	-13.1 *	0.5
Grand Island	-25 *	0.9	-13.9 *	0.5
Scotts Bluff	-29 *	0.9	-15.8 *	0.5
Omaha	-24 *	0.9	-13.7 *	0.5
North Platte	-27 *	0.9	-14.6 *	0.5
KANSAS				
Goodland	-28 *	0.9	-15.5 *	0.5
Dodge City	-21 *	1.0	-12.4 *	0.6
Wichita	-20 *	0.8	-12.2 *	0.5
OKLAHOMA				
Tulsa	-8 *	0.9	-10.4 *	0.6
Okla. City	-16 *	0.9	-10.8 *	0.6
TEXAS				
Amarillo	-17 *	1.0	-11.3 *	0.6
Brownsville	-11 *	1.4	-13.8 *	2.0

*Greater than 2x SD % change.

APPENDIX 5. CERES-WHEAT MATURITY DATE GFDL $2xCO_2$ EXPERIMENT

a) DRYLAND

Site	MEAN DIFF	SD MEAN DIFF	%Δ	SD %Δ
NEBRASKA				
Norfolk	-22 *	0.9	-11.8 *	0.5
Grand Island	-22 *	0.9	-12.1 *	0.5
Scotts Bluff	-29 *	0.9	-15.3 *	0.5
Omaha	-21 *	0.8	-11.8 *	0.5
North Platte	-24 *	0.8	-13.0 *	0.4
KANSAS				
Goodland	-27 *	0.8	-15.0 *	0.5
Dodge City	-22 *	0.9	-13.4 *	0.6
Wichita	-21 *	0.8	-13.1 *	0.5
OKLAHOMA				
Tulsa	-27 *	0.9	-18.3 *	0.6
Okla. City	-18 *	0.9	-12.1 *	0.6
TEXAS				
Amarillo	-23 *	0.9	-14.7 *	0.6
Brownsville	-15 *	1.6	-18.5 *	2.2

b) IRRIGATED

Site	MEAN DIFF	SD MEAN DIFF	%Δ	SD %Δ
NEBRASKA				
Norfolk	-21 *	0.9	-11.5 *	0.5
Grand Island	-21 *	0.9	-12.0 *	0.5
Scotts Bluff	-28 *	0.8	-15.1 *	0.4
Omaha	-21 *	0.8	-11.7 *	0.5
North Platte	-24 *	0.8	-12.9 *	0.4
KANSAS				
Goodland	-28 *	0.8	-15.5 *	0.5
Dodge City	-22 *	1.0	-13.3 *	0.6
Wichita	-21 *	0.8	-13.1 *	0.5
OKLAHOMA				
Tulsa	-27 *	0.9	-18.3 *	0.6
Okla. City	-18 *	0.9	-11.9 *	0.6
TEXAS				
Amarillo	-23 *	1.0	-14.9 *	0.6
Brownsville	-13 *	1.5	-16.8 *	2.1

*Greater than 2x SD % change.

THE ECONOMIC EFFECTS OF CLIMATE CHANGE ON U.S. AGRICULTURE:
A PRELIMINARY ASSESSMENT

by

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CONTENTS

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FINDINGS[1]

In this study a model of U.S. agriculture is used to measure the economic effects of changes in crop yields and water availability arising from projected long-term changes in climate associated with a doubling of CO_2. The resulting economic effects are conditional on the validity of the data on crop yields and water availability. These data are, in turn, a function of the validity of the general circulation models (GCMs) that forecast global climate change and the crop yield and hydrologic models that translate climate change into its physical effects. Given the uncertainties involved in each component of this analysis, and the general difficulties of forecasting the structure of a dynamic industry such as agriculture over a 60 to 70-year time period, caution should be exercised in interpreting and applying the economic estimates.

This analysis encompasses (1) a range of possible climate changes as predicted by the GISS and GFDL climate models under a doubled CO_2 environment; (2) a diverse set of yield and water availability assumptions for each climate change; and (3) some fundamental assumptions concerning the structure of agriculture over the next 70 years. To keep the analysis tractable, "common themes" are used to limit possible combinations of assumptions and parameters. First, all crop yield changes are based on yield estimates from the CERES and SOYGRO plant models. The models predict yield changes for corn, soybeans, and wheat in various regions of the U.S. (for each GCM). An average of yield changes for these three crops is then used to develop surrogate responses for other crops in each region for which no plant model estimates are available. Uncertainties in crop yield data are captured in sensitivity analyses reflecting one standard deviation (plus and minus) around midpoint yield responses. Changes in irrigation water availability and crop water demands (for irrigated crops) are based on ratios of GCM forecasts of evaporation and of rainfall. Uncertainties are measured in sensitivity runs (higher rain, lower evaporation and vice versa) for each GCM's grid point estimates. Finally, potential changes in technology and in future U.S. and world food demand, as well as the direct effects of CO_2 on crop yields, were introduced into the climate change analyses.

As expected, these varying assumptions give rise to a range of probable economic effects. For the GISS $2xCO_2$ scenario, "midpoint" changes in crop yields and in water availability and demand result in an aggregate net loss in economic welfare of approximately $6.0 billion per annum (in 1982 $). The distribution of these effects is sharply skewed, as consumers lose over $7 billion while producers experience a net gain of $1.1 billion owing to the generally inelastic demand for modeled crops. All crops except hay experience minor to moderate reductions in production. Regionally, more southern production areas decrease land in crop production (e.g., Appalachia, Delta, and Southern Plains) while land use increases in northern and western regions (Lake States, Corn Belt, Mountain, and Pacific). For most irrigated areas, slight increases in water availability offset increases in evaporative water loss, except for the Pacific, where increases in availability are substantial. Nationally, irrigated acreage increases by about 5 million acres (11 percent) owing to (1) an increase in the comparative advantage of irrigated versus dryland yields under the climate change scenarios, and (2) the rise in commodity prices that makes irrigated production economically feasible.

The GFDL midpoint case implies substantially greater potential losses from climate change. The net annual loss in economic welfare is approximately $33 billion with consumers losing $37 billion and producers gaining $4 billion. Regionally, northern and western areas increase cropped acreage (Pacific, Mountain, Northern Plains) while other areas experience reductions (Corn Belt, Appalachia, Southeast, Delta States, Southern Plains). As in the GISS analyses, irrigated acreage increases in all regions (about 40 percent nationally), again due to rising commodity prices and the increased comparative advantage of irrigated production.

Imposing long-term changes in technology and food demand on these analyses alters the above effects. For GISS, potential technological change appears capable of offsetting yield reductions from climate yield change,

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[1]Although the information in this report has been funded wholly or partly by the U.S. Environmental Protection Agency under Cooperative Agreement No. CR811965-01, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

even with increased food demand. Under the larger yield reductions forecast by GFDL, 40 to 50 years of technology change is required to offset the yield reductions attributed to climate change. Finally, the potential yield-enhancing effects of CO_2 may moderate the economic consequences of a doubling of CO_2. When such direct CO_2 effects are combined with the generally adverse effects of climate change, the GISS analyses show slight to moderate increases in economic welfare. For GFDL, however, CO_2 yield enhancement does not completely mitigate climate change, resulting in a net loss of approximately $10 billion. As in the other analyses, northwesterly shifts in crop production and increased irrigation use are observed across the combined CO_2-climate change evaluations.

The results of these varied analyses suggest that climate change is not a food security issue; the production capacity of U.S. agriculture is adequate to meet domestic needs, even under the more extreme climate changes. However, major resource and environmental quality adjustments are likely. Expansion of irrigation and shifts in regional production patterns imply more competition for water resources, greater potential for ground and surface water pollution, loss of wildlife habitat, increased soil erosion, and major structural changes in local economies. The costs of these changes on the well-being of future generations are not addressed here.

It should be noted that these results consider the effects of climate change on the U.S. in isolation. If other areas of the world benefit from climate change/CO_2 increases or are less severely affected than the U.S., then U.S. agricultural export trade could be changed from the patterns assumed in this analysis. Also, the analyses performed here do not consider the effects of climatic variability. Greater variability in precipitation, for example, would be expected to have greater adverse effects than measured here. Changes in crop pest and disease infestations due to climate change are not considered in the plant yield forecasts used in these evaluations. Finally, CO_2 increases beyond those forecast here could imply more severe implications for agriculture, as the yield-enhancing effects of CO_2 increases are likely to plateau, thus failing to mitigate increasingly adverse climate effects.

CHAPTER 1

INTRODUCTION

Global climate change arising from anthropogenic increases in atmospheric CO_2 and trace gas concentrations is an issue of international concern. The implications of climate change are complex, occurring on a global scale with potential effects on virtually all ecosystems and ecosystem service flows (Wigley et al., 1981). One ecosystem of particular importance to human welfare is agriculture. The consequences of crop failure arising from unfavorable climate are apparent. Recent notable examples include the famine in Northern Africa arising from prolonged drought and, within the U.S., the 1983 and 1988 droughts. While the level of human suffering manifested in these two examples are undeniably different, both provide dramatic evidence of the susceptibility of agriculture and agriculture's constituents to changes in regional climates.

The direct and indirect effects of global climate change on agriculture are discussed in qualitative terms in numerous studies (Decker et al., 1986; Rosenzweig, 1986; Callaway et al., 1982). For example, Rosenzweig has identified the following consequences on agricultural productivity of climatic change: (1) changes in yield due to increased atmospheric CO_2 concentration, increased temperature, and the likelihood of increased pest and pathogen populations arising from a warmer global climate; and (2) the indirect consequences on agricultural productivity associated with potential reductions in irrigation water supplies. To this list, one could add yield effects of increases in tropospheric ozone and UV-B radiation incidence at the Earth's surface arising from the same trace gas emissions associated with climate change. In combination, some or all of these factors may alter the yields of major food and fiber crops. Forecasting the exact magnitude and distribution of long-term changes in yield and water availability from global climate change models is a challenging task for plant scientists, hydrologists, and others. Once obtained, these physical and biophysical responses need to be translated into economic or other measures of human welfare for use in policy formation. The latter task may be even more challenging than forecasting the likely physical/biological manifestations of climate change, given the adaptive behavior of producers, consumers, and other economic agents likely to occur over the long-time horizons associated with climate change.

OBJECTIVES

The purpose of this research is to provide a preliminary measure of the economic consequences of long-term climate change on U.S. agriculture. The results provide a general impression of the importance of global climate change with respect to the welfare of agricultural producers and consumers. Specific objectives include the following:

(1) Estimate the regional and national economic implications of changes in yield, and water availability and use, for a set of major U.S. commodities (e.g., corn, soybeans, and wheat) associated with alternative global climate change scenarios arising from a doubling of CO_2;

(2) Determine the sensitivity of these estimates to selected assumptions concerning critical biological, physical, and economic dimensions of the analysis; and

(3) Based upon the outcome of objective 2, define a set of longer term research objectives aimed at improving the ability of economists and others to provide policy analyses concerning global climate change.

ORGANIZATION

The remainder of this report consists of three sections. Section two describes the methodology used to measure the economic effects of climate change at different levels of aggregation. Critical data sources and assumptions, along with limitations of the analysis, are discussed. The third section presents the results of applying the methodology to crop yield and water availability changes associated with two global climate model scenarios that reflect a doubling of CO_2 concentrations. The implications of these results are evaluated in the fourth section. This last section draws some preliminary implications and conclusions from these climate change analyses. Future research needs are also outlined.

CHAPTER 2

METHODOLOGY

Performing the bioeconomic assessment defined in the above objectives requires critical input from several disciplines. Such assessments typically involve a series of steps to link physical and biological phenomena to an economic valuation model. The starting point in the current assessment is definition of likely changes in global climate due to a doubling of CO_2 and, specifically, how they will be manifested in terms of changes in temperature, precipitation, and other climatic variables across agricultural production regions in the United States. Two forecasts of climate change based on general circulation models (GCMs) are used here. One comes from the Goddard Institute of Space Studies (GISS), the other from Princeton University Geophysical Fluid Dynamics Laboratory (GFDL).

The GCMs forecast changes in regional temperature, precipitation, evaporation and other climate variables due to the doubling of CO_2. Such changes are likely to lead to changes in crop yields and water available for irrigation. These measures of climate change become inputs into the second stage of this process, which requires knowledge of how changes in regional climate affect items that people value, e.g., the quantity and quality of food and fiber production. This information is provided by crop yield response models that incorporate the likely mechanisms of yield change arising from climatic alterations. Specifically, crop yield changes were predicted by plant scientists using the CERES family of plant physiology models and SOYGRO, a soybean model of comparable design. In the assessment, information is also required on how long-term climate changes will affect both crop water demand and water supply in irrigated areas of the U.S. Since water is, perhaps, the most important input in the agricultural production process, forecasts of water demand and availability are an important aspect of an economic assessment of climate change. These water forecasts were derived from the GCM scenarios (see Appendix A). Once quantified, resulting yield and irrigation effects were used to modify an economic model of the U.S. agricultural sector to translate the physical and biological effects into economic consequences.

The primary focus of this research is on applying an "appropriate" economic model to the crop yield and hydrologic assumptions arising from CO_2 changes. Appropriate is defined in terms of the model's economic credibility, as established by its theoretical and empirical content, coupled with how well the model captures critical dimensions of global climate change. Specifically, since change in climatic variables is not homogeneous across agricultural production areas in the U.S., the model must contain sufficient regional detail to account for these variations in regional climate. Second, since global climate change is likely to affect both yields (as measured by the CERES and SOYGRO crop response models) <u>and</u> the supply of irrigation water, the model needs a detailed characterization of irrigation requirements, by crop and region, as well as regional water availabilities. Third, since the model is to be used for policy analysis, it should measure economic consequences at various levels of aggregation including producer welfare at the regional and national levels, as well as effects on both domestic and foreign consumers.

The assessment model used here conforms to the above requirements and is based on an economic model used in several recent analyses of the economic effects of tropospheric ozone on agriculture (e.g., Adams et al., 1984; Adams et al., 1988). In general, the model and its application are conceptually similar to the numerous induced change analyses found in the agricultural economics literature. Specifically, the economic model is a spatial equilibrium model formulated as a mathematical programming problem (Takayama and Judge, 1971). An alternative to this type of partial-equilibrium model formulation is a compatible general equilibrium (CGE) model with an agricultural subsector. However, submodels are extremely consumptive of data and it is doubtful that a tractable CGE curve could be constructed with the degree of resolution required to meet the needs of this study. Further, Kokoski and Smith have shown that the differences in welfare measures between a partial equilibrium analysis and a CGE solution are minor if the size and duration of indirect price effects are consistent.

The model represents production and consumption of 30 primary agricultural commodities, including both crop and livestock products. Processing of agricultural products into 12 secondary commodities is also included. The production and consumption sectors are assumed to be made up of a large number of individuals, each of whom operates under competitive market conditions. This leads to a model which maximizes the area under the demand curves less the area under the supply curves. Following Samuelson, this area can be interpreted as a measure of economic welfare (ordinary consumers' plus producers' surplus) equivalent to the annual net income lost or gained by agricultural producers and consumers as a consequence of global climate change, expressed in 1982 dollars. Both domestic and foreign consumption (exports) are included. The assumptions and methodology are discussed in Appendix B. Additional detail is provided in Adams et al. (1984) and McCarl and Spreen (1980).

The model consists of two components, a set of micro or farm-level models integrated with a national (sector) model. Producer-level behavior is captured in a series of technical coefficients that portray the physical and economic environment of agricultural producers in each of the 63 homogeneous production regions in the model, encompassing the 48 contiguous states. These regions are then aggregated to 10 macro regions, as defined by the U.S. Department of Agriculture (USDA) (Figure 1). Of importance in this assessment is the inclusion of both irrigated and nonirrigated crop production and of water supply relationships for each region. Availability of land, labor, and irrigation water is determined by supply curves defined at the regional level depicted in Figure 1. Farm-level supply responses generated from the 63 individual regions are linked to national demand through the objective function of the sector model, which features demand relationships for various market outlets for the included commodities. The model simulates a long-run, competitive equilibrium as reflected in 1981-1983 economic and environmental parameters. This three-year base period was selected because (1) a multi-year period was deemed more reasonable than a single year as a base against which to assess long-term changes, and (2) while not a period of equilibrium in supply and demand, the period had more stability than alternative recent multi-year periods. It should be noted that this period differs from the base period used in the GCMs (1951-1980) to model climate change. Given the rate of change in the agricultural sector (particularly since 1951), the use of a recent base period was viewed as more appropriate for economic modeling.

PROCEDURE

To implement the assessment, specific scenarios of global climate change are required. Of these, we focus on two scenarios of doubled CO_2 equilibrium, where the base-level CO_2 corresponds to the 1951-1980 period. Specifically, the climatic consequences of the $2xCO_2$ equilibrium scenario are estimated via the GISS and the GFDL GCMs.

Estimated yield and water resource changes associated with regional climate changes forecast by each GCM are introduced into the model through modifications in (1) regional crop yields; (2) crop water use coefficients; and (3) regional water supply functions. The subsequent model simulations then generate a picture of their economic effects, including shifts in regional market shares (i.e., comparative advantage), changes in producers' returns, changes in consumers' well-being and other economic aspects. In addition to the model solutions for the climate scenarios, sensitivity analyses are performed to establish "bounds" on these economic estimates. The sensitivity analyses focus on uncertainties in the yield and water availability estimates, as well as on the effects of uncertainty in economic assumptions, including changes in technology and demand. A final set of analyses incorporates the direct (yield enhancing) effects of CO_2 in both the GISS and GFDL climate change evaluations.

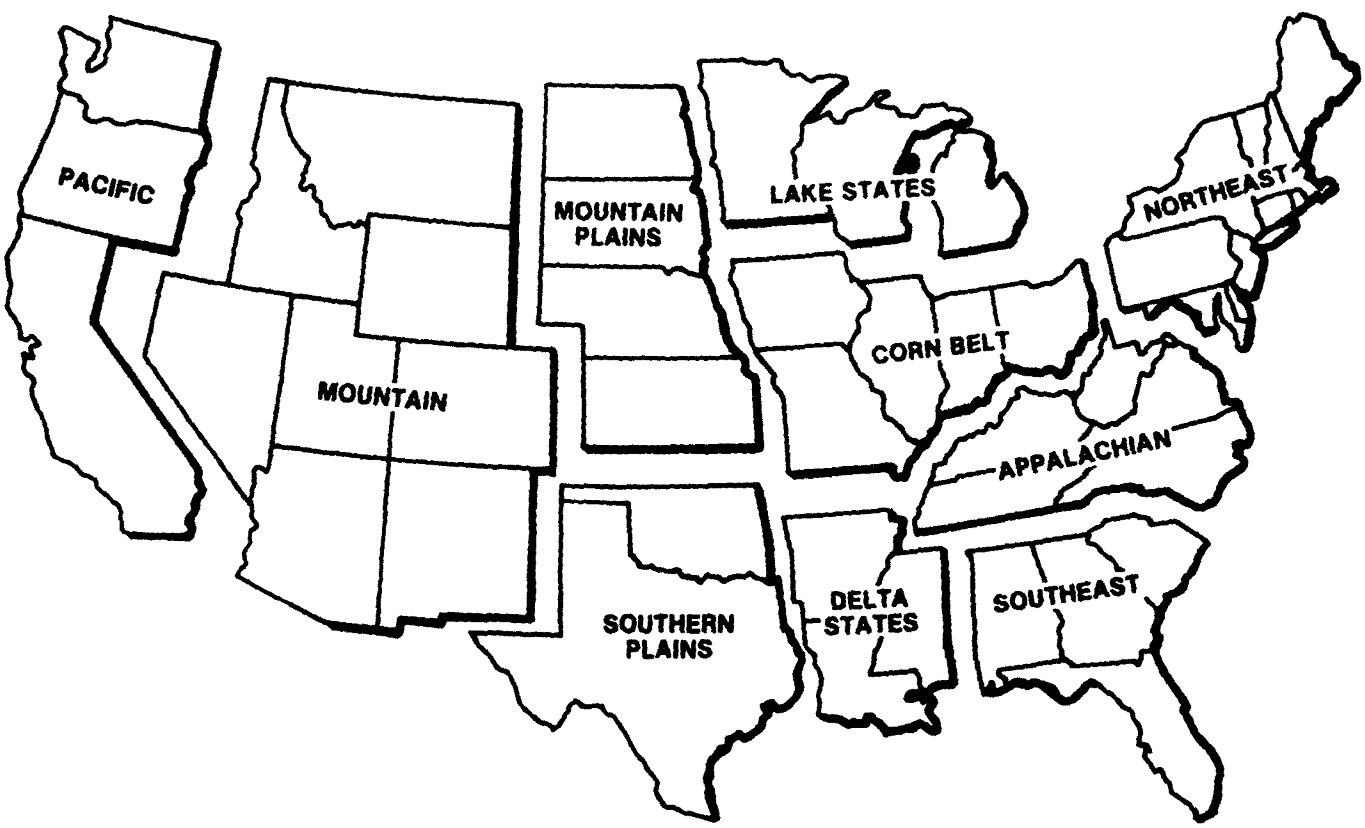


Figure 1. Farm production regions in the United States.

Source: USDA ERS.

SUPPORTING CROP YIELD DATA

Crop yield implications of regional climate changes are provided by plant scientists at Goddard NASA's Space Flight Center Institute for Space Studies, University of Florida, and Michigan State University. Specifically, Cynthia Rosenzweig (at GISS), Jim Jones, Bruce Curry, and Bob Peart (at the University of Florida) and Joe Ritchie (at Michigan State University) provided regional crop yield changes for wheat, corn, and soybeans using the CERES and SOYGRO models. Coverage was limited to soybeans in the Corn Belt, Lake States, and Southeast; corn in the Corn Belt, Lake States, and the Southeast; and wheat in the Great Plains states. These regions represent major production areas for each crop. For cotton and other excluded crops, responses obtained from the CERES and SOYGRO model predictions for corn, wheat, and soybeans were averaged to develop surrogate responses. Yield changes were extrapolated to the Northeast and West from the regions that are modeled. Because most of the production in the western regions is from irrigated crops that were much less affected by the climatic shifts than their dryland counterparts, these extrapolations may be less than they appear.

For most crops, the plant models indicate lower yields associated with the GCM forecast climate conditions, with the GFDL climate projections resulting in substantively lower yields than for GISS. Potential yield reductions are greater for dryland crops than for irrigated. In general, potential yield reductions are greater in the South, the Southern Plains, and the Southwest. For soybeans, slight yield increases are predicted in more northern latitudes (e.g., Minnesota). Crop yield projections and associated standard deviations for various locations, along with details of the CERES and SOYGRO model estimation procedures, are reported in studies by Rosensweig, Peart et al., and Ritchie et al. in this volume.

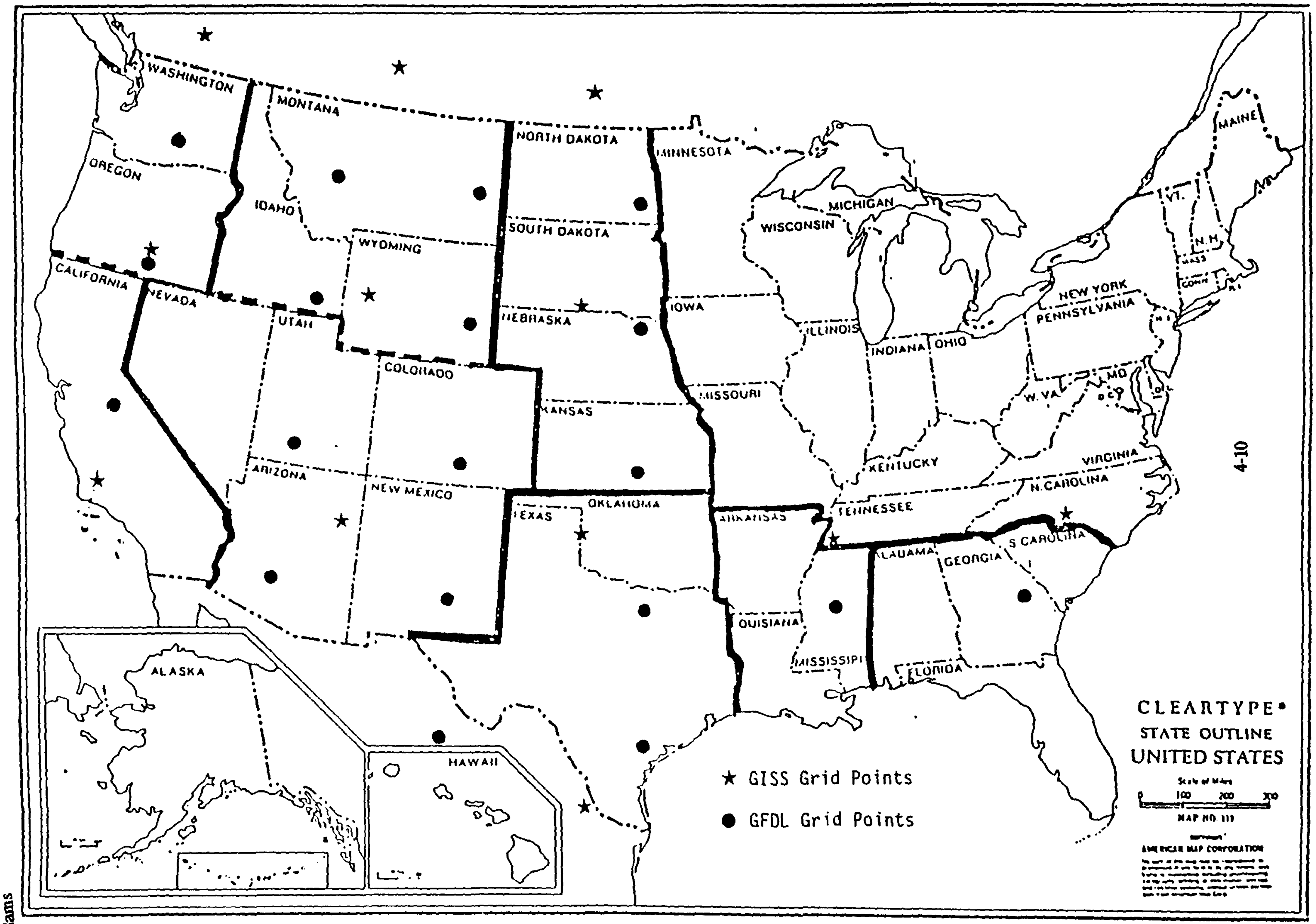
SUPPORTING HYDROLOGIC DATA: ASSUMPTIONS AND DEFINITIONS

Hydrologic information on potential changes in ground and surface water levels and crop water demands associated with regional changes are another component of this assessment. Total precipitation and evaporation estimates from the GISS and GFDL models are used to develop a first approximation to such potential changes in water demand and availability. This section describes how these "first approximations" are developed and applied in the subsequent analyses.

Any analysis of the hydrologic implications of climate change projections from the GCMs requires numerous assumptions. Changes in temperature, evaporation, and precipitation specified for one or two grid boxes extending over a large region may not adequately reflect changes within the region. The relative changes in the climatic values estimated by GCM model grid points were assumed to adequately represent the changes in the region in which they fall. For each grid point, both baseline and $2xCO_2$ values for each climate variable (e.g., rainfall) were estimated. The ratio of the $2xCO_2$ estimate to baseline then provides an indication of the percent change in that particular variable. When more than one grid box falls within a region, a weighted average of grid box values was assigned to the region, based on the proportion of that region's geographical area contained in each grid box. Figure 2 shows the regional boundaries and the GISS and GFDL grid points utilized for the hydrologic regions; note that they do not correspond exactly to the USDA regions in Figure 1. Changes found in the hydrologic regions are adjusted to USDA definitions in the application of the economic model. The hydrologic regions used here do not cover the northeastern quarter of the U.S. because the area accounts for only 2% of irrigated acreage.

These hydrologic assumptions take a broad view of potential changes and, at best, are qualitative generalizations. The economic model incorporates both water requirements, by crop and region, as well as the supply function of water available for irrigation (ground and surface). To estimate changes in water demand for each region in the model, the interaction of changes in evaporation and precipitation was considered. This was done by calculating the ratio of the predicted values in the $2xCO_2$ scenarios to predicted current ($1xCO_2$) values for both evaporation and rainfall. The ratio of these two ratios was then calculated for each grid point to arrive at a net change in crop water requirements. Thus, if evaporation is forecast to increase more (in relative terms) than local rainfall, water requirements (net evapotranspiration) are expected to increase. The data on which these calculations are based are shown in Table 1 for both the GISS and GFDL GCMs.

The other component of interest is irrigation water. Like the estimates of water demand, potential changes in irrigation water should reflect the interaction of forecasts of evaporation and rainfall. If changes in long-term, mean rainfall are expected to be greater than long-term mean evaporation, some "surplus" should result, leading to increased runoff or aquifer storage, shifting out the supply curve of irrigation water. Conversely, if rainfall increases less than evaporation, then a decrease in the supply curve may be expected. Using the estimated ratios for rainfall and evaporation, a ratio of net change in supply was estimated. This ratio was then used to adjust the baseline water supply levels (specified for the period 1981-1983) for each irrigated region in the economic model. For surface water, it is assumed here that irrigation use is a "senior" water right within the applicable water doctrine for each state. Further, it is assumed that those irrigation rights are currently oversubscribed (insufficient water to meet current irrigation rights). Therefore, any increases in streamflow will be allocated to irrigation. Given the timeframe of this analysis, we assume that it is feasible to build new dams to adjust to changes in the timing and quantity of runoff. Also, we assume that reservoir management will adjust to new climatic and streamflow regimes, thus storing water earlier in the winter runoff period. Specific hydrologic assumptions for the GISS and GFDL results are provided in Appendix A.



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Adams

Figure 2. Hydrologic Regions and GCM Grid Points.

Table 1. Climatic Characteristics of Nine Agricultural Regions as [a] Predicted by GISS and GFDL Models under the $2xCO_2$ Scenario

	Evaporation Ratio		Precipitation Ratio[b]		Temperature[c] Increase, C°	
	GISS	GFDL	GISS	GFDL	GISS	GFDL
Northwest	1.166	1.099	1.230	1.027	4.4	4.5
California	1.069	0.970	1.062	1.018	4.9	4.9
Northern Mountain	1.151	1.097	1.180	1.017	4.8	5.5
Southern Mountain	1.062	1.031	1.050	0.986	4.9	5.1
Northern Plains	1.085	0.989	1.070	0.966	4.7	5.9
Southern Plains	0.985	1.018	0.922	0.997	4.4	4.5
Delta	1.024	1.016	1.024	1.003	5.3	4.4
Southeast	1.084	0.927	1.105	0.922	3.5	4.9

[a] These are relative to values predicted by the models for $1xCO_2$.

[b] Net relative changes in supplies of (demands on) water are obtained by taking the ratio of rainfall to evaporation (evaporation to rainfall) for each scenario.

[c] GISS is about 1° more in winter than in summer, GFDL is about 1° less.

CHAPTER 3

RESULTS

The previous section presents some key features of the economic model and its application to this assessment. As discussed, the economic model includes features that reflect the complex set of interactions that underlie economic markets. It also integrates across diverse components of the U.S. agricultural sector to obtain measures of aggregate and regional economic activity, including measures of producer and consumer welfare. As with any model, however, complexity does not guarantee predictive ability. Thus, it is important to establish that this model is a reasonable approximation to the agricultural sector over the period of interest. As described earlier, the economic model is solved as a mathematical programming problem, where the optimal solution is characterized by a set of prices and quantities that maximize the sum of producers' and consumers' surplus. To validate the model, we test these endogenous prices and output for the base years (1981 through 1983) against the actual price and output values for these years for the modeled commodities. Successful validation provides one indication that the model is appropriate for evaluating the effects of climate change on agriculture.

Table 2 provides a comparison of actual average prices and quantities produced with those determined by the model solution at 1981-1983 environmental and economic conditions. As is evident, the prices for all commodities match reasonably well, while the quantities generally understate actual levels by 5 to 10%. Overall then, model prices and quantities for both crop and livestock commodities appear to capture the relative magnitudes of equilibrium prices and quantities observed in the 1981 through 1983 period. It should be stressed, however, that while the model is reasonably "tuned" to 1980s economic and technological conditions, there is no assurance that it will be representative of the agricultural sector in 70 years. Indeed, a quick look at changes in U.S. agriculture over the last 70 years (from 1918 to today) indicates that agriculture in 2060 is likely to be dramatically different from today, even in the absence of global climate change.

EFFECTS OF CROP YIELD//WATER CHANGE ASSUMPTIONS

As is evident from Table 2, the economic model predicts current conditions fairly well. In addition to the prices and quantities reported in Table 2, the model solution contains a number of measures of other economic activity, including total social welfare (both consumers' and producers' surplus), regional crop acreage, regional resource use (water, labor, land), exports, and other items. Together, this array of economic "indicators" for the 1981-1983 period make up the baseline solution of the economic model.

The interesting question in this assessment of global climate change is: How does the economic model solution change as the model is altered to reflect differing climate assumptions? Thus, it is the change in various economic measures reported by the model between the baseline case and the altered model that provides the estimates of the economic effects of climate change. Each change in crop yields and/or water availability will give rise to changes in economic measures in comparison with the baseline case. The direction and magnitude of the changes in economic measures provides an indication of whether the agricultural effects of the underlying climate change are trivial or substantial in terms of social welfare.

The model simulations (analyses) described in this report are derived from the GISS and GFDL 2xCO_2 scenarios. We start first by examining the results of the GISS climate change projections. Results of the GFDL-based climate changes are then presented. Finally, combined climate change and CO_2 effects for both models are discussed.

Table 2. Model Prices and Quantities vs. Actual: 1981-1983

	Prices ($ per unit)		Quantities (millions)	
Commodity	Model	Actual	Model	Actual
Cotton	284.09	281.90	10.25	11.79
Corn	2.68	2.68	6,703.26	6,839.00
Soybeans	5.78	5.65	1,974.86	1,915.00
Wheat	3.58	3.50	2,260.78	2,419.00
Sorghum	2.53	2.50	555.68	730.00
Rice	8.25	8.01	118.96	145.00
Barley	2.24	2.20	431.14	498.00
Oats	1.54	1.67	509.56	526.00
Silage	21.95	n.a.	48.02	n.a.
Hay	65.64	65.76	77.58	82.00
Milk	13.39	13.65	1,288.61	1,359.80
Pork	169.24	165.90	139.38	151.70
Fed beef	232.27	239.70	135.81	156.25
Nonfed beef	131.99	145.15	87.60	78.37

Prices for all crops are dollars per bushel, except for cotton ($ per 480 pound bale), rice ($ per hundredweight), and silage and hay ($ per ton). Meat prices are $ per cwt. and are average retail prices for finished meat products.

Sources: USDA, ERS, Statistical Bulletin No. 715, Washington, D.C.
USDA, Agricultural Statistics, 1984. Washington, D.C.

GISS RESULTS

The specific GISS climate change analyses are defined in Table 3. These consist of the baseline case (1981-1983) and four analyses that reflect various combinations of crop yield changes, and water demand and supply levels. As described in the table, the range of potential climate change effects increases across the various analyses, from only three crops and no water changes in Analysis 1 to assumed changes in all crop yields as well as water demand and supply in Analysis 4.

The first points of comparison among these climate analyses and the base solution are the measures of direct economic welfare: producers' and consumers' surplus. Table 4 reports the changes in economic surplus for consumers, producers, and the total for each analysis. The right-most column is the most important for this discussion, as it provides evidence of the total per annum change in welfare from these various changes in yields and water demand. The negative economic effects increase as the range of potential effects is expanded, from approximately $3.5 billion for only three crops to $5.9 billion when all crops are assumed to experience climate change effects. At the aggregate level, the economic effects of water change assumptions are small in comparison to the yield effects. This relatively small effect of the water change is due to several factors, including (1) irrigation expenses are only a modest portion of total cost of producing the modeled crops, and (2) there is a balancing of increases in both supplies of and demands for water in most regions.

The four analyses reported in Table 4 reflect increasing magnitudes of yield and water changes. As noted earlier, Analysis 1 uses actual crop yield estimates from the CERES and SOYGRO models for corn, wheat, and soybeans. No changes in crop yields for other crops are included. While this analysis may be viewed as more "defensible" because it reflects only crop yield changes predicted by plant models for each crop, it is not realistic in terms of national level economic modeling. The reason is simple: by not changing other crop yields in the model, one is implicitly assuming no yield effects from climate change on these crops. The economic implication of this the base case. In Analysis 2, the production of corn, wheat, and soybeans is reduced, but the acreage and production of all other crops increase. Analyses 4, while involving a surrogate response for all other crops, does present a more realistic picture of the process likely to occur under climate change; that is, all crops are likely to be affected, some more than others. As indicated in Table 5, production of most crops is now reduced.

Table 5 reflects another feature of the economic modeling process of potential importance. Specifically, economic adjustments undertaken by producers e.g., crop substitution or substitution of summer fallow, can often mitigate initial yield reductions due to environmental change. In Analysis 4, the net reductions in corn, wheat, and soybean production are 12, 10, and 12%, respectively. However, the average yield losses predicted by the plant models and used in the analysis are approximately 20% for each crop. Thus, the production consequences of these yield losses are partially mitigated by the economic adjustments included in the economic model, including a relative expansion of irrigated production.

The distributional effects of these yield and water changes are quite distinct as almost all the aggregate loss is borne by consumers, while producers (in the aggregate) experience relatively trivial losses or may gain in welfare (net income). This is due to the generally inelastic nature of agricultural commodity demand, so that when crop yields (and production) are reduced, there is a correspondingly greater increase in price. This does not mean that all producers are unaffected, however, as producers of some commodities (e.g., livestock producers who pay higher prices for feed grains) or producers in some regions are losers due to the yield changes. Within the consumer groups, losses are also borne disproportionately because foreign consumers (i.e., the export market) typically absorb over half of the consumer losses, although exports make up less than 20% of the aggregate consumers' surplus in the base solution. This loss in consumers' surplus generated in export markets is driven by the crops that experience the greatest production declines, i.e., soybeans, rice, and feed grains. Typically, 50% or more of the production of these commodities moves into export markets.

Table 3. Description of Yields and Water Demand Availability Assumptions Underlying Alternative Economic Analyses

Model Specification	Description
Baseline	The base line case reflects economic, agronomic and environmental conditions for 1981-1983. Yields and water availability specified at actual 1981-1983 levels.
Analysis 1:	
Corn, Wheat and Soybean	Analysis 1 involves yield changes for corn, wheat and soybeans in each of the 63 regions of the economic model, based on predicted crop yield changes from CERES and SOYGRO models.
Analysis 2:	
Corn, Wheat and Soybeans Plus Water Adjustment	Analysis 2 includes the corn, wheat and soybean changes defined above plus changes in irrigation water demand (by crop and region) as well as changes in regional ground and surface water supplies for irrigation.
Analysis 3:	
All Crops	Analysis 3 includes the CERES and SOYGRO estimates for corn, wheat and soybeans plus a yield adjustment for all other crops in the model (cotton, barley, rice, sorghum, oats and hay) equal to the average change of corn, wheat, and soybeans for each region.
Analysis 4:	
All Crops Plus Water Adjustment	Same as Analysis 3 but with the addition of water demand and availability adjustments defined in Analysis 2.

Table 4. Aggregate Economic Effects of GISS $2xCO_2$ Global Climate Change on U.S. Agriculture, in 1982 Dollars

Yield/Water Assumptions	Economic Surplus			Change in Surplus (from Base)		
	Consumers	Producers	Total	Consumers	Producers	Total
	($ billion)			($ billion)		
Base Model	77.318	17.259	94.577	---	---	---
Analysis 1	73.990	17.191	91.181	-3.328	-.068	-3.386
Analysis 2	73.688	17.417	91.106	-3.630	+.158	-3.471
Analysis 3	70.627	18.370	88.997	-6.691	+1.111	-5.580
Analysis 4	70.009	18.715	88.724	-7.309	+1.456	-5.853

Table 5. Aggregate U.S. Crop Production: Comparison of Base and GISS Analyses 2 and 4

Crop	Unit	Base	Analysis 2	% Change	Analysis 4	% Change
		(million units)			(million units)	
Cotton	Bales	10.25	10.20	0	9.57	- 7
Corn	Bushels	6,703.26	5,724.47	-15	5,883.90	-12
Soybeans	Bushels	1,974.86	1,736.99	-12	1,743.02	-12
Wheat	Bushels	2,257.48	2,066.68	- 8	2,036.42	-10
Sorghum	Bushels	555.68	657.15	+19	437.30	-21
Rice	Cwt.	118.96	112.88	- 5	104.01	-13
Barley	Bushels	431.14	458.81	+ 6	427.51	- 1
Oats	Bushels	509.56	525.94	+ 3	492.83	- 3
Hay	Tons	77.58	86.45	+11	78.55	+ 1

It should be stressed here that while the economic model includes excess demand relationships for the major export commodities, changes in consumers' surplus in this assessment are generated only by changes in U.S. production. Hence, any changes in production in the rest of the world due to climate change are not explicitly accounted for in the analysis. If production areas outside the U.S. experience yield declines of the magnitudes suggested by the GISS or GFDL scenarios, then the losses in foreign consumers' surplus reported in this analysis will understate such impacts.

In addition to changes in aggregate economic welfare (as measured by producers' and consumers' surplus), changes in climate may impose differential effects on a regional basis. To assess projected regional effects of long-term climate change, Table 6 presents a comparison of two regional indices, total land use and gross revenue, for the base case and Analysis 4.

Analysis 4 is selected for reasons described above -- it includes the most complete combination of crop changes and adjustment processes. As can be seen from Table 2, some regions increase total land use devoted to model crops, such as the Lake States, Corn Belt, Mountain, and Pacific states, while others, such as Appalachia, the Delta, and Southern Plains, experience reductions. This northward and westward shift in land use is due to the relative advantage of some regions with respect to the predicted crop yield, water supply, and demand changes, and the increasing relative advantage of irrigated production. Overall, there is a small net reduction in total cropped acreage. Similarly, gross revenues for some regions increase, while others experience slight decreases. Revenue changes do not always directly mirror changes in acreage (or economic welfare) because the mix of crops varies by region and because inelastic demands can mitigate against acreage reductions, as evidenced by the Southern Plains, which has reduced acreage but increased gross revenue.

A final feature of the GISS analyses concerns changes in irrigated acreage. Changes in precipitation and temperatures under doubled CO_2 tend to favor irrigated crop production relative to dryland activities. Also, the rising commodity prices that result from general reductions in total output enhance the feasibility of irrigation activities, particularly those associated with groundwater use. As a result of these factors, there is an increase in irrigated crop acreage in most regions of the model, as shown in Table 7. The largest increases occur in the Northern (+29%) and Southern Plains (+28%). Overall, irrigated acreage increases by about 5 million acres or 11% from 1981-83 levels. Such an expansion could only be accommodated with increased overdraft of some aquifers and a large investment in irrigation capital. The long-term feasibility of such overdrafts to accommodate irrigation is open to question unless gains in water use efficiency are achieved.

SENSITIVITY ANALYSES

The preceding four analyses represent midpoint or "best guess" assumptions concerning crop yields and water demand and availability. The economic consequences of the midpoint assumptions underlying Analysis 4 imply a possible loss in social welfare of approximately $6 billion (1982 dollars). However, the errors inherent in these assumptions are considerable. It is reasonable, then, to inquire as to how errors in these "best guess" assumptions may affect the economic estimates. The stability of such midpoint economic analyses is typically tested by sensitivity analyses. In this case, the sensitivity of the midpoint economic estimates resulting from Analysis 4 is tested against more extreme changes in yield/water assumptions.

For this sensitivity analysis, we focus on uncertainties in (1) crop yield assumptions, and (2) water change assumptions. Within each general category of uncertainty, some possible upper and lower limits can be defined by looking at standard deviations or other measures of variability. Table 8 provides a description of four sensitivity analyses that represent alternative crop yield, water demand, and water availability characterizations. These four are obviously a small subset of possible combinations of these uncertainty factors. They do, however, imply a wide range of climatic conditions and, hence, may "bound" the economic effects of yield and water manifestations of climate change.

Table 6. Regional Land Use and Gross Revenue Values; Comparison of Baseline and GISS Analysis 4

Region	Land Use			Revenue		
	Base	Analysis 4	Change	Base	Analysis 4	Change
	(million acres)			($ billion)		
Northeast	3.956	2.331	-1.625	0.928	0.745	-0.183
Lake States	33.786	34.840	+1.054	7.430	8.149	+0.719
Corn Belt	95.457	97.259	+1.802	23.636	23.073	-0.563
North Plains	101.684	101.592	-0.092	9.534	10.208	+0.674
Appalachia	15.583	14.096	-1.487	4.291	4.086	-0.205
Southeast	12.513	11.512	-1.001	3.541	3.057	-0.484
Delta States	19.876	17.677	-2.199	4.705	4.511	-0.194
Southern Plains	54.709	42.609	-12.100	9.543	12.925	+3.382
Mountain	21.667	22.739	+1.072	6.559	6.632	+0.073
Pacific	9.671	11.427	+1.756	3.891	5.110	+1.219
Total	368.902	356.142	-12.760	74.053	78.496	+4.438

Table 7. Regional Irrigated Acreage: Comparison of Base and GISS Analysis 4

Region	Base Case Acreage	GISS Analysis 4 Acreage	Change from Base	Percent Change
		(millions)		
Northern Plains	10.389	13.395	+3.006	+29
Southeast	1.715	1.968	+ .253	+15
Delta	3.087	3.597	+ .510	+17
Southern Plains	5.318	6.888	+1.520	+28
Mountains	16.139	15.629	- .510	- 3
Pacific	7.738	7.941	+ .203	+ 3
Total	44.387	49.419	+5.032	+11

The results of the four sensitivity analyses are presented in Table 9. For comparison purposes, changes as measured against both the base case and Analysis 4 are provided. The latter information implies a set of bounds around the assumed midpoint estimates for crop yield and water demand changes.

A sensitivity analysis of primary importance here is the effect of uncertainty in the yield estimates. As noted in Table 8, standard deviations associated with the yield estimates are derived from the CERES and SOYGRO models. The derivation of these standard deviations is described by Rosenzweig in this volume; these deviations are representative of the year-to-year variations in weather conditions. However, they do not necessarily capture the uncertainties inherent in extrapolations to crops of regions other than those analyzed by plant scientists. Table 9 presents the aggregate economic effects of these sensitivity evaluations. Sensitivity Analysis 1 (SA.1) represents the lower bound on yield effects (reduced from yield changes in Analysis 4 by one standard deviation). The aggregate effect of this change is a slight increase in economic welfare from the base case, where producers' gains are about equal to consumers' losses. Producer gains arise from the interaction of the mix of affected crops and the associated inelastic demands for those crops. Consumer losses are due to increases in most commodity prices. SA.2 addresses the case of more extreme yield losses, where midpoint yield reductions used in Analysis 4 are further reduced (by one standard deviation). This leads to a net annual loss in aggregate economic welfare of over $12 billion in 1982 dollars. While producers still experience a moderate gain, consumers' losses are substantial (in excess of $13 billion). The magnitude of yield reductions in this analysis (exceeding 60% for some crops in some regions) causes major adjustments in crop production, including declines of 50% for rice, 25% for soybeans, 22% for corn, and 13% for wheat. This decline in feed grains triggers 10 to 15% reductions in the production of many livestock commodities, including poultry and pork. Over half of the welfare losses accrue to the foreign sector, which is a large consumer of U.S. feed grains.

Water adjustment uncertainties are portrayed in SA.3 and SA.4. The changes in water supplies and demands were adjusted in both an optimistic (SA.3) and pessimistic (SA.4) scenario. These were obtained by increasing (decreasing) rainfall and decreasing (increasing) evaporation by 50% of the change from the base scenario for the optimistic (pessimistic) scenario of each GISS grid point. The optimistic assumption results in a slight reduction in the economic losses suggested by Analysis 4. The pessimistic water scenario increases the losses observed in Analysis 4 by approximately $.6 billion. These relatively modest responses in economic estimates to rather large changes in water assumptions imply that the effects of water demand and availability are not as serious as the direct yield assumption. Regionally, however, these water adjustments portend some major adjustments in land acreage, particularly in the Southern Plains, which potentially faces sharp reductions in total acreage, but an increase in irrigated acreage. Western regions, particularly in the Pacific region, may substantially increase irrigated acreage and share of total U.S. production.

EFFECTS OF CHANGES IN TECHNOLOGY AND WORLD FOOD DEMAND

The midpoint and sensitivity analyses presented above provide an impression of the potential economic effects of long-term climate changes when those changes are imposed on present day (1980's) agriculture. The use of a model calibrated to 1980's conditions to measure such long-term effects is required to keep the assessment problem tractable. However, if CO_2 continues to increase over the next 70 years with its associated climate effects, then the structure of agriculture on which those effects are ultimately imposed will differ from that portrayed in the economic model.

It is useful, then, to consider what the estimated economic effects of climate change might be if some aspects of the agricultural structure were to change. In this section we investigate two fundamental adjustments likely to occur in agriculture over the next 70 years, technological change and changes in U.S. and world demand for agricultural commodities. Technological change, as embedded in such practices as genetic improvements, chemicals, fertilizers, and mechanical power, has historically enabled agriculture to produce more output from the same or less land, labor, and other resources. World food demand increases steadily with population growth. Both forces are likely to continue over the next 70 years.

Table 8. Description of Alternative GISS Sensitivity Analysis Reflecting Crop Yield and Water Demand Uncertainties

Sensitivity Analysis	Description	Source of Data
SA.1	Midpoint crop yield changes decreased by one standard deviation. Applied to Analysis 4 yield adjustments. Results in lower potential yield losses (and absolute gains for some crops) than used in Analysis 4.	Derived from CERES and SOYGRO estimates. Procedure for estimation described in Rosenzweig.
SA.2	Same as SA.1 but yields increased by one standard deviation. Results in greater potential yield reductions than used in Analysis 4.	Same.
SA.3	An optimistic water availability analysis; the changes in water supply are increased by 50% and in water demand are decreased by 50% from GISS grid point ratio estimates.	GISS grid point ratios for evaporation and precipitation.
SA.4	A pessimistic water availability analysis; the changes in water supply are decreased by 50% and in water demand are increased by 50% from GISS grid point ratio estimates.	Same

Table 9. Sensitivity Analyses of GISS Aggregate Economic Effects

Sensitivity Analysis	Change in Economic Surplus from Base			Change in Total Surplus from Analysis 4
	Consumers	Producers	Total	
	($ billion)			($ billion)
Analysis 4	- 7.309	+1.456	- 5.853	---
SA.1	- 1.636	+1.910	+ .276	+6.129
SA.2	-13.048	+ .883	-12.165	-6.312
SA.3	- 6.154	+ .877	- 5.277	+ .576
SA.4	- 7.765	+1.274	- 6.490	- .637

To examine how changes in technology and/or world food demand may alter the economic effects of climate change, we construct four additional analyses. The first two focus only on technology. Of these, one analysis represents potential agricultural yields in the year 2060 in the absence of climate change effects. The other analysis combines the technologically induced increases in yields with the climate change yield reductions used in Analysis 4. Comparing these two analyses provides a measure of the potential economic loss due to climate change. These values are then compared with the 1981-1983 baseline case to estimate absolute changes in social welfare.

The two food demand projection analyses include both changes in technology and food demand. The first represents agriculture in 2060 under increased food demand in the absence of climate change. The second food demand analysis includes changes in climate, as used in Analysis 4, imposed on agriculture under elevated levels of technology and demand. The specific procedures used to develop the technological change and world demand analyses are defined below.

Technology Assumptions

Projecting crop yield 70 years into the future is a speculative enterprise. For example, it is believed that most yield gains observed during the 1955-1987 period occurred because of the rapid increase in pesticides and fertilizer utilization in the 1950s and 1960s, coupled with an increase in irrigation. Increases in fertilizer and pesticide use and in irrigation acreage are unlikely to be major determinants of yield in the future changes. On the other hand, the potential yield enhancements from biotechnology may replicate the average gains experienced over the last three decades.

The projected yield changes were estimated with data on yields for the period 1955 through 1987 (USDA, 1987). Specifically, yield projections were obtained for each crop using the general Box-Cox functional form (Box and Cox, 1964) to transform $y' = f(y,\lambda) = (y^{\lambda}-1)/\lambda$. This transformation contains the linear and log-linear specifications as special cases ($\lambda = 1$ and 0, respectively) without imposing it. Transformed yields were regressed on time, solving for the optimal λ's using maximum likelihood techniques. The resultant yield adjustments are somewhat more regular across crops than using a standard log-linear regression model; they range from 41.2% (0.72%/annum) for cotton to 128.8% (0.72%/annum) for corn. These estimates also were used to project yields for each crop through 2060.

Demand Assumptions

Population is a major factor influencing the demand for agricultural commodities. Since the economic model includes both domestic and foreign consumption, increases in U.S. and world population to 2060 were used to shift domestic and export demands. A projected U.S. population increase of 42% was used to alter domestic demands while a projected world population increase of 114% was used for exports (Merrick). Specifically, the demand curves for all crops in the model were shifted equally to reflect changes in aggregate demand caused by population increases. Elasticities were not changed (owing to a lack of information on which to base such changes), but the price and quantity points that the demand curves pass through were increased. Ideally, crop models in combination with projected climatic variables (as used in this chapter) could be used to model foreign supply and demand, but such information is currently lacking.

Clearly, these adjustments are gross approximations. For example, foreign yields will be affected by changes in technology, cultural practices, and economic organization. In addition, since CO_2 increases are a worldwide phenomenon, climate change will affect foreign as well as domestic producers. Changes in income and tastes will also affect demands. Finally, one should note the changes which have occurred in the last 50-75 years to the composition of demand and supply in the U.S. resulting in differential demand changes across crops. For example, oat production decreased as horsepower was replaced with mechanical power. If similar changes (such as fuel production from corn) occur in the next 70 years, then the uniform demand shifts in this analysis are questionable.

Economic Consequences

The aggregate economic effects of changing technology and world food demand in the context of this climate change assessment are represented in Table 10. The base case and Analysis 4 are provided for purposes of comparison. As the numbers indicate, changing technology (yields) has the potential to sharply change the economic consequences predicted in the model. For example, if crop technology is assumed to continue to evolve in the pattern of the past 30 years, the net social value of agricultural output per annum will rise over 34%, or by over $32 billion. All of this gain accrues to consumers. When climate change is imposed on this "new" agricultural setting, the effect is approximately a $2.1 billion annual loss in potential agricultural production. However, the level of agricultural surplus will still be approximately $30 billion more than in 1983. Thus, technology appears to have a much larger impact on agricultural production than the climate changes predicted by the GISS model, though losses due to these changes still occur.

The last two analyses in Table 10 address the interactions of technological change and food demand assumptions. That is, both technological change and increased demand are imposed on the economic model. Such a combination gives rise to a new "base case" against which the effects of climate change (as imposed on that same new "base case") can be measured. The total economic surplus values in these demand analyses should not be compared with the total surplus values in the Base or Analysis 4 case, given the shift in demand curves (i.e., the interval of integration is not constant across analyses). The important point of comparison is the last column, which records the difference between the new base and the climate change analysis. The effect of climate change under the new demand level is approximately a $6.8 billion economic loss, which consists of $4.7 billion of gains to producers and $11.5 billion in consumers' losses, 63% in the foreign sector. The large foreign component is a function of the large projected increase in world population. Hence, increases in U.S. and world food demand increase the potential adverse economic effects of climate change.

GFDL RESULTS

The GFDL climate model predicts greater temperature and precipitation changes for a doubling of CO_2 than does the GISS model. Thus, it is not surprising that the associated yield changes predicted by the CERES and SOYGRO models are also greater (up to an 80% reduction -- substantially larger yield reductions than were obtained from the GISS climate forecasts). This section reports the economic consequences of those GFDL-induced yield and water changes. The same set of analyses performed on the GISS data is repeated for GFDL.

The first set of GFDL analyses follows the four analyses described in Table 3, i.e., various combinations of crops and water assumptions: these are presented in Table 11. As expected, the aggregate economic consequences associated with each analysis is greater than for GISS. For each case, there is about a fivefold increase in economic losses compared with GISS. Analysis 4 results in annual economic losses of almost $34 billion in 1982 dollars. This is approximately 30% of the 1981-83 gross value of crop and livestock products in the U.S. Even the three crop-no water adjustment analysis (No. 1) results in losses exceeding $24 billion or about 20% of the value of crops and livestock products. Thus, if a doubling of CO_2 were to result in climate changes as portrayed by the GFDL model, the adjustment costs to agriculture would be substantially greater than implied by GISS.

These relatively large economic losses are the consequence of some rather severe changes in crop production. These are depicted in Table 12 for Analysis 4, along with the base levels and those for the comparable GISS case. As is evident, the reductions under GFDL for corn, wheat, and soybeans are from 80 to 300% greater than under the GISS Analysis 4 case. These large reductions in production are responsible for the large consumer losses and producer gains noted in Table 11.

Table 10. Economic Effects of GISS Climate Change with Increased Technology and Food Demand, in 1982 Dollars

Analyses	Total Economic Surplus	Change in Surplus from 1981-83 Base	Change in Surplus Due to Climate Change
		($ billion)	
Base	94.577	---	
Analysis 4	88.724	-5.853	-5.853
Technological Change to 2060	126.987	+32.410	---
Technological Change to 2060 with Climate Change	124.854	+30.277	-2.133
Demand <u>and</u> Technological Change to 2060	191.041	+96.464	---
Demand <u>and</u> Technological Change to 2060 with Climate Change	184.256	+89.679	-6.785

The effects of GFDL climate changes on crop acreage for Analysis 4, along with base and comparable GISS results, are presented in Table 13. Figure 3 provides a graphical display of regional land uses changes relative to the base. In total, both analyses show reductions in total cropped acreage (about 11 million acres or 3% for GISS and 7 million acres or 2% for GFDL). However, the direction of acreage shifts is somewhat different. The general shift for GFDL is slightly more northwesterly than for GISS. Specifically, under GFDL, the Northern Plains experience a major increase in acreage (6%), along with the same general increases in the Pacific (20%) and Mountain (10%) areas that were noted in the GISS case. Unlike the GISS case, however, Corn Belt acreage declines (by 6%). Irrigated acreage expands even more in the GFDL case, by 18 million acres or 40% from 1981-1983 levels, due to the even greater relative advantage of irrigated crop yields (vis-a-vis the base and GISS) compared to dryland and the resulting rise in commodity prices that makes increased groundwater pumping feasible. As in the GISS case, however, it is questionable whether the overdrafting involved in this adjustment could be sustained. Note, however, the impact of the hydrologic assumptions (Analysis 3 vs. 4) is quite small.

Technology and Demand Assumptions

Inclusion of potential changes in technology and demand in the GISS analyses had a substantial effect on possible economic consequences of climate change. These same technology and demand assumptions were also imposed on the GFDL analyses. Specifically, Analysis 4 results derived from GFDL climate change (reported in Table 11) were resolved, allowing for changes in either technology or food demand plus technology. The results of these simulations are presented in Table 14.

The effects of technological change (i.e., a continued increase in crop yields over the next 70 years) increase the base economic level in the model, as expected. When the adverse yield consequences of climate change are combined with the positive yield adjustments associated with the technology assumption, the resultant level of aggregate economic welfare is still greater than the 1981-1983 base value (by $12 billion). However, the climate change effects reduce the potential increase by over $20 billion per annum. Put another way, the adverse effects of climate change are approximately equal to almost 50 years of technological change.

Increases in U.S. and world population will increase the demand for food over the next 70 years. Within the context of the economic model, such increases in demand may be viewed as increasing the value of food to consumers. As a result, the level of aggregate economic activity in the model increases dramatically when demand and technology are changed in the model. The effects of climate change in this new characterization of demand and yields are noted in the last analysis reported in Table 14. In this setting, climate change imposes an economic cost of over $44 billion in 1982 dollars. Thus, increasing food demand will aggravate the economic losses of climate change as recorded under the no technology-no demand case (Analysis 4).

As discussed earlier, the technology-demand assumptions used here are at best gross approximations of these factors. Their inclusion, however, does point to the potential importance of these factors on the magnitude of the climate change effects derived from this (or any) economic model. The results also show that technological change has the potential to mitigate against adverse consequences of environmental stress, like long-term climate adjustments. Climate change does, however, reduce the overall potential welfare of society. Finally, increases in demand will increase the potential costs of adverse climate change.

Direct Effects of CO_2 on Crop Yields

The GISS and GFDL climate changes evaluated in this report are driven by an assumed doubling of CO_2. According to the CERES and SOYGRO model simulations, these climate changes will result in a general depression of crop yields of up to 80%. However, chamber studies with some field crops have documented that increases in CO_2 enhance plant growth and crop productivity. This suggests that the GISS and GFDL crop yield adjustments, which do not include this direct yield-enhancing CO_2 effect, may be overstating the adverse yield consequences of the doubling of CO_2.

Table 11. Aggregate Economic Effects of GFDL 2xCO_2 Global Climate Change on U.S. Agriculture, in 1982 dollars

Yield/Water Assumption	Changes in Economic Surplus		
	Consumers	Producers	Total
		($ billion)	
Analysis 1[a]	-28.720	+4.259	-24.462
Analysis 2	-29.234	+4.717	-24.518
Analysis 3	-37.203	+3.845	-33.358
Analysis 4	-37.461	+3.863	-33.599

[a] Analyses correspond to the definitions provided in Table 3.

Table 12. Aggregate U.S. Crop Production: A comparison of Base, GISS and GFDL Analyses 4

Crop	Unit	Base	GISS	% Change	GFDL	% Change
Cotton	Bales	10.25	9.57	- 7	9.13	-11
Corn	Bushels	6,703.26	5,883.90	-12	3,496.78	-47
Soybeans	Bushels	1,974.86	1,743.02	-12	931.26	-53
Wheat	Bushels	2,257.48	2,036.42	-10	1,850.94	-18
Sorghum	Bushels	555.68	437.30	-21	528.71	- 5
Rice	Cwt	118.96	103.011	- 7	66.55	-44
Barley	Bushels	431.14	427.51	- 1	290.09	-32
Oats	Bushels	509.96	492.83	- 3	383.82	-25
Hay	Tons	77.58	78.57	+ 1	50.76	-35

Table 13. Regional Land Use: A Comparison of Base, GISS and GFDL Analyses 4

Region	Base	GISS Total Land Use	GISS Change from Base	GFDL Total Land Use	GFDL Change from Base
		(mil. acres)	(%)	(mil. acres)	(%)
Northeast	3.956	2.331	-40	3.891	- 2
Lake States	33.786	34.840	+ 3	33.654	0
Corn Belt	95.457	97.259	+ 2	89.560	- 6
Northern Plains	101.684	101.592	0	108.065	+ 6
Appalachia	15.583	14.096	-10	-12.882	-18
Southeast	12.513	11.512	- 8	-11.174	-11
Delta States	19.876	17.677	-11	-16.178	-19
Southern Plains	54.709	42.609	-22	51.392	- 6
Mountain	21.667	22.739	+ 5	23.834	+10
Pacific	9.671	11.427	+19	11.568	+20
Total	368.901	357.083	- 4	358.657	- 2

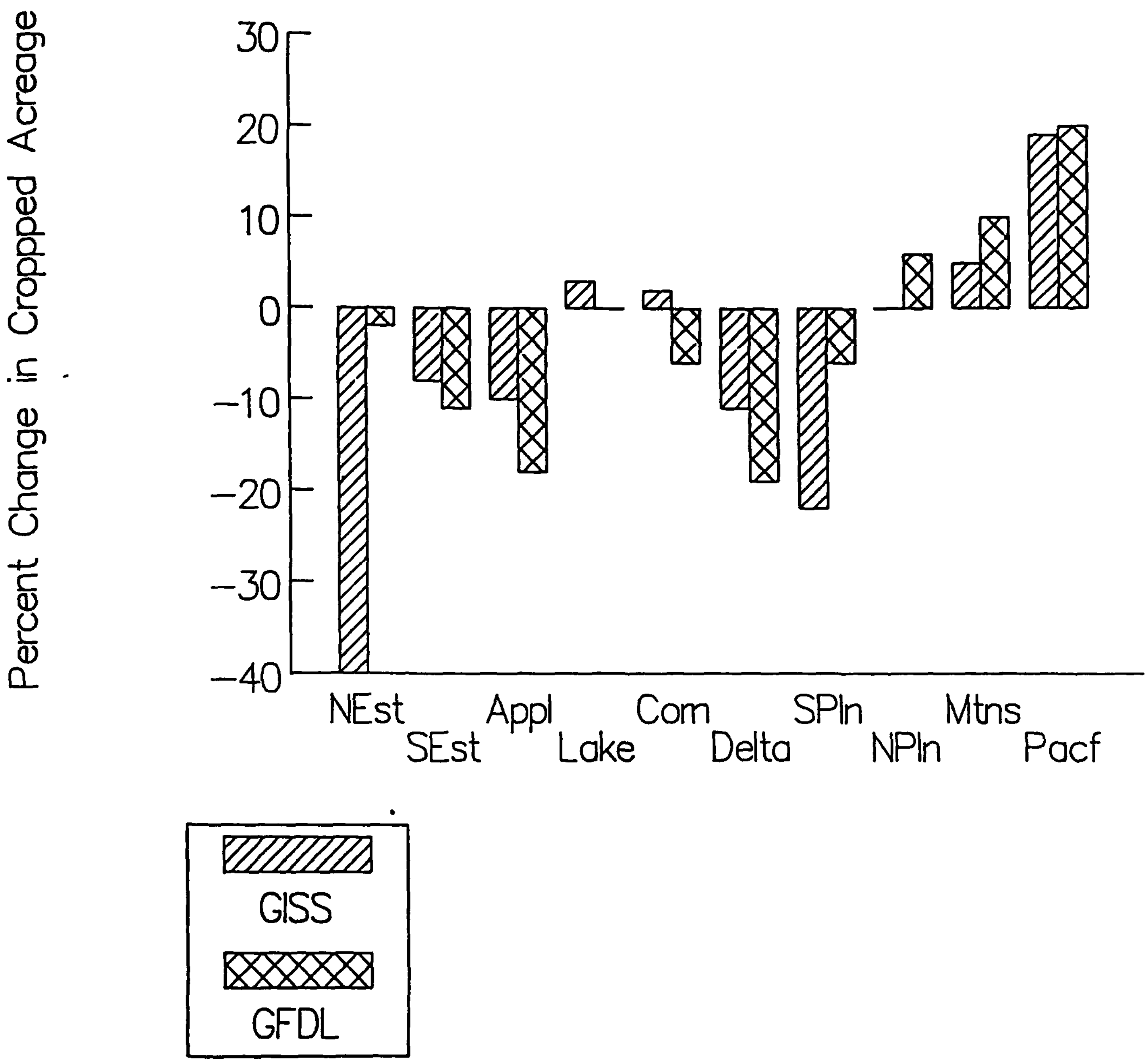

Figure 3. Change in regional land use for Analysis 4, by climate forecast.

Given the potential importance of a direct CO_2 effect on this preliminary analysis of global climate change, an additional set of CERES and SOYGRO analyses was performed that included both climate change and CO_2-induced yield adjustments. The procedures by which these direct effects were included in these models are described in Rosenzweig in this volume. The result of the CO_2 addition was to dramatically alter the yield consequences as originally predicted by the plant models and as used in the preceding analyses. Specifically, for GISS, some crops now realized actual increases in crop yields under the combined climate change-CO_2 effect. For GFDL, the large yield reductions reported earlier were moderated to levels more comparable to the non-CO_2-adjusted GISS yield changes, i.e., from 70 to 80% yield reductions to losses of 20 to 30%. Such upward adjustments in yields would be expected to dampen or even offset the adverse economic consequences reported in Tables 4 through 14.

The economic consequences of combined climate change and CO_2 effects are evaluated for both the GISS and GFDL GCM forecasts. These are reported in Table 15. In addition to the Analyses 4 "midpoint" estimates, Table 15 also presents sensitivity analyses based on yield adjustments of plus or minus one standard deviation around the midpoint case (SA.1 and SA.2, Table 8). These latter evaluations provide an indication of the importance of uncertainties in the CO_2 yield adjustments.

As expected, the inclusion of direct CO_2 effects alters the magnitude (and direction for GISS) of the earlier economic estimates. Specifically, the combined effects of climate change and CO_2 now result in a net increase in economic welfare under the GISS evaluations. For the Analysis 4 midpoint case, the previous loss of approximately $6 billion per annum in 1982 dollars is now a $10 billion gain. Both sensitivity analyses around the GISS midpoint also indicate net gains under the doubled CO_2 environment. For GFDL, the direct effect of CO_2 is to reduce, but not totally offset, the economic losses measured in the climate change-only analyses. In this case, the previous loss estimate is reduced from $33 billion to approximately $10 billion. Under both sensitivity runs, the net economic consequences are still negative.

Although the inclusion of CO_2 adjustments alter the nature and magnitude of aggregate economic consequences, regional shifts in agricultural cropping activity still occur. Table 16 presents the regional acreage adjustments for GISS and GFDL Analyses 4 under the CO_2 effect. Figure 4 displays regional land use changes for GISS and GFDL with and without the direct effects of CO_2. For the GISS analysis, slight increases are observed in the Pacific and Lake States regions (8 and 1%, respectively). The Corn Belt and Northern Plains are relatively unaffected. However, rather severe reductions in acreage are noted in Appalachia (-80%), the Delta (-53%), and the Southeast (-30%). A somewhat similar pattern is observed under GFDL, where the Pacific and Lake states regions each experience increases of 12%. The most severe reductions again occur in the Appalachia (-51%), Southeast (-35%), and Delta (-13%) regions. In relative terms, the combined effects of climate change and CO_2 on regional crop acreage are consistent with the previous regional adjustments, namely a northward and westward shift in crop production. A similar consistency occurs in irrigated acreage response under the combined climate change-direct CO_2 effects. That is, an expansion of irrigated acreage over 1981-1983 levels is observed under both GISS (2 million acres or 5%) and GFDL (17 million acres or 38%). Figure 5 presents changes in irrigated acreage under the GISS and GFDL cases, with and without direct CO_2 effects. While somewhat less than for the non-CO_2 analyses, the GFDL adjustments still suggest a major expansion of irrigated agricultural activity in the U.S.

These findings suggest the importance of the CO_2 adjustments as well as the specific GCM used in the assessment. If CO_2 has positive effects on yields of the magnitude modeled here, then the aggregate production consequences of climate change may not be as severe as presented earlier in this report. However, if the doubling of CO_2 results in climate changes similar to those as suggested by GFDL, then even the mitigating effects of CO_2 are insufficient to prevent the occurrence of substantial losses in economic welfare.

Table 14. Economic Effects of GFDL Climate Change with Increased Technology and Food Demand, in 1982 Dollars

Analysis	Change in Economic Surplus from Base	Change in Economic Surplus Due to Climate Change
Analysis 4	-33.599	-33.599
Technological Change to 2060	+32.822	---
Technological Change to 2060 with Climate Change	+12.008	-20.814
Demand <u>and</u> Technological Change to 2060	+133.815	---
Demand <u>and</u> Technological Change to 2060 with Climate Change	+89.227	-44.588

Table 15. Combined Effects of Direct CO_2 and Climate Change on Agriculture: GISS and GFDL Analyses 4

	Change in Economic Surplus (from Base)		
Model/Assumption	Consumer	Producer	Total
GISS Analyses 4: without CO_2	- 7.309	1.456	- 5.853
GISS Analyses 4: with CO_2	9.354	1.291	10.646
a) Plus One Standard Deviation in Yields	14.199	.598	14.797
a) Minus One Standard Deviation in Yields	3.338	2.321	5.659
GFDL Analyses 4: without CO_2	-37.461	+3.863	-33.599
GDDL Analyses 4: with CO_2	-10.291	.607	- 9.683
a) Plus One Standard Deviation in Yields	- 2.649	- .148	- 2.797
b) Minus One Standard Deviation in Yields	-17.343	- .488	-17.832

Table 16. Regional Land Use: A Comparison of Base, GISS and GFDL Analyses 4 with CO_2 Direct Effects

Region	Base	GISS		GFDL	
		Total Land Use	Change (%)	Total Land Use	Change (%)
	(million acres)			(million acres)	
Northeast	3.956	0.038	-49	3.434	-13
Lake States	33.786	33.923	+ 1	37.188	+10
Corn Belt	95.457	96.985	- 1	89.531	- 6
North Plains	101.684	100.560	- 1	99.543	- 2
Appalachia	15.583	2.818	-80	7.349	-53
Southeast	12.513	8.665	-30	7.832	-37
Delta States	19.876	9.275	-53	16.701	-16
Southern Plains	54.709	43.813	-20	52.213	- 5
Mountain States	21.667	20.439	- 6	21.422	- 1
Pacific States	9.671	10.491	+ 8	10.881	+13
Total	368.902	324.505	-12	346.134	- 6

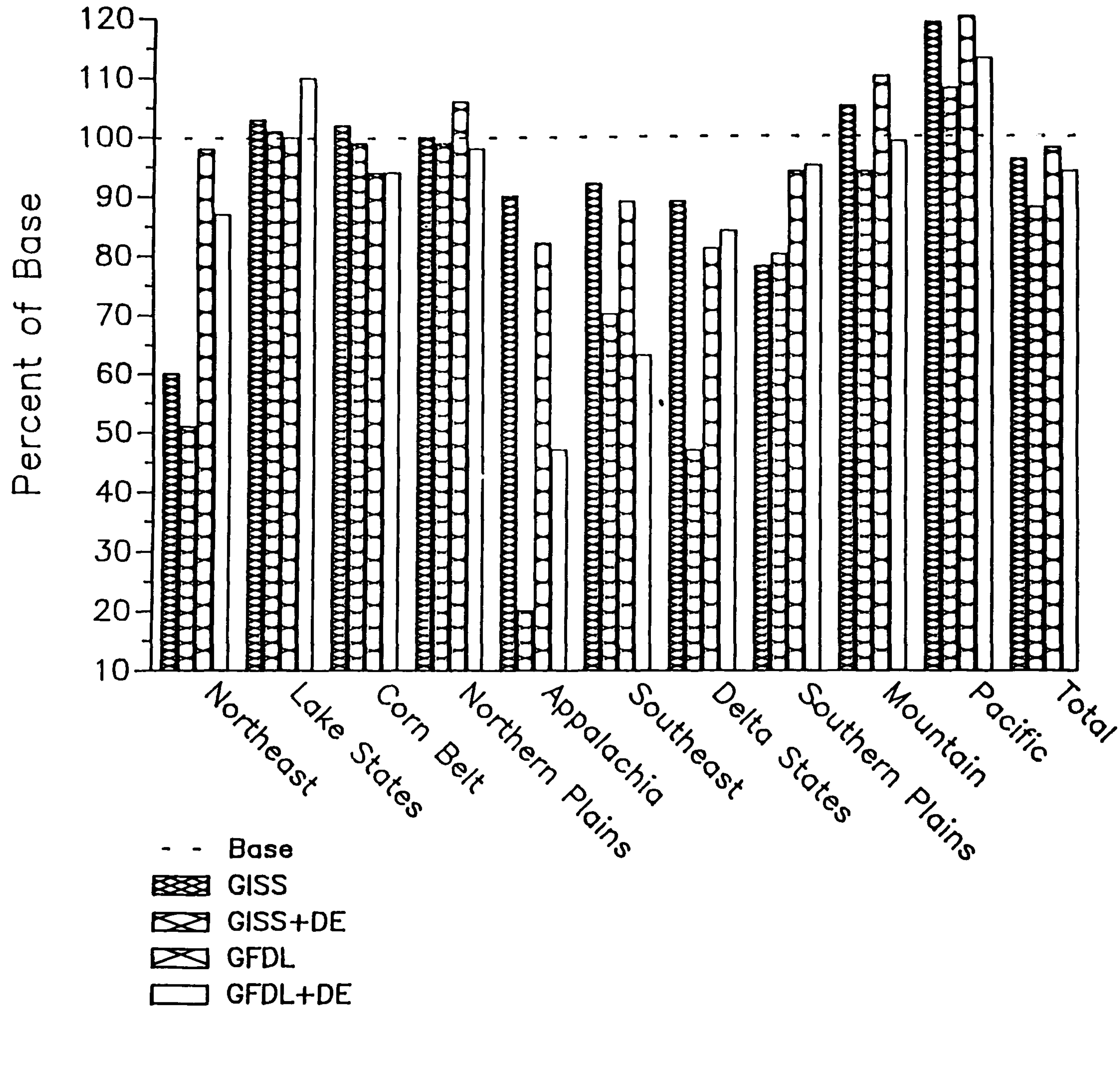

Figure 4. Changes in regional land use: Analysis 4 with and without direct CO_2 effects.

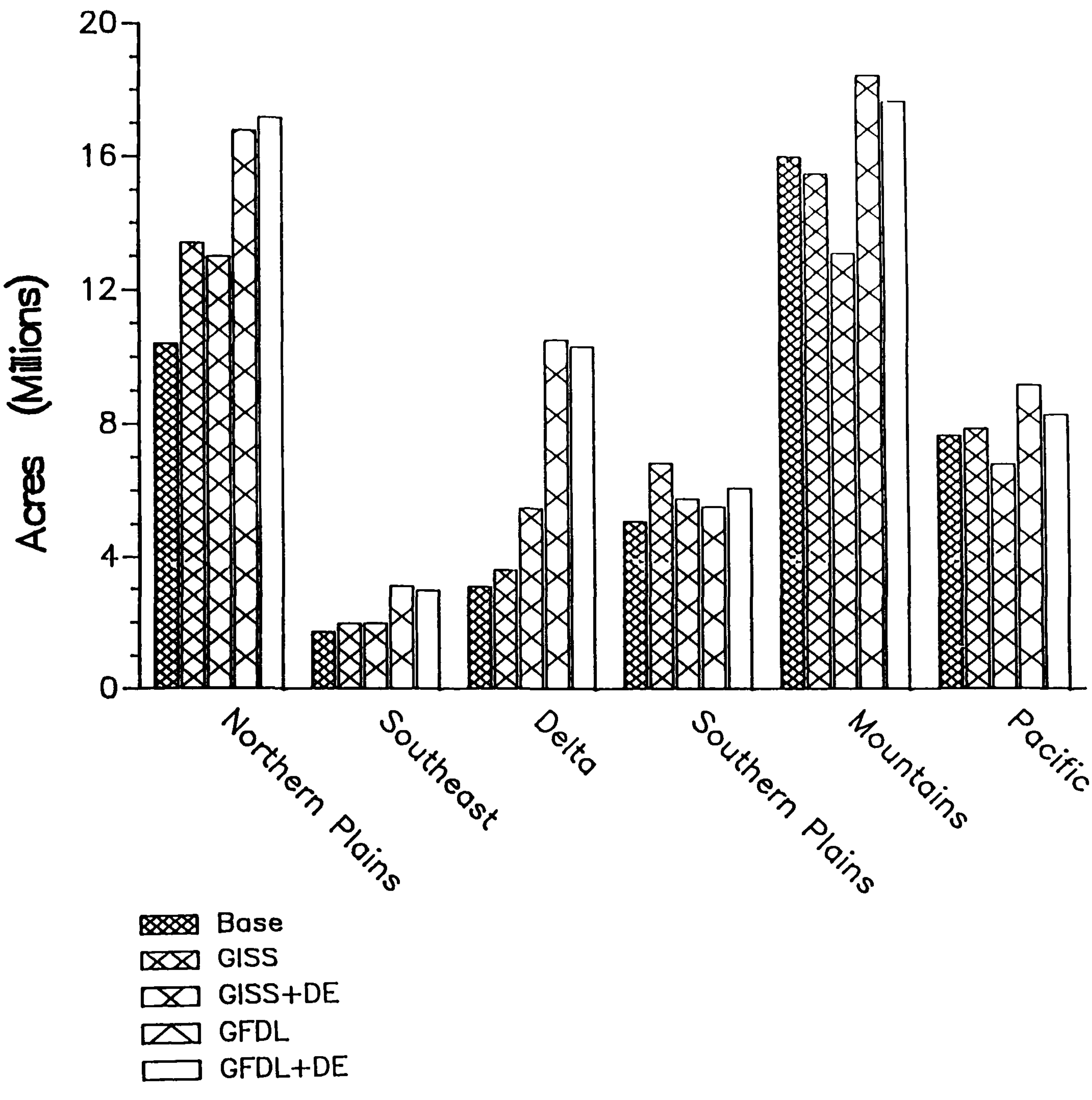

Figure 5. Regional irrigated acreage: Analysis 4 with and without direct CO_2 effects.

CHAPTER 4

IMPLICATIONS AND CONCLUSIONS

The results of the various analyses performed here suggest a range of possible economic effects associated with climate change in agricultural production areas of the U.S. The diverse set of assumptions explored in these analyses (different GCMs, different crop and water assumptions) reflect uncertainties inherent in predicting long-term changes in biological and economic phenomena. This, in turn, gives rise to a set of results that can tell many stories. This section attempts to interpret those results with respect to common themes that emerge. Implications of these changes are also drawn.

As a starting point, one should put the estimated aggregate economic effects into perspective. These aggregate consequences of climate change vary substantially across analyses. Midpoint or Analyses 4 results (in the absence of technology or CO_2 effects) range from approximately 6 to 30 billion 1982 dollars on an annual basis. On a per capita basis, these net surplus losses range from $6 (GISS) to $65 (GFDL) per U.S. citizen. The larger relative losses per capita for GFDL are due to a higher proportion of consumer losses falling on domestic consumers. As noted in the previous discussion, the aggregate loss estimates are from about 5 to 28% of the 1982 value of crop and livestock commodities produced in the U.S.

To put these estimates into a somewhat different perspective, they are also compared to economic effects of some other environmental stresses. For example, the economic consequences of tropospheric ozone on U.S. agriculture are estimated to be about $2 to 3 billion per year in 1982 dollars (Adams et al., 1988). Similarly, the effects of a 15% depletion in the stratospheric ozone column are estimated at $2.5 billion in 1982 dollars. Thus, the effects of a doubling of CO_2 imply economic costs 2 to 10 times greater than some other environmental stresses. With the inclusion of technology assumptions or yield enhancements from CO_2, the magnitude of economic effects is greatly reduced (e.g., to an economic loss about four times greater than the other stresses for the GFDL analysis).

An important policy concern in addressing a major environmental adjustment, such as climate change, is whether that adjustment threatens the food and fiber base of a society. The results of the analyses reported here, even in the most extreme cases (e.g., GISS SA.2 or GFDL Analysis 4), indicate that the productive capacity of agriculture may be reduced by climate change but not to a level that implies any major disruptions to the supply of basic commodities. Domestically, consumers would face slightly to moderately higher prices under some analyses but supplies would be adequate to meet current and projected domestic demand. Exports, however, do experience a major reduction (up to 70% for most exported commodities). Changes in total world food production due to climate change will influence the net effects of these U.S. production changes on the welfare of foreign consumers and producers. Allowing for technological change, or a yield enhancing effect of CO_2, the productive capacity of agriculture will likely be greater in 70 years than it is today, even in the presence of climate change, offsetting most or all of the adverse climate effects. For example, under GISS, both technology and CO_2 direct effects appear capable of offsetting climatic effects. For a GFDL-type of climate change, the picture is not so comforting. Midpoint losses without technology approach 30% of current agricultural value. While technology can offset these losses, continued and substantial improvements in yields are required to realize such an outcome. However, even without major technological gains, it appears the U.S. could still meet domestic needs but with little residual for exports. If the rest of the world experiences similar yield reductions, then the welfare effects on major food importers could be severe.

One relatively unambiguous finding in this assessment is that shifts in U.S. agricultural production patterns are highly likely. Specifically, all analyses show a north or northwest shift in production of major commodities such as wheat, corn, and soybeans. This has implications for regional economies, with major changes in the capital structure of agriculture and likely increases in input demands for areas of expanded crop acreage and corresponding reductions in regions experiencing acreage declines. The changes in capital requirements will be of particular importance if irrigated acreage expands as predicted in these analyses. For many rural communities, this may further weaken an economic base already under pressure from long-term structural changes under way in U.S. agriculture.

Shifts in crop production also imply demands or pressure on environmental and natural resources, including water quantity and quality, wetlands, soil, fish and wildlife, and other resources. For example, a northward shift in corn and soybean production (through the Dakotas to southwestern Canada) may exacerbate the loss of critical prairie wetlands by making drainage and conversion to crop production more profitable. A westward shift may increase wind and water erosion of fragile soils. The substantial (2 to 18 million acres) increase in irrigated acreage suggested in all analyses enhances the likelihood of ground and surface water pollution. Recent evidence concerning selenium poisoning in California indicates that long-term irrigation poses potential environmental problems. Obtaining water for increased irrigation also implies more and larger reservoirs, which in turn implies greater pressure to develop remaining wild or scenic rivers. Groundwater overdrafts would likely be required to accomplish this expansion. The current analyses do not address the issues of whether the physical and institutional changes required to accommodate such an increase in irrigated acreage are feasible.

Overall, the analyses reported here indicate possible directions of economic effects arising from climate change. The directions of these economic changes are generally consistent with expectations. The relative magnitudes of the economic estimates, which vary substantially between GISS and GFDL, may also suggest whether the agricultural consequences of climate change are important from a policy perspective. Both GCMs imply adjustments within agriculture, with GFDL implying some major adjustment problems, particularly for consumers and specific regions and resources. Another purpose of this preliminary assessment, however, is to indicate areas for future research; for example, a large potential effect may merit additional research to confirm such a finding.

Given the crudeness of the data used to develop these analyses, and the wide range of results elicited from alternative treatment of these data, a longer term research agenda seems warranted. An area in need of improvement is the quality of the crop yield data used here. The extent of crop coverage, both genetically and geographically, needs expansion. Only three crops are modeled in this current agricultural effects program and then for only a limited number of sites or regions. Possible changes in genetic materials (i.e., cultivars) may also be as important as climate changes. Such cultivar switching was not included in the plant science modeling, suggesting that the yield effects may be overstated. Finally, the belated inclusion of CO_2 effects in the CERES and SOYGRO analyses, while a worthwhile effort in terms of providing a more complete treatment of the likely consequences of climate change on agriculture, needs further refinement. The availability and adaptability of the CERES and SOYGRO models could be further exploited within a relatively short period of time to improve the quality of the crop yield estimates.

Measures of the hydrologic consequences of climate change require much more refinement. While the analyses in this assessment attempted to incorporate some of these potential effects, it is not clear that the <u>signs</u> of the adjustments are correct, let alone the <u>magnitudes</u>. Cooperative research involving hydrologists, meteorologists, agriculturalists, economists, lawyers, and others is needed to define how climate change will influence the long-term physical and institutional arrangements concerning irrigation.

Economic models in general do not forecast well when projecting over long time periods. The economic model used here is a comparative static, spatial equilibrium model keyed to the 1980s. It is thus not intended to address some of the dynamic or long-term effects inherent in climate change over 70 years. For example, each region in the model uses 1980s cropping mixes and cultivars, which understates potential mitigation adjustments in the long term. This implies that the economic effects may be biased upwards. Also, while we attempted to include two important forces in shaping agriculture, changing technology and demand, the accuracy of these adjustments is questionable. These specific adjustments can be refined but will not address the problem of using models with fixed production (i.e., technological) relationships to measure long-term effects. Improvements in model capabilities are possible, however, if one is willing to sacrifice the level of detail in the assessment. The tradeoff between more accurate modeling of dynamic processes and loss of detail needs to be weighed in terms of how the economic input may affect the regulatory process.

Finally, the quality of the GCM forecasts that drive all of the above is critical. While the models are "state of the art," the quality of the forecasts appears to deteriorate from the macro to the micro scale (grid box level), where predictions seem highly variable within each model. Across the two GCMs, great differences in climatic consequences are observed, with associated differences in economic effects. Therefore, improvements in GCM performance appear to be a high priority, particularly if agencies are going to use forecasts of such models to assess impacts on a relatively small geographical scale, such as at the state or regional level, as in this economic analysis.

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APPENDIX A

HYDROLOGIC CHARACTERISTICS AND ASSUMPTIONS

In the six regions west of the Mississippi River, runoff water is typically routed over hundreds to thousands of km. The mountainous regions of the western states supply most of the irrigation water used in arable land. In particular, changes which take place in the vast chain of the Rocky Mountains influence water supply more than do changes in local precipitation.

In the GISS scenario, regions east of the Mississippi are likely to experience a slight to significant increase in water available for irrigation. The Southern Plains and California Region are both expected to feel a significant decrease in water available from within the region, while the Northern Plains and Southern Mountain Regions are likely to have no change to a slight decrease in available water. The Northern Mountain and Northwest Regions are assumed to have slight to significant increases in available water.

The climate changes modeled by GFDL indicate a warmer climate with less rainfall east of the Rocky Mountains, more evaporation and switch in precipitation from summer to winter. Because of the warmer temperatures, less of the winter precipitation may be available during the growing season. As a result, water available for irrigation decreases in all areas except California.

Northwest Region

This region currently has the highest annual precipitation of any of the regions. A majority of the precipitation falls as rain, but the snowpack accumulation above 900m elevation is a crucial source of irrigation for the region. Large reservoirs on the Columbia and Snake Rivers receive most of their water from snowmelt from the Rocky Mountains in Idaho, Montana and from as much as 350 km into Canada. Irrigation is primarily from surface water stored in reservoirs, but some groundwater is pumped from shallow aquifers.

GISS

The expected increase in summer temperature of 4.2°C is shown to be accompanied by an increase in annual precipitation of 23 percent. The additional water is likely to make it possible to extend the irrigation season to correspond with the longer growing season. As some of the increased precipitation will occur in the growing season, drawdown of reservoirs will not be significantly affected.

There will be an increase in the proportion of precipitation as rain and the area covered by a snowpack accumulation will be reduced. This means that the reservoirs will begin filling earlier in the winter and streamflow should not be as drastically reduced in summer. Groundwater aquifers should be fully recharged as a result of the increased summer and winter precipitation. Assuming reservoir capacity is sufficient, additional water is likely to be made available for irrigation. Specifically, we assume that the new equili- brium level will increase by approximately 7 percent. This is the largest increase in runoff projected for any area in the analysis. Water demand will be reduced by approximately the same percent.

GFDL

The modest increase in rainfall of 1.7% will not be sufficient to offset the large (10%) increase in evaporation. Some increase in runoff from the Rockies and an earlier start of the growing season may enable better use of the remaining water, especially if the earlier runoff can be captured in the Columbia-Snake reservoir system. Otherwise, the drawdown on the reservoirs may be rather severe, increasing pumping costs and decreasing irrigated acreage.

California Region

The major agricultural activity in California is located in the southern half of the state. These irrigated lands typically receive little precipitation. Statewide, rainfall ranges from as little as 250mm to about 1200mm. A 70- to 100-day dry season is common. Water for irrigation is supplied by reservoirs in the northern, wetter part of the state, fed by snowmelt from large snow accumulations in the Sierra Nevada, Siskiyou and Klamath Mountains. The Colorado River is also a major source of water for the southern desert region of Imperial County which gains its flow from snowmelt in the Rocky Mountains. This region may be unique in that the major sources of water for irrigation may be over a 1000 km away from the point of application. Some groundwater is pumped from both shallow and deep aquifers probably recharged by water from the Sierra Nevada Mountains.

GISS

Snowmelt will occur a few weeks earlier and a slightly higher proportion of precipitation as rainfall will mean reservoirs will fill earlier, helping to accommodate a somewhat earlier start of the irrigation season. There will be an irrigation water deficit within the Imperial Valley region of California which will be supplied by the increase in precipitation in the Rocky Mountains.

The GISS grid point in southern California shows an expected increase in evapotranspiration of 6.9 percent. There is also an apparent decrease in precipitation by three percent. Thus irrigation demands may increase by approximately ten percent. There is not likely to be any increase in length of the irrigation season. However, most of the water for irrigation in California comes from mountainous regions far from the agricultural lands. The expected increase in annual precipitation and somewhat higher expected increases in summer precipitation in the northern mountainous areas are likely to provide for a slight increase in irrigation water of 2 percent. Similar increases in the Rocky Mountains will increase Colorado River flow, with slight increases in California's appropriations.

GFDL

With evaporation decreasing by 3% and rainfall increasing by 1.8% California does better hydrologically than any other region under the GFDL model prediction. In addition, increased rainfall in the Rockies and extreme northern California should more than counter any decrease in the snow pack caused by warmer termperatures. The already long growing season should be increased further, given the availability of additional irrigation water.

Northern Mountain Region

This region experiences a cold, continental climate only slightly modified by marine air masses from the Pacific Ocean. The climate is strongly influenced by air circulation over Canada. There is a relatively short frost-free period. Cold winters are followed by cool to warm summers. Extreme fluctuation in streamflows occur between the peak snowmelt season
and the summer low flows. Most irrigation water is drawn from reservoirs but a significant amount is pumped from shallow aquifers assumed to be recharged by subsurface flows from the Rockies.

GISS

The potential for evaporation is expected to increase by 15 percent under the GISS $2xCO_2$ scenario and annual precipitation is expected to increase by 18 percent. A slightly higher proportion will come in summer and a significant increase in winter precipitation will come as rainfall. This more uniform distribution should facilitate the management of water for irrigation. With a longer frost-free season, sites not now suitable for agriculture will be within an acceptable climate for some crops.

The snowpack will accumulate at a higher elevation and will on average be deeper where it does accumulate. The net effect of the climatic change will be an increase in water available for irrigation, both within and outside of the region. The specific assumption here is for a 3 percent increase in available irrigation water. Water demand by crops in this region will decrease by 2 percent.

GFDL

As in the Northwest, modest increases in precipitation (1.7%) will not be sufficient to overcome a large (9.7%) increase in evaporation. In the western portion this will not be the case; but the eastern region with an increase in winter precipitation will not compensate for a large drop in the summer. However, both portions will benefit by a substantial lengthening in the growing season occasioned by a temperature 5 to 7° warmer. Effective capture of earlier runoff will be important as net water availability decreases by 7.9%.

Southern Mountain Region

While this region experiences a fairly cold winter, it differs from the Northern Mountain Region by having a hot dry summer. The area of most intensive agricultural activity is located in the southern part of the region and is characterized as typical of Sonoran climates. Precipitation ranges from under 300mm to 500mm per year. Extremely low humidities prevail much of the year.

Large scale agriculture is sustained primarily by impoundment and diversion of water from the Colorado River. Some water is provided by the Gila River and by pumping from deep aquifers. The southeastern portion of the region is supplied by the Rio Grande River which is in turn primarily fed by snowmelt from the southern Rockies. Even at the higher elevations in this region, the precipitation is typically under 750mm. Groundwater is thought to be primarily from a slow process of recharge from water originating in the southern Rockies.

GISS

The GISS 2xCO_2 scenario for this region is a 6.2 percent increase in evaporation and a 5 percent increase in precipitation. If the increase in precipitation is gained mostly in the summer it may be effective in offsetting most of the increase in evaporation. However, the precipitation in this region is generally so low and erratic that a 5 percent increase may not be of much use. A 6.2 percent increase in evaporation will need to be made up by increased import of water from the Northern Mountain Region.

The runoff from the 18 percent increase in precipitation in the Northern Mountain Region, if not claimed by other water rights, should be able to supply the need. Thus, in this study, it is assumed that there is a modest one percent increase in available water in this region. Water demand, however, will be increased by approximately 2 percent.

GFDL

As for the northern monitor area, under GFDL the eastern and western portions of the southern mountains will see different precipitation patterns. The increased rainfall in the western half will compensate for most of the increased evaporation, while the substantial rainfall decline in the east is not enough to offset a modest decline in evaporation. Sustained increases in groundwater pumping are not feasible and the area will be adversely affected by the net increase in water demand at almost 53.

Adams

Northern Plains Region

This region experiences a cold, continental climate with a relatively short frost-free season. Winters are dominated by a polar air mass circulating from the Canadian shield. Cold winters are followed by a relatively short growing season, but May, June and July are the wettest months of the year. Much of the agricultural production is dependent on the spring and summer rainfall. It also depends on winter snowfall and the practices of water conservation (snow trap, summerfallow, etc.).

Where irrigated agriculture is practiced, the water is primarily supplied from reservoirs fed by rivers originating in the Rocky Mountains. The headwaters of the Missouri, North Platte and Arkansas Rivers all originate from high elevation snow fields. Groundwater is also used where aquifers are recharged by deep percolation from the east slopes of the Rockies.

GISS

This region is expected to experience an 8.5 percent increase in evaporation. This is roughly equivalent to 65-70mm annual increase in water consumption. This is partially offset by a 7 percent increase in precipitation, the majority of which will come in the growing season. However, it is likely that a part of the increased evaporation will have to be made up from water originating in the Rocky Mountains which presently feeds the reservoirs of this region. Allowing for a moderate increase in run-off from the Rockies, we assume a one percent increase in available water, but a 3 percent increase in water demand.

GFDL

Under the GFDL predictions, both precipitation (-3.5%) and evaporation (-1%) decline while the temperature increases by about 6°C. This results in a net decrease in water availability of 2.4%, which will be exacerbated by the shift from summer to winter precipitation. However, a longer growing season may make use of winter precipitation more efficiently and plants may mature before available moisture disappears.

Southern Plains Region

This region is strongly influenced by weather patterns generated in the Gulf of Mexico, but is in a transition from the continental steppe climate. Short, cool winters are followed by long hot summers. Precipitation is dominated by rainfall which ranges from 250mm in the northwest corner to about 1500mm in the southeast portion of the region. The precipitation is generally well distributed over all months of the year.

Irrigation water in the northern portion of this region is largely from impoundments on the Canadian and Red Rivers which rise in the Southern Rockies. The southwest portion of the region is supplied by the Rio Grande River which also drains from the southern Rockies. Extensive use of groundwater is made from deep aquifers thought to be partially recharged by water from the southern Rockies.

GISS

The GISS forecast for this region is for it to be warmer by 3.9°C but that evaporation will decrease by about 1.5 percent. Winter temperatures are expected to increase more than summer temperatures which may help to moderate the effect of the overall temperature increase on crop water usage. The reduction in precipitation, however, is estimated to be about 8 percent. It appears that some water deficit will occur, particularly in the later part of the growing season. This will have to be drawn from the increases in precipitation in the mountainous areas to the northwest. Given that the southern Rockies are not likely to show any increase in run-off, a 3 percent drop in available irrigation water, coupled with a 5 percent increase in water demand is assumed.

GFDL

As with the southern mountains, the wet, dry high plains region will see a decrease in rainfall, especially during the growing season. The humid eastern portion is not similarly affected. Hence, the region's modest decrease in available water of 2% will not be evenly distributed. Since the eastern Rockies will be drier, reservoirs and aquifers which supply irrigation demands will not be refilled by winter precipitation.

Delta Region

Arkansas, Mississippi and Louisiana make up this region. The area has a warm, temperate rainy climate which receives from 1000 to 2000mm of rainfall per year. The rainfall is quite consistent from year-to-year and well distributed over all months of the year. Numerous major streams and rivers bisect or border this region. Both surface water and shallow aquifers are used in irrigation. High summer humidities are common throughout this region.

GISS

The GISS model shows that the Delta Region will be significantly warmer but that evaporation increases only by 2.4 percent. Precipitation is predicted to increase by 2 percent. As precipitation is a larger component in this region than is evaporation, the overall effect could be from none to a slight increase in water available for irrigation. Specifically, we assume a one percent increase in run-off but a 2 percent decline in water demand.

GFDL

The GFDL projections are similar to the GISS model (rainfall +.2%, evaporation +1.6%, temperature +4.5%) except a shift from summer to winter rainfall may increase irrigation demands and require more storage capacity. Drought conditions may occur with greater frequency; increasing the efficiency of irrigation. The high levels of moisture should support this transition.

South East Region

The warm, temperate rainy climate found in this region has precipitation amounts ranging from 1000 to 1500mm. Rainfall is nearly equally distributed throughout the year. Irrigation is largely from diversion from the consistent streamflow, but shallow aquifers are also utilized. There is a remarkably small difference in winter to summer temperatures, averaging around 21°C, plus or minus 5°C. High humidity prevails through several months of the year.

GISS

This region is expected to have an 8.4 percent increase in evaporation and a 12 percent increase in annual precipitation. It appears that this region will experience a warmer, wetter climate, with the change in precipitation closely balancing the increased evaporation. We assume the interaction of evaporation and precipitation changes translate into a 3 percent increase in water availability and a 4 percent decrease in water demand.

Adams

GFDL

Both evaporation and rainfall are assumed to decrease by 7 to 8% with net irrigation supply decreasing marginally. As in the Delta, increased temperatures (+5°C) and change in the rainfall pattern from summer to winter will increase the efficiency of irrigation and necessitate more seasonal storage of runoffs.

APPENDIX B

AN OVERVIEW OF THE ECONOMIC MODEL

Economists devote considerable effort to assessing the consequences of changes in policy and technology on the agricultural sector. Assessments of the benefits of such change are performed at both the farm and sectoral levels. There are, potentially, major differences in the results of such evaluations depending upon the level at which the evaluations are performed. The evaluation of changes at the sectoral (i.e., aggregate) level often require one to sacrifice microeconomic detail in order to keep the problem tractable. This can have serious consequences. For example, appraisals of induced changes with aggregate programming models often result in extreme specialization in production (solutions where whole regions are devoted to a single crop). This situation usually leads to the imposition of inflexible "flexibility" constraints.

McCarl (1982) recently argued that linking microeconomic considerations with the sector model through a Dantzig-Wolfe decomposition scheme using heuristic procedures avoids this specialization in production within a sectoral analysis. The analysis used in this assessment incorporates this approach. Implementing the methodology requires both farm-level data and a macro (sector) model. Both the structure of the sector model and the microeconomic detail embedded in the model are discussed in this appendix.

The Sector Model

In this study the agricultural sector model component is a price-endogenous mathematical programming model of the agricultural sector; i.e., an activity analysis spatial equilibrium model (Takayama and Judge, 1971). Such sector models are used extensively by agricultural economists to simulate the effects of alternative agricultural policies or of technological change (Heady and Srivistava, 1975). Mathematical programming is a particularly useful tool given its ability to simulate potential consequences of as-yet-unrealized policies. This general methodology has been applied to air pollution effects by Adams et al., 1986; Adams et al., 1988; and Rowe et al., 1984.

The sector model features constant-elasticity demand relationships for the outputs (commodities) of the micro models. The elasticities vary with end use and across domestic and export markets. Assuming supply and demand functions which are integrable and independent of sector activity, first order conditions are then achieved in the macro model specification. The objective function of this specification is:

$$\text{maximize} \quad \pi = \Sigma\, g_i(Z_i) - \Sigma\, e_j(X_j) - \Sigma\, C_m Y_m$$

where π is the sum of ordinary consumers' and producers' surplus and the integrals are evaluated from zero to Z_i^*, the amount of i^{th} commodity produced and sold to consumers; and from zero to X_j^*, the amount of the j^{th} factor used. The parameters are as follows:

$g_i(Z_i)$ is the area under the demand function for the i^{th} product;

$e_j(X_j)$ is the area under the supply function for the j^{th} factor;

C_m is the miscellaneous cost of production;

subject to a set of technical and behavioral constraints. Given the micro and macro structure of the model, the solution then simulates a long-run, perfectly competitive equilibrium.

Following Samuelson (1952), the objective function (π) may be interpreted as a measure of ordinary consumers' and producers' surplus (quasi-rents) or net social benefit. Analytically, this is defined as the area between the demand and supply curves to the left of their intersection. The demand functions are specified at the national level, as are aggregate production responses, providing national-level consumers' and producers' surplus welfare measure. The use of economic surplus in policy analysis is well documented in the literature (Willig, 1976; Just et al., 1982), and is particularly relevant to agricultural uses where aggregate distributional consequences are of concern. The economic implications of alternative climatic scenarios are assessed by measuring changes in consumers' and producers' surplus which result when crop yields and input supplies are altered as predicted by the scenarios.

The sector model was solved under constant-elasticity demand curves using the MINOS software package (Murtaugh and Saunders). The model works from a set of budgets for 30 primary crops and livestock activities. For production purposes the U.S. is disaggregated into 63 geographical sub-regions. Each region possesses different endowments of land, labor and water as well as having different crop yields. This regionally specified information is an important feature in this model. Details on the items mentioned above follow. The model distinguishes between primary and secondary commodities with primary commodities being produced directly by the farms while secondary commodities involve processing activities.

Primary Commodities

Thirty primary commodities are listed in Table B-1. The primary commodities are chosen so as to depict the majority of aggregate agricultural production, land use and economic value. They can be grouped into field crops and livestock.

Both supply and demand information (i.e., equilibrium prices, quan- tities, and elasticities) are required in the model. The total supply consists of domestic production from all agricultural regions plus imports. Total demand is made up of domestic and foreign (export) components. Domestic demand includes consumption, stocks, government programs, livestock feeding and processing. Transportation costs to market are included in the supply budgets. Livestock feed and processing are endogenously determined, derived demands. Price and quantity data come from Agricultural Statistics, Agricultural Prices Annual Summary, and Livestock and Meat Statistics Supplement. Elasticity, and other demand information were supplied by Bob House, Economic Research Service, U.S.Department of Agriculture.

Secondary Commodities

The processing of secondary commodities is modelled at the sector level. Table B-2 lists the 18 secondary commodities in the model. These are chosen based on their linkages to agriculture. Some primary commodities are inputs to the processing activities and certain secondary products (feeds and by-products) are in turn inputs to other agricultural activities. The main data sources are Agricultural Statistics, Agricultural Prices Annual Summary, Livestock and Meat Situation, and Livestock Slaughter Annual Summary.

National Inputs

The model contains 27 national inputs listed in Table B-3. For the most part these are specified in dollar terms; for example, ten dollars worth of nitrogen, twenty dollars worth of repair costs. In doing so, the input usage is converted into a homogeneous commodity. These inputs are assumed infinitely available at whatever price was entered in the 1982 Farm Enterprise Data System (FEDS) budgets.

Regional Inputs

There are three inputs that are available in the regional level: land, farm labor and water. Production of crops and livestock compete for these scarce resources in each state or region. Therefore, the price and quantities of these inputs are endogenously determined on a regional basis.

Two types of land are specified. The first (type 1) is land suitable for crop production. The second (type 2) is suitable for pasture or grazing. The information on land utilization by states or regions was derived from Agricultural Statistics; regional prices of land were derived from the information in Farm Real Estate Market Development. Cash rental prices of land were used to reflect annual opportunity costs to the owners.

The labor input also includes two components: family labor and hired labor. The model requires specification of a maximal amount of family labor available and a reservation wage for family labor. Additional hired labor is available, based on an upward-sloping supply schedule with a reservation wage higher than that of family labor. The regional information on wages and employment was obtained from Farm Labor.

Water can be obtained from both fixed (surface) and variable (pumped groundwater) source. Surface water is available at a constant marginal cost but groundwater has a rising supply schedule; increasing amounts of water are available only at a higher price. The information on water is from USDA personnel, the Farm and Ranch Irrigation Survey and other government sources.

Regional Disaggregation

The model operates with two levels of regional disaggregation. The fundamental unit of disaggregation is 63 state and/or substate areas. In addition, these 63 areas are grouped into the ten USDA production regions for the purposes of land, labor and water supply. A list of these two levels of disaggregated regions and areas are given in Table B-4.

Regional Production Activities

Currently a total of 1683 production possibilities (budgets) are specified to represent agricultural production. These include major field crop production, livestock production and some miscellaneous transfer activities. Most field crop activities are also divided into irrigated and nonirrigated according to the irrigation facilities available in each state or area.

In some cases, the production activities produce more than one commodity. All commodities can be produced by more than one set of input combinations. Most field crops (except rice) are produced by either irrigated or nonirrigated production practices. Livestock production is somewhat more complicated. (See Chang and McCarl, 1988, for details.)

For each activity, information on yields and usages of national and regional inputs or other commodities is required. The basic source of this information is the 1982 USDA FEDS budgets. The irrigated/nonirrigated budget breakdown was developed by the USDA water group based on the FEDS surveys, the survey of irrigated acreage, extension budgets and Soil Conservation Service budget sets. The Livestock budgets are from the FEDS system for 1982.

Processing Activities

The secondary commodities are produced by three types of processing activities: soybean crushing; combining feed ingredients into various livestock and poultry feeds; and conversion of livestock and milk into consumable meat and dairy products. The processing cost of each commodity is calculated as the difference between its price and the costs of the primary commodity inputs.

Soybean crushing involves conversion of soybeans into meal and oil. Two soybean crushing activities are included, the model solution selects the more profitable one. Meat processing includes conversion from culled animals to slaughter and from slaughter to meat. Dairy processing involves conversion of raw milk to five different dairy products. The conversion of feed and feed supplements involves more than one processing activity, the model solution selects the least cost combination of feed ingredients.

Crop Mixes

The sector model is disaggregated into 63 internally "homogeneous" production areas. However, within each region least-cost production is represented by few, often one, crop budget. This can lead to misleading results since such representation cannot capture the full factor-product substitution possibilities in each of those areas. This is avoided by requiring crop production in each region to fall within the mix of crops observed in cropping records over the past 25 years.

Table B-1. Primary Commodities

List of Commodities	Units	List of Commodities	Units
1. Cotton	Bales (480 lbs.)	16. Hogs for slaughter	Cwt. LW
2. Corn	Bushel	17. Feeder pigs	Cwt. LW
3. Soybeans	Bushel	18. Live (beef feeder) calves	Cwt. Lw
4. Wheat	Bushel	19. beef feeder yearlings	Cwt. LW
5. Sorghum	Bushel	20. Slaughtered calves	Cwt. LW
6. Rice	Cwt	21. Slaughtered nonfed beef	Cwt. LW
7. Barley	Bushel	22. Slaughtered fed beef	Cwt. LW
8. Oats	Bushel	23. Culled sows	Cwt. LW
9. Other livestock (horses)	GCAU	24. Poultry	GCAU
10. Cull dairy cows	Head	25. Slaughtered lambs	Cwt. LW
11. Cull beef cows	Cwt. LW	26. Feeder lambs	Cwt. LW
12. Cull dairy calves	Head	27. Culled ewes	Cwt. LW
13. Milk	Cwt	28. Wool	Cwt.
14. Silage	Ton	29. Wool incentive payments	$
15. Hay	Ton	30. Unshorn lamb payments	$

Note: LW indicates live weight. GCAU is in terms of grain consuming animal unit.

Table B-2. Secondary Commodities

List of Commodities	Units
1. Soybean meal	1000 Lbs.
2. Soybean oil	1000 Lbs.
3. Fluid milk	Cwt
4. Feed grain	1000 Lbs.
5. Dairy protein feed	1000 Lbs.
6. High protein swine feed	1000 Lbs.
7. Low protein swine feed	1000 Lbs.
8. Low protein cattle feed	1000 Lbs.
9. Fed beef	Cwt. CW
10. Veal	Cwt. CW
11. Nonfed beef	Cwt. CW
12. Pork	Cwt. CW
13. High protein cattle feed	1000 Lbs.
14. Butter	Lb.
15. American cheese	Lb.
16. Other cheese	Lb.
17. Ice cream	Lb.
18. Nonfat dry milk	Lb.

Note: CW means carcus weight.

Table B-3. National Inputs

List of Inputs
1. Nitrogen
2. Potassium
3. Phosphorous
4. Lime
5. Other variable costs
7. Custom operation
8. Chemicals
9. Seed costs
10. Interest on operating capital
11. Repair costs
12. Vet and medical costs
13. Marketing/storage costs
14. Insurance (except crop)
15. Machinery
16. Management
17. Land taxes
18. General overhead costs
19. Non-cash variable costs
21. Fuel and energy costs
22. Crop insurance
23. Land rent
24. Set-aside(conservation cost)
26. Processing Labor
27. Irrigation energy cost

Table B-4. Assignment of States to Regions

NORTHEAST	CORNBELT	SOUTHERN PLAINS
Connecticut	North Illinois	Oklahoma
Deleware	South Illinois	Texas Central Blacklands
Maine	North Indiana	Texas Coast Bend
Maryland	South Indiana	Texas East
Massachusetts	North East Iowa	Texas Edwards Plateau
New Hampshire	Central Iowa	Texas High Plains
New Jersey	South Iowa	Texas Rolling Plains
New York	West Iowa	Texas South
Pennsylvania	Missouri	Texas Trans Pecos
Rhode Island	North East Ohio	
Vermont	North West Ohio	
	South Ohio	
LAKE STATES	**SOUTHEAST**	**MOUNTAIN**
Michigan	Arizona	Colorado
Minnesota	Alabama	Idaho
Wisconsin	Florida	Montana
	Georgia	Nevada
	South Carolina	New Mexico
		Utah
		Wyoming
NORTHERN PLAINS	**DELTA STATES**	**Pacific**
Kansas	Arkansas	North California
Nebraska	Louisiana	South California
North Dakota	Mississippi	Oregon
South Dakota		Washington
APPALACHIAN		
Kentucky		
North Carolina		
Tennsessee		
Virginia		
West Virginia		

CLIMATE CHANGE IMPACTS UPON AGRICULTURE AND RESOURCES: A CASE STUDY OF CALIFORNIA

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CONTENTS

FINDINGS[1]

This study assesses the impacts of climate change on California's agricultural and water resource systems. The methodology employed explicitly links predictions of climate changes from general circulation models (GCMs) of the atmosphere with an agricultural productivity model. These productivity impacts are introduced into the California Agriculture and Resources Model (CARM), which determines the economic and market implications of such changes. The climate changes assessed include temperature, evapotranspiration, precipitation, and cloudiness. The implications of such changes for water resource supplies were separately evaluated for the Sacramento and San Joaquin Valley Basins by a team of hydrologists and engineers (Lettenmaier et al., Volume A; Sheer and Randall, Volume A).

To assess climate change driven productivity impacts, an existing agro-ecological zone model (De Wit) was adapted. For several general crop groups, this method estimated that climate changes, in general, would reduce yields. The greatest impacts are expected in interior southern regions on cool season crops such as sugarbeets. Reductions in crop productivity from climate changes ranged from modest 3% declines to more serious 40% impacts for the crop groups and regions studied. Including CO_2 enrichment effects significantly alters the overall result. Net productivity changes range from a 41% increase to a 27% decline. This radical change reflects the differential potential ability of crops to utilize the increased CO_2.

Our economic system of markets and private decisions exerts compensating influences which tend to modulate the ultimate influence of direct physical productivity changes. Market incentives act to reallocate production activities and resources to maximize value to society under the environmental conditions specified in the scenarios. Scenarios for the economic model were constructed from the climate changes predicted by alternative GCMs, by the specific set of productivity impacts analyzed, by the availability of water resources, and assumed social response to such changes. Results from CARM indicate that even after market responses function, statewide average yields would be significantly reduced for all crop groups as a result of climate changes. Vegetables would be least severely impacted with average yields reduced from 6 to 15%. Fruit and nut crops would be hardest hit with average declines from 23 to 33%. After CO_2 enrichment is factored in, vegetable yields improved substantially to levels above the statewide average base, but most fruit, nut, and field crop yields remained reduced.

Regional changes in the production of agricultural commodities and in the use of resources by agriculture dominate the results. The hydrologic study team has estimated that surface water reductions under a changed climate would be greatest in those regions served by California's state water project (SWP). For a 30-year simulation of hydrologic flows under alternative future climates, SWP deliveries were reduced by 25 to 28% on average. Overall, climate change effects reduced the net economic well-being produced from agricultural operations between 14 and 17%. Statewide crop acreages were reduced between 4 and 6%, depending upon scenario, from a base level of slightly more than 9 million acres. Regionally, acreage declines were greatest in the Imperial Valley. Although no assessment was made of future groundwater stocks or pumping lifts, pumping declined from roughly 20% statewide as a result of reduced crop profitability. Overall surface water use declined roughly 16% as a result of both supply and demand changes. Regional water use changes were most dramatic throughout the San Joaquin and Imperial Valleys.

Factoring in CO_2 effects produced significantly different results. Total crop acreage either slightly declined or increased with net economic well-being, rising approximately 1.4% in each case. Surface water supplies remained short in state water project service areas which required large increases in groundwater pumping to

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compensate. Despite increasing marginal costs for groundwater withdrawals, increased pumping was economically supported by the generally elevated yields.

The last phase of this study evaluated social responses to climate change and their potential to reduce the impacts of such changes. This analysis focused on the introduction of irrigation water markets and improved on-farm irrigation management. All publicly provided surface water supplies were offered for sale as long as transfer charges were profitably covered. For all scenarios, including the base, water marketing produced net economic benefits. In the scenarios emphasizing climate change effects, impacts were reduced. When CO_2 enrichment effects were included as well, similar gains were recorded.

In summary, this case study has demonstrated the importance of including all related climate change impacts within a single analytical framework. In particular, it is not possible to translate physical crop productivity or water supply changes directly into impacts without accounting for the effect of market forces. Commodity markets operate to induce shifts in crop locations producing average yields close to the minimum biologic impact. Introducing markets for water resources similarly offsets supply reductions by improving the efficiency of use of what is available.

Market forces play a crucial role in creating the flexibility to respond to climate changes and in mitigating their ultimate impact. However, in the absence of radical changes in agricultural production technologies or environmental management institutions, nonmarket effects such as nonpoint source pollution will be exacerbated as agriculture relocates in response to climate changes. Some problems, such as drainage and salinity, may improve marginally as acreage and average water use are reduced. However, groundwater overdraft problems are likely to be exacerbated in the San Joaquin Valley although it is not known .fovi whether future energy prices or groundwater levels would support these withdrawal rates.

Climate changes and increased competition for water likely will have negative impacts on existing aquatic ecosystems. Increased temperatures and altered flow regimens in managed and free-flowing river systems may change species composition from cold to warm water varieties. Altered precipitation patterns would reinvigorate interest in large-scale public works including expansion of both the federal Central Valley Project and the State Water Project. Increased reservoir capacity would also affect fishery resources and the mix of recreational opportunities. Intensification of cropping and water use in the Sacramento Valley could negatively impact migratory waterfowl in critical Pacific flyway habitats. In short, many of the most severe consequences of climate change for California's environment remain to be studied.

CHAPTER 1

INTRODUCTION

THE PROBLEM

The increasing atmospheric concentration of radiatively active gases within the troposphere has been the focus of substantial concern within the environmental and scientific community. These cumulating gases are expected to produce a global climate change unprecedented in human history. Current atmospheric modeling results indicate that a climate change equivalent to that from a doubling of CO_2 concentration is expected in the first half of the next century if current growth rates of atmospheric CO_2 and trace gases continue. An actual ambient doubling of CO_2 concentrations is not expected until the later part of the 21^{st} century, depending upon the specific emissions trajectory produced by our use of fossil fuels. These changes are expected to produce up to a 4-5° Celsius increase in the average global temperature. These global average increases underestimate the extent of potential regional changes since the impacts will be differentially distributed from the poles to the equator with the greatest effects predicted at the high latitudes.

Temperature changes are the most certain of climate impacts. For central and southern California, mean temperatures are predicted to rise 3.8-4.4°C in an atmosphere with a doubled CO_2 concentration. In the northern part of the state, the increases range from 4.3 to 5.0°C. Other climate impacts will include changes in the pattern and distribution of precipitation, changes in sea level and the total area of dryland, and changes in the frequency of severe weather events. For example, increased temperatures in California would produce more rain and less snow during the winter. In addition, the snowpack would melt earlier in the spring reducing total effective reservoir storage and available supplies.

Of primary concern is the effect of climate change upon our food and fiber system and the resources used to support it. Agriculture is one of the most weather-sensitive sectors of our economy. Previous attempts to quantify this sensitivity to climate change have highlighted the particular sensitivity of irrigated agricultural regions (Dudek, 1987c). This study is designed to explore that sensitivity in greater detail through a case study of California's irrigated agriculture.

CALIFORNIA AGRICULTURE

California agriculture annually produces about 10% of total cash farm receipts in the United States. In 1986, California's farm income was first in the Nation at $14.5 billion, followed by Iowa and Texas with $9.1 and $8.5 billion, respectively. Grapes, cotton, hay, lettuce, almonds, tomatoes, strawberries, oranges, broccoli, walnuts, sugarbeets, peaches, and potatoes represent, in descending order, the major irrigated crops ranked in terms of gross receipts. As a sector, California agriculture produces 3-4% of total state income. The major sectors in the state's economy are petroleum and chemicals, banking and finance, real estate, electronics, and services.

Acreage harvested in California has varied between 7.5 and 9.0 million acres during the 1980s (2.467 acres are equivalent to 1.0 hectare). Agricultural irrigation accounts for approximately 80% of all consumptive water uses annually in California. By hydrologic basin, the major agricultural water uses in 1980 were San Joaquin and Tulare -- 51%; Sacramento -- 25%; and Colorado -- 12%. Cotton, feed grains and hay, and pasture are the largest water-using crops. Evapotranspirative water demands (ET) of crops vary by weather, soils, and locations. They range from 7.9 acre-feet per acre of rice in the Sacramento Valley to 1.2 acre-feet for an acre of wine grapes on the Central Coast.

CALIFORNIA'S WATER SYSTEM

California's water system is supplied by a statewide average annual precipitation of 23 inches, 60% of which is evaporated and transpired by native trees, brush, and other vegetation. Approximately 71 million acre-feet run off as streamflow and groundwater recharge in an "average hydrologic year." An additional 1.4 million acre-feet is inflow from Oregon streams, and the Colorado River has contributed another 4.8 million acre-feet in recent years.

The state's developed water supply system yields annual consumptive use of approximately 1/2 of annual stream run-off. Current categories of supply sources by percentage of annual use are as follows: (1) local surface water (27%); (2) groundwater safe yield (17%); (3) groundwater "overdraft" (6%); (4) Federal Central Valley Project (20%); (5) State Water Project (7%); (6) Colorado River (15%); and (7) other (8%). The State of California has jurisdiction over 1,188 dams and reservoirs with a gross storage capacity of 19.7 million acre-feet, and the U.S. has an additional 125 dams and reservoirs with 22.9 million acre-feet of capacity. Various estimates can be made of the economic value of this installed capacity. A very rough indicator of the magnitude of the investment in this system is that at an average cost of $500 per acre-foot of installed water supply delivery capacity, a $15-$20 billion investment exists to deliver 30-40 million acre-feet of annual water applications.

The driest year in California's recorded history was 1977. That year was also the second successive dry year of the worst drought California has experienced in over 100 years of record. The water year ending on September 30, 1977, yielded precipitation 45% of average. The fourth driest year of record was 1976, with precipitation at 65% of normal at the end of the water year. Run-off in streams and rivers was 47% and 22% of average flows during 1976 and 1977, respectively. The state's storage in its surface reservoirs hit a record low in 1977. Heavy precipitation and snow in early 1978 ended the drought. There have been no droughts since 1976-77, although 1987 was a critically dry year.

Groundwater was heavily pumped to offset reduced surface water supplies during the drought. In the San Joaquin and Tulare basins alone, overdraft increased in 1977 by 3.6 million acre- feet over the 1975 overdraft level of 1.3 million acre-feet. Saltwater intrusion in the Sacramento and San Joaquin River Delta was extensive. Economic damages during the 2-year period were estimated to total $2.7 billion (1978 dollars), of which 55% were agricultural. The second largest loss category was in forests, where fires and insects accounted for 25% of total losses. The third significant loss was in energy production (oil, gas, and imports substituted for reduced hydroelectric generation), which accounted for nearly 18% of total losses.

The remainder of this report will describe the methodology employed and its limitations, will present and interpret the results, will address the environmental and socioeconomic implications of those results, and will recommend policy changes.

CHAPTER 2

METHODOLOGY

The objective of this study is to characterize potential shifts in the demand for resources for agricultural production that might occur in California under a changed climate. The general methodology is that employed for the assessment of impacts of ambient pollutants upon agriculture (Wetzstein). Four types of models -- climate, yield, hydrologic, and economic -- are required for this assessment. The models used are the Goddard Institute for Space Studies (GISS) and General Fluid Dynamics Laboratory (GFDL) GCMs described elsewhere, crop productivity models, and the California Agriculture and Resources Model (CARM). A general description of the crop productivity model and CARM follows.

CROP PRODUCTIVITY ANALYSIS

Physiologically, plant growth has been limited by the availability of atmospheric CO_2. The effects of increased carbon dioxide concentrations in the atmosphere upon plants have been studied (Kimball, 1983). These studies have emphasized productivity gains from enhanced CO_2. However, crops are also influenced by a host of other climatic variables. Phenological studies of crop response are necessary for an enhanced understanding of the net physiologic and climatic effects upon yields. Temperature itself is a determinant of yield. For example, the number of consecutive days above 95°F is a critical determinant of corn yield (Mearns et al., 1984). Rosenzweig (1985) has demonstrated the importance of considering climatic change as well as enhanced CO_2 in studies of varietal wheat response.

In general, crop phenology models are the best choice for evaluating the impacts of general environmental changes upon crop productivity (Ritchie and Otter, 1984). These semi-empirical yield models are designed for large-area yield prediction using a whole-plant framework and including the effects of the major factors on crop growth -- climate, soil, and management. Requirements are few: daily solar radiation, minimum and maximum temperatures, and precipitation. Crop phenology models are being employed in the national assessment of climate change impacts upon agriculture, but limited crop coverage restricts the general application of this approach to the California case study.

At the other extreme, general response assessments have been previously employed to assess climate change effects upon crop productivity (Bolin et al., 1986). These general assessments have been culled from existing literature and presented as potential response ranges for both C3 and C4 crops. C3 plants have photosynthetic mechanisms which allow efficient exploitation of CO_2 concentration increases, while C4 types benefit relatively less. The review by Bolin et al. indicated that yield reductions in the 3-17% range would be associated with a 2°C temperature rise, while a doubling of CO_2 would indicate a 10-50% yield increase for C3 crops, while C4s would only have increases from 0 to 10%. The productivity impact methodology applied in this study attempts a balance between the extremes of the detail of crop phenology models and the generality of literature reviews.

In order to estimate the effect of climate change upon crop production in California, the agro-ecological zone method developed by Kassam (1977) was adapted. Given data on environmental conditions, this method was originally developed to match crops to regions most likely to support high potential yields under the assumption that "the maximum yield level of a crop is primarily determined by its genetic characteristics and how well the crop is adapted to the prevailing environment" (Doorenboos and Kassam, 1979).

The three factors considered by Doorenbos and Kassam as generally contributing to maximum potential yield are temperature, length of growing season, and incident solar radiation (which is in turn a function of cloud cover, season, and latitude). By definition, this method does not account for the effect of soil conditions, availability and quality of water, insect pests and plant pathogens, and farm management practices. Based on empirical studies of plant yield response to environmental factors under good growing conditions (e.g., De Wit, 1965), Doorenbos and Kassam provide the following equations as means of relating ambient environmental conditions to potential maximum yield (Y_{mp}). The following example uses coefficients for sugarbeets.

When $y_m > 20$ kg/ha/hour

$$Y_{mp} = c_L * c_N * c_H * G\,[F(0.8 + 0.1y_m)y_o + (1\text{-}F)(0.5 + 0.025y_m)y_c]$$

When $y_m < 20$ kg/ha/hour

$$Y_{mp} = c_L * c_N * c_H * G\,[F(0.5 + 0.025y_m)y_o + (1\text{-}F)(0.05y_m)y_c]$$

where:

c_L = correction for crop development and leaf area.

c_N = correction for dry matter production, 0.6 for cool and 0.5 for warm conditions.

c_H = correction for harvest index.

G = total growing period.

F = fraction of daytime the sky is clouded.

y_m = maximum leaf gross dry matter production rate of a crop for a given climate, kg/ha/hour.

y_o = gross dry matter production of a standard crop for a given location on a completely overcast (clouded) day.

y_c = gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day.

In this study, data on average monthly temperatures and average monthly cloud cover for five California weather stations and data on crop planting time and length of growing season for four indicator crops in various California regions (see Table 4) were employed. Using these equations, estimates of maximum potential yield for each crop (sugarbeets, tomatoes, cotton, and corn grown for grain and seed) by location were generated. As expected, the maximum potential yield results obtained from this method are substantially higher than those obtained in actual production. However, since only relative changes in yield are relevant for this study, the equations are evaluated for both current and projected conditions. The projected condition results are then ratioed to the baseline figures to yield an estimate of proportional productivity change. This procedure is completely analogous to that employed for GCM predictions applied to observed data.

In order to estimate the effect of changes in climate, the baseline temperature data for each weather station were converted into degrees Kelvin, multiplied by the average monthly temperature ratios obtained from the GISS and GFDL gridboxes corresponding to northern and central/southern California, and converted back to degrees Celsius. In the climate change scenarios, monthly average mean sky cover data in the baseline case are replaced by cloud cover data from the GISS and GFDL $2xCO_2$ model outputs.

As expressed in the Doorenbos and Kassam equations, growing season is an important variable; if plant growth is increased as a response to temperature, a reduced growing season could well eliminate any overall increase in yield for a single crop season. For example, temperature triggering could be advanced as a result of faster accumulation of growing degree day requirements with less time for production of harvestable yield. As a consequence, yields may decline despite increased temperatures and seemingly more favorable growing conditions.

Maximum leaf gross dry matter production rate of a crop for a given climate, y_m, is determined as a function of the average daily temperature over the growing season. For three crop types examined in this study, the form of this function is displayed in Figure 1 from tabular data supplied by Doorenbos and Kassam (Table 5). These functions ignore differences between canopy and air temperatures.

While the primary focus of this study is the evaluation of climate change effects upon California agriculture, increases in CO_2 concentrations in the atmosphere will also attend the climate changes. As previously noted, CO_2 is a limiting factor in photosynthesis and its increased availability will tend to increase productivity depending upon crop type. Consequently, yield response to both doubled CO_2 concentrations and climate changes is required to accurately assess impacts upon agriculture. Estimates of productivity increases under doubled CO_2 conditions were taken from Cure (1985) and Kimball (1983). These response factors were used to adjust Y_m.

CALIFORNIA AGRICULTURE AND RESOURCES MODEL

Since the 1960s, researchers at the Department of Agricultural Economics at the University of California, Davis, have been producing spatial optimization models of California agriculture. The earliest such model is a linear program developed by Shumway (1970) and applied in federal planning studies of California's resource base. Adams (1979) began with Shumway's general spatial production and resource structure converting the model to a quadratic form which adjusts equilibrium market prices in response to underlying supply changes. Howitt and Mean (1985) converted this model to one capable of calibrating model results to specific conditions. The specification of CARM employed in this case study was derived from the latter research.

CARM is a quadratic programming model which maximizes the sum of producers' and consumers' surplus, an approximate measure of social welfare, given available production opportunities and resources. More formally, the model may be stated as:

$$\text{Maximize } Z = c'x_t + 1/2x_t'Dx_t - (k'x + 1/2x'Sx)$$

$$\text{subject to } Ax \leq b$$

$$x \geq 0$$

where:

- x_t = vector of crop commodities produced and marketed.
- x = vector of alternative regional crop production activities.
- c = vector of intercept terms for linear demand functions.
- D = diagonal matrix of demand function slope terms.
- k = vector of variable production costs.
- S = diagonal matrix of regional linear supply functions.
- A = matrix of input-output coefficients for the regional production activities.
- b = vector of resource availabilities.

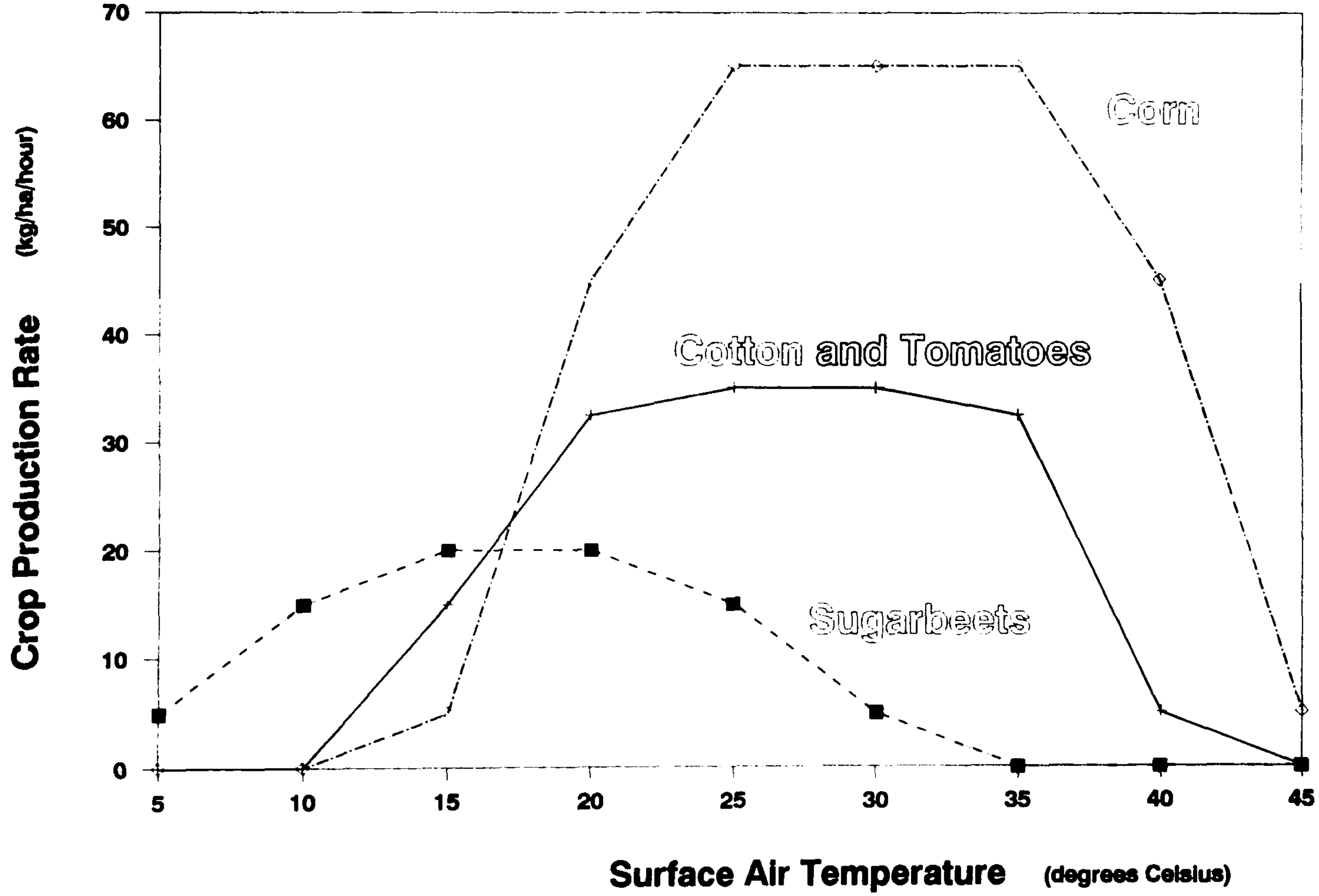
The modeling of agricultural production activities begun with the crop productivity models previously described must be translated into both economic and spatial dimensions in order to assess the implications of crop productivity changes stemming from climate change. As currently configured, the spatial equilibrium mathematical programming model used in this study has 7 production regions with 16 crop commodities (91 total crop production activities). The crop commodities included and their base acreages are presented in Table 1.

Table 1. Crop Commodities in CARM

CROP	1986 Acreage (thousands of acres)
Vegetables	
Broccoli	106.4
Cantaloupes	79.1
Lettuce	145.5
Potatoes	49.4
Tomatoes	239.0
Fruits and Nuts	
Almonds	412.7
Grapes	670.8
Oranges	174.7
Peaches	54.0
Walnuts	179.3
Field Crops	
Cotton	1,037.5
Sugarbeets	188.0
Grains	
Corn	250.0
Rice	363.0
Wheat	675.0
Hay	
Alfalfa	1,680.0
Total	6,304.4

Source: California Department of Food and Agriculture (1987).

Figure 1. Production Rates for Crop Groups by Temperature



Source: Doorenbos and Kassam (1979), p. 12

These crops accounted for slightly more than 76% of California's total crop acreage. Each of these commodities was used to represent a set of cropping activities not explicitly represented within the current model configuration to ensure that resource use is accurately modeled. For example, wheat is used to represent barley and oat production as well.

CARM has traditionally had between 14 and 17 production regions. The 14-region configuration is depicted in Figure 2. For the purposes of this study, these 14 regions were collapsed into 7 locations. Table 2 presents the regional correspondences between the 14-region specification and the more compact form employed in this study. As indicated in Figure 2, CARM regions 1, 2, 5, and 6 have been aggregated into a single production region, the Sacramento Valley. The other spatial aggregations are as defined by the shadings in Figure 2 and the correspondences specified in Table 2. Given the spatial resolution of the GCMs, the increased level of aggregation employed in CARM is not a serious compromise given the improved responsiveness and ability to analyze alternative scenarios. Since all model results are expressed relative to a base model, little bias is expected.

Costs of production for each of these commodities for each of the production regions were specified from base budgets prepared by the California Cooperative Extension Service. Where necessary, these budgets were indexed to a common 1985 basis. Other critical inputs into the programming model include the availability of soil and water resources within each of the production regions. The rest of the agricultural economy of the United States is presumed to be functioning normally -- an analytic fiction given the climate changes under analysis. However, since California agriculture is highly diversified and unique, this assumption is limiting only for the major grain crops where national price changes would have the greatest effect. International trade in agricultural commodities must also be exogenously assessed and specified as an input to the model. Since all agricultural regions around the world will experience degrees of change, changes in agricultural trade demand will be particularly difficult to project. Since trade is one of the elements of uncertainty expected to strongly condition the demand for agricultural resource use in the United States (Horner et al., 1985), a range of estimates covering a variety of demand scenarios should be evaluated. However, given the time and resource limitations of this study, export market sensitivity was not included.

CARM has been modified to allow ease in aggregating production activities, regions, and resources. In addition, in order to improve the accuracy of response under the water marketing scenarios, trade-offs between irrigation efficiency and capital expense have been developed. Thus, growers may sell or lease "saved" water generated from improved on-farm efficiencies with no potential diminution of yield, but with some capital and management expense. In principle, deficit irrigation could be employed to trade-off between reduced crop revenues and increased water marketing sales. Including a range of management choices avoids the all-or-none responses typical of some previous studies.

HYDROLOGIC MODELING

The importance and complexity of water resource systems in California required the development of several integrated case studies in order to assess climate change effects. Just as climate changes will affect the biologic processes governing plant growth, changes in temperature, precipitation, and evaporation will impact hydrologic processes. Given these impacts, it is not possible to evaluate the impact of climate change upon California agriculture without estimates of impacts upon water supplies. Within California, the Sacramento Valley Basin was selected as the focus for the hydrologic case study. This region is the site for major surface water supply investments including central units of the federal Central Valley Project (CVP) at Shasta and the State Water Project (SWP) at Oroville.

Figure 2. California Production Regions

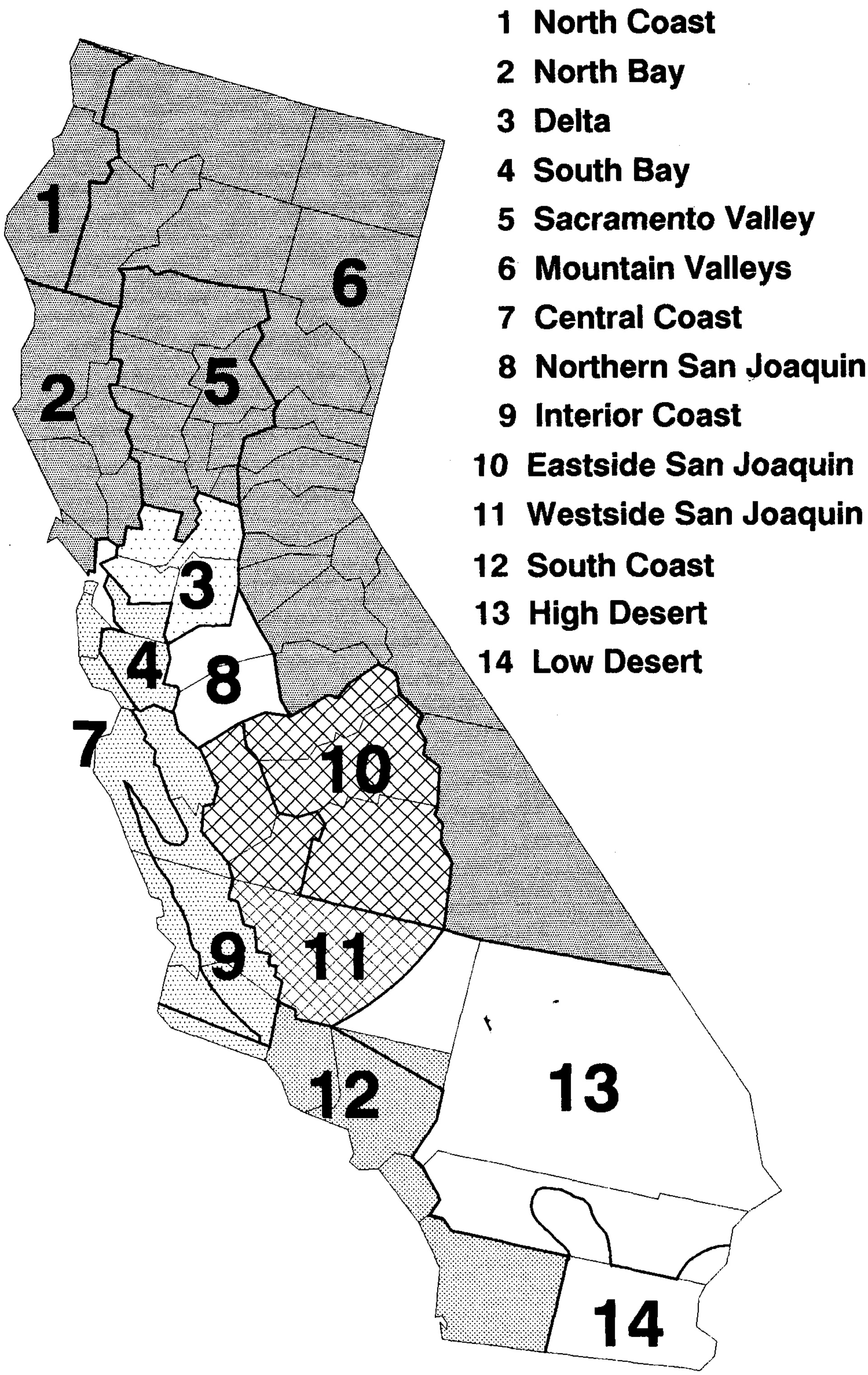


Table 2. Production Region Correspondences

14 Region Model	7 Region Model
1 North Coast 2 North Bay 5 Sacramento Valley 6 Mountain Valleys	Sacramento Valley
3 Delta	Delta
4 South Bay 7 Central Coast 9 Interior Coast	Central Coast
8 Northern San Joaquin	Northern San Joaquin
10 Eastside San Joaquin 11 Westside San Joaquin	Southern San Joaquin
12 South Coast	South Coast
13 High Desert 14 Low Desert	Imperial Valley

The first component of the hydrology study is the simulation of basic rainfall and runoff processes (Lettenmaier, Volume A). The results of this model are estimates of virgin or unimpaired flows under alternative climate scenarios. Basically, precipitation, temperature, and wind changes predicted from individual GCMs and scenarios are translated into proportional changes and then overlaid on a historic record. These virgin flows were then adjusted for land use changes and analyzed in a simulation model of the joint operations of the SWP and the CVP (Sheer and Randall, Volume A). On the basis of the existing reservoir operating rules predicated on the existing pattern of water rights developed under California's appropriation doctrine, any water shortages are allocated. The joint operating model then produces estimates of deliveries to users throughout the state. It is these delivered quantities under alternative climate scenarios which are input into CARM.

ASSUMPTIONS AND LIMITATIONS

The outcomes produced from this set of linked models are strongly conditioned by the quality of the data inputs flowing between the various analytical components. For each of the model subsystems employed, critical assumptions or limitations are briefly noted below. In most respects, the limitations reflect either those imposed by the time and resource restrictions imposed by the stringent study schedule or the limitations of current science.

Crop Productivity Model

As indicated in the section describing the crop response methodology, the technique developed by Kassam and adapted in this study is less than perfect. Detailed crop phenology models would have given better estimates of crop response to climate changes, but even these detailed models have not yet incorporated CO_2 effects. The agro-ecological zone method employed in this study has an empirical basis; however, it has not been explicitly calibrated for California production regions. Further, a subset of crops were selected on the basis of data availability to act as indicator crops in the response analysis. Percentage yield changes in these indicator crops were proportionally applied to crops with similar characteristics.

While the differential productivity enhancement of CO_2 increases were included, interaction between CO_2 and climate factors in productivity response were not. This omission reflects the current status of knowledge rather than any limitation inherent to the methodology. Changes in water use efficiency as a result of stomatal response to elevated CO_2 were not included. Water use efficiency responses by crop are neither completely understood nor widely available (Acock and Allen, 1985).

Given the need to employ detailed weather data in the evaluation of yield impacts, first order weather stations were employed. These stations tended to be located near larger urban centers, not all of which were well correlated with agricultural production regions (see Table 4). Lastly, the response methodology did not include possible variations in productivity due to soils or management practices.

Economic Model

The following is not an exhaustive list of the assumptions underlying this research since many are common to all forms of economic analysis. Rather, the intent is to highlight areas of particular limitation or import for this issue. CARM is limited by the accuracy of both GCM predictions and the performance of the productivity impact methodology employed in this study. CARM itself, however, has other limitations. Technical change has not been included in any of the analysis or construction of the scenario experiments. Other than simple exponential growth rates, technical change assessments are beyond the scope of this study. In the absence of precise dating for the doubling of ambient CO_2 concentrations, even the compound growth approach is problematic.

As previously indicated, some critical demand and supply conditions for both crops and resources have been omitted. The export demand situation under a changed climate is unknown. Changes in underlying consumer tastes and preferences, even using extrapolations from current trends, have not been included. On the supply side, no crop pest changes have been introduced and no assumptions concerning the status of ambient pollutant levels such as tropospheric ozone have been made. No attempt has been made to predict the status of groundwater resources at the doubling time, a potentially critical omission for the integrated water analysis. In addition, only the relatively simple predictions of ET change from the GCMs were used to portray changes in crop water demand. Lastly, the future status of current resource problems was not projected. For example, no attempt was made to account for the extensive drainage and salinity problems of the San Joaquin Valley Basin. Nor was any attempt made to project the conversion of agricultural land to urban uses or the availability of land resources in general.

There are a few sources of explicit model bias within the current structure of CARM. First, to the extent that there are differences in price responsiveness between indicator commodities and the underlying set of crops represented, the results will be biased. Model results have a downward bias (greater costs of climate change) because neither new crop varieties nor planting dates were included within the range of alternatives evaluated by CARM. Nor were new crop/location combinations not currently in evidence in California considered. Each of these production responses would act to further reduce the impact of climate changes. Lastly, with the exception of the grain crops, there was no national context of climate changes conditioning price signals for California producers. Since these are the crops for which prices are set in global or national markets, national rather than regional elasticities were employed.

Hydrologic Limitations

From the vantage of assessing the implications of a changing climate for California agriculture, the most serious limitation of the hydrologic modeling is the absence of forecasts for groundwater resources which account for roughly 25% of the state's developed supply sources. Changes in precipitation and runoff as well as project deliveries will affect groundwater recharge and therefore its availability and cost. For much of California's agriculture, groundwater is the marginal supply source since it is generally more expensive than surface sources. Further, as surface supplies are altered by climate or weather, the intensity of groundwater extraction varies. Thus, the availability and depth of groundwater resources is central to estimating the impact of surface water supply changes on agriculture. In the absence of other information, groundwater availability was not altered in the economic model. However, nonlinear cost functions were introduced to reflect the increasing cost of pumping from greater depths as extraction increases.

Other concerns surrounding the hydrologic component include the representativeness of the historic period 1951-80 used in the simulation. In hydrologic terms, this is a relatively short span of time which may not capture all of the variability in northern California's water resources. For example, the drought of record in California's Central Valley occurred between 1927 and 1934. In addition, in the climate change scenarios, there was no change in the underlying variability of precipitation as only the variability contained in the historic record was used in the simulations. For a system designed to manage the extremes of weather, this assumption may be very inadequate in describing the nature of a changed climate under doubled CO_2 atmosphere. Further, the adequacy of a highly engineered water system like that in California depends upon its performance under a sequence of adverse years. The linked methodology used in this study is inherently static, but since the underlying variabilities have not changed, this is not a serious limitation.

A final set of issues concern technical assumptions employed in the hydrologic study. For example, the joint SWP/CVP operating model uses forecasts of the needs of end use sectors such as agriculture in determining the quantity and pattern of releases. However, the agricultural demand for irrigation water is likely to differ in magnitude and location under a changing climate (Dudek, 1987c). The lack of feedback between the economic and hydrologic components of this analysis likely overstate the impact of surface water supply changes. Another key ingredient in both the agricultural and hydrologic analyses is evapotranspiration (ET). In the present study, ET changes are derived from GCM output. However, ET may depend critically upon local and regional phenomena such as wind. Poor ET assumptions affect both the water supply results from the hydrology study and the agricultural demands reported in this study.

THE SCENARIOS

This case study was designed to combine the results from several detailed analyses in order to produce a more realistic view of the potential impacts of climate change upon an irrigated agricultural system. Unique to this study is the use of detailed hydrologic assessments of surface water changes under specific climate scenarios. To understand both the magnitude and source of changes in such a complex system, it is important to carefully construct scenarios as sets of precise assumptions about uncertain variables. For this study, there are four main sources of change, each of which is identified in Table 3.

Since there are a number of competing GCMs, there are a number of alternative projections of future climate. As has been previously discussed in the crop productivity analysis, climate differences can be very significant in crop productivity terms. There are at least four alternative climates. In general, crop productivity changes have been driven by climate change impacts such as the effects of temperature and cloudiness changes. These changes have been the easiest to assess with existing agronomic models. However, the changing concentration of CO_2 will also affect yields. Assessing these latter effects is the subject of significant contemporary research. Consequently, there will be at least two sets of productivity changes, one of which will account for the effects of CO_2 in addition to climate change impacts.

Assumptions concerning water and the institutions for its management complete the specification of variables comprising a particular scenario experiment. The hydrology study which focused on the Sacramento Valley produced 30-year simulations of surface runoff and flows under alternative climates. Since CARM is a static single period model ill suited for time series simulations, the 30-year hydrologic simulations need to be translated into meaningful estimates of surface water deliveries. The limitations of time and resources for this study dictated a focus on the mean change within the simulated period. This narrow scope does not allow an analysis of the implication of the extremes in altered water supplies, but it does emphasize the expected change. While physical flows are important, the set of institutions and rules governing the allocation of water supplies are a critical determinant of the economic outcome produced under a particular water supply assumption. One important institutional innovation in California water management would be water marketing.

Overall, there are three alternative climates, two sets of productivity impacts, two water supply characterizations, and two alternative institutional arrangements. The ten scenario experiments described in Table 3 were analyzed.

Table 3. Scenario Experiments

VARIABLES	ALTERNATIVES
Climate	Base, GISS, GFDL
Productivity Impact	Climate Change Only Climate Change plus CO_2
Water Supply	Base, GISS, GFDL
Institutional Response	None, Water Markets

CHAPTER 3

RESULTS

The primary focus of this study is to evaluate the implications of a changing climate for the agricultural and water resources of California. To this end, a set of models were linked to conduct a set of scenario experiments each describing different climatic conditions and responses. As previously indicated, climate change is a complex phenomenon stemming from the acumulation of trace gases in the lower atmosphere which trap radiation. The trapped radiation acts to alter temperature, weather, and climate with implications for crop productivity, hydrology, and the agricultural economy. One of the gases causing this change, CO_2, also has direct effects upon plants in general and agriculture in particular. As a result, this case study separately analyzes the effects stemming from climate changes and net effects which include CO_2 impacts.

CROP PRODUCTIVITY CHANGES

Climate Change Effects

Table 4 presents the percentage yield reductions estimated for four indicator crops, five California locations, and two GCMs. The productivity changes driven by climate change effects without accounting for CO_2 concentration effects are reported under the column headings CC. The specific mapping of these productivity changes to CARM production regions is presented in Figure 3. In general among the indicator crops, cool season C3 crops represented by sugarbeets were estimated to suffer the most serious productivity declines. Sugarbeet yield reductions from climate changes ranged from approximately 21 to 40%. Sugarbeets were estimated to have the largest individual productivity decline (40.1%) when using Blythe weather station data. Elsewhere, corn yield declines ranged from 3 to 31 percent. Cotton, the warm season C3 crop, exhibited a very similar pattern of yield impacts from climate change as corn. Vegetable crops, represented by tomatoes, were least affected with reductions ranging from 5 to 16%.

As generally expected, the severity of these productivity impacts from climate change effects alone were distributed along a south to north gradient (see Figure 3). In addition, with the exception of corn, yield impacts were greatest in interior production regions where temperatures are less modulated by marine influences. Overall, yield reductions under the GISS $2xCO_2$ scenario were greater than under projections from the GFDL GCM owing to the greater temperature increases for California produced by the GISS model. Differences were most severe for corn and least severe for vegetables. Other than the absolute magnitude of effect, the scenarios from the two GCMs are in general agreement.

Net Effects Including CO_2

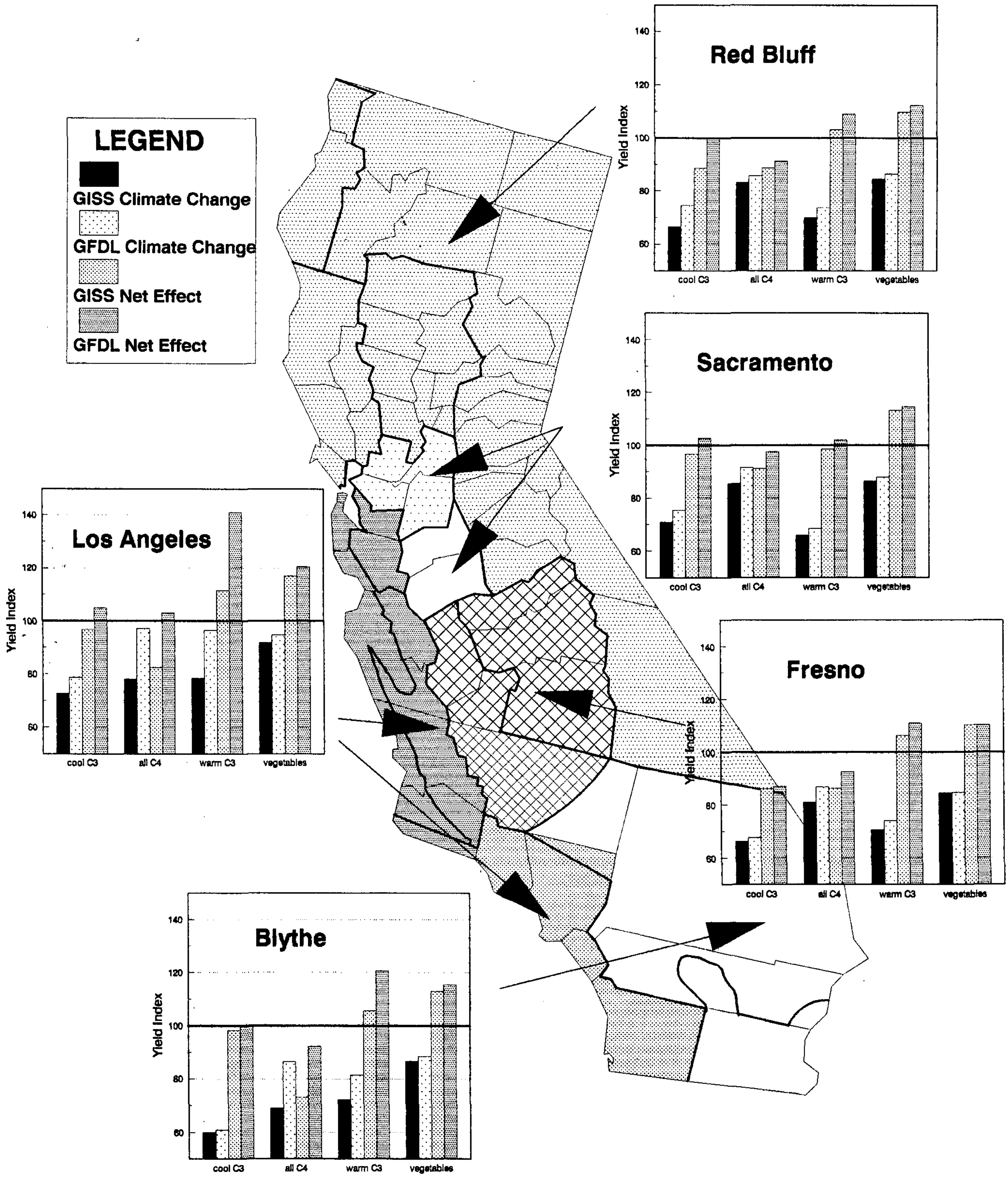
When the effect of inadvertent fertilization due to the increased CO_2 concentrations is introduced, however, some of the productivity changes alter direction, i.e., yields increase. These results are displayed in the columns labeled NET in Table 4. For example, the warm C3 crops such as cotton and the vegetable group all generally exhibit increases over base period yields. Overall, among the crop groups evaluated, the warm C4 crops as represented by corn exhibited the greatest yield declines relative to base conditions. As a C4 crop, corn is less able to take photosynthetic advantage of the increased CO_2. Consequently, climate change effects continue to dominate in productivity changes for that crop. Cotton, a C3 type, would benefit the most from CO_2 concentration increases with yield changes ranging from a modest 1.5% decline to a 41% increase. Differences between the climate change and net effects scenarios were also dramatic for sugarbeets.

Table 4. Predicted Yield Changes, Agro-ecological Zone Method

REGION	SCENARIO	Sugarbeets		Corn		Cotton		Tomatoes	
		%%%%%%% mean percentage yield changes* %%%%%%%							
		CC	NET	CC	NET	CC	NET	CC	NET
Coastal Regions									
Los Angeles (LAX)	GISS	-27.4	-3.2	-22.1	-17.7	-21.7	11.4	-8.3	16.9
		(2.1)	(3.0)	(3.7)	(3.9)			(3.9)	(5.0)
	GFDL	-21.4	4.8	-2.8	3.0	-3.5	40.9	-5.3	20.4
		(2.7)	(3.8)	(5.1)	(5.3)			(3.5)	(4.4)
Interior Regions									
Red Bluff	GISS	-33.6	-11.3	-16.8	-11.5	-30.3	3.07	-15.6	9.7
		(4.2)	(5.9)	(2.8)	(3.0)	(3.9)	(5.7)	(1.1)	(1.4)
	GFDL	-25.5	-0.2	-14.4	-8.8	-26.4	8.9	-13.5	12.18
		(3.0)	(4.3)	(3.2)	(3.4)	(3.6)	(5.4)	(0.9)	(1.2)
Sacramento	GISS	-29.1	-3.4	-14.4	-8.7	-34.1	-1.5	-13.5	13.2
		(3.3)	(4.6)	(3.4)	(3.6)	(3.1)	(4.6)	(1.4)	(1.9)
	GFDL	-24.5	2.8	-8.4	0.2	-31.5	2.1	-12.1	14.8
		(3.8)	(5.4)	(3.7)	(3.9)	(3.8)	(5.7)	(1.3)	(1.8)
Fresno	GISS	-33.7	-13.5	-18.9	-13.5	-29.2	6.4	-15.4	10.4
		(3.3)	(4.3)	(4.1)	(4.3)	(2.7)	(4.0)	(1.8)	(2.4)
	GFDL	-32.1	-12.8	-12.9	-7.2	-25.8	11.1	-15.1	10.5
		(3.6)	(4.7)	(5.3)	(5.6)	(2.8)	(4.2)	(2.1)	(2.6)
Blythe	GISS	-40.1	-1.8	-31.1	-26.9	-27.8	5.5	-13.4	12.9
	GFDL	-39.2	-0.1	-13.5	-7.9	-18.7	20.6	-11.5	15.4

The mean values reported in this table are computed from 30 years of model simulated yield effects for the historical period 1951-80. The figures reported in parentheses below the mean values are the standard deviations.

Figure 3. Regional Productivity Changes



Since the analysis of crop productivity impacts followed the general procedure established for all impact studies in this series, i.e., superimposing new climatic values upon historic series, the results reported in this section have focused upon the mean changes for the 30-year simulation. The standard deviations associated with these mean values are reported in parentheses in Table 4. When comparing the climate change only versus climate change plus CO_2 scenarios, the standard deviations of yield changes increased when CO_2 effects were included. Yield variability has been used as one measure of risk for agricultural enterprises. Using this measure, then, risk would incrase under climate change despite the positive effects of CO_2 fertilization.

From the spatial view of the results presented in Figure 3, both the coastal-interior and south-to-north change gradients previously observed persist. Coastal region productivity for sugarbeets and tomatoes in general, and for cotton under GFDL, is less affected than that for interior regions. Corn, a warm season crop, fares more poorly in the hotter southern production regions represented by Blythe and Fresno. As Figure 1 illustrated, corn exhibits the greatest tolerance and increase in productivity with temperature, but also the sharpest declines beyond 35°C. South-to-north changes were generally observed, although not as pronounced as when climate changes only were assessed. Overall, the pattern of results under the two GCM scenarios were consistent in the direction of change. Net productivity impacts varied most for cotton owing to the strong productivity increases produced when CO_2 effects were included. Corn and sugarbeet yields were also significantly affected. The corn declines for all interior regions were due to the higher temperatures predicted by the GISS model and the reduced ability of corn to benefit from increased CO_2.

WATER RESOURCE SUPPLY IMPACTS

Table 5 presents estimates of surface water supply changes in percentage terms. These estimates are summary statistics derived from the hydrologic simulations produced by Lettenmaier et al. and Sheer and Randall. The estimates in Table 5 refer to changes in deliveries to various regions within the state. Refer to Figure 2 for the geographic location of these CARM regions.

Table 5. Surface Water Supply Changes

SCENARIO	Sacramento Valley	Delta	San Joaquin Valley (Federal)	San Joaquin Valley (State)	South Coast
		- percentage changes -			
GISS $2xCO_2$					
mean	0.000	-0.003	0.000	-24.677	-1.125
standard deviation	0.000	0.409	0.000	10.044	0.411
maximum	0.000	1.634	0.000	-2.696	-0.227
minimum	0.000	-0.789	0.000	-34.365	-1.583
GFDL $2xCO_2$					
mean	0.000	-0.030	0.000	-28.109	-1.250
standard deviation	0.000	0.349	0.000	11.322	0.467
maximum	0.000	-1.535	0.000	-3.209	-0.377
minimum	0.000	-0.233	0.000	-48.537	-2.112

Source: Dan Sheer, Water Resources Management, Inc., personal communication, March 11, 1988. Percentage changes calculated from the 1951-80 simulations run for a changed climate according to the scenarios identified. In each case, the reference scenario is the GISS $1xCO_2$ run.

From Table 5, it is clear that the major supply impacts predicted from these hydrologic simulations would occur in state water project delivery areas primarily in the San Joaquin Valley. Federal CVP service area deliveries are not similarly affected because of differences in the seniority of water rights. The GISS scenario produces a hydrology with increased surface water flows seasonally shifted. Flow is increased in winter months and reduced in spring and summer. Effectively, the warmer temperatures result in the loss of storage provided by snowpack.

The need to provide flood control storage in reservoirs particularly in the state water project facility at Oroville does not permit retention of the increased winter flows with existing storage capacity. Consequently, state water project deliveries would be reduced by approximately 384,000 acre-feet. Results under the GFDL $2xCO_2$ scenario were similar, but with slightly greater water supply impacts due to less severe temperature changes and decreased precipitation. Total SWP deliveries are reduced by some 438,000 acre-feet under the GFDL scenario.

ECONOMIC IMPACTS: AGRICULTURE AND RESOURCES

The preceding results have focused on climate change impacts upon biologic and hydrologic systems. This section describes the implications of those productivity and water supply changes for California's agricultural economy. This portion of the case study is a departure from previous sections since it emphasizes the collective responses of both agricultural producers and consumers to the changes comprising each scenario. The interaction of supply and demand responses in a market economy is critical to correctly estimating the nature and magnitude of climate change impacts. Productivity declines first act to reduce farm revenues by decreasing the quantity of produce available for sale. The precise impact upon farm revenues depends upon the responsiveness of demand and supply, particularly from competing regions. In order to maximize farm profitability, growers switch among crops matching their most profitable alternatives with available resources. They also respond by altering management techniques and therefore production as well as costs. In this case study, irrigation system options are assessed. Consumers respond to price changes both by altering consumption and by substituting among food items. These price changes are also received by growers who adjust their production plans accordingly.

Aggregate Results

The result of the operation of this market system is best illustrated by comparing the statewide average yield changes from CARM (Figure 4) with the crop productivity results from the Doorenbos and Kassam model. Figure 4 presents the statewide average yields produced by CARM under alternative scenario experiments -- the GISS and GFDL $2xCO_2$ climates coupled first with productivity changes driven by those climate changes only and then with CO_2 effects included (discussed in section E). In each case, evapotranspirational changes predicted by those GCMs and the mean surface water deliveries under each climate were included.

Overall, the results for the two climate change scenario experiments are broadly similar with consistent directional changes. In contrast to Figure 3 and Table 4, which displayed the direct estimated crop productivity changes from the modified Doorenbos and Kassam model, Figure 4 presents the statewide average yields that result after economic incentives have operated to reallocate production activities and resource use. As such it is a good example of how the economic system operates to modulate direct productivity changes. Corn, for example, was predicted to have productivity declines between 14 and 31% depending upon location under the GISS $2xCO_2$ climate projections. CARM produced statewide average corn yields roughly 18% lower than the base run, an overall result which is very close to the lower bound of direct productivity impacts under the GISS scenario. Results were similar under the GFDL scenario. Corn productivity impacts ranged from reductions of from 3 to 13.5%. The CARM analysis produced a statewide average decline of only 10%.

Figure 4. Statewide Average Yield Changes

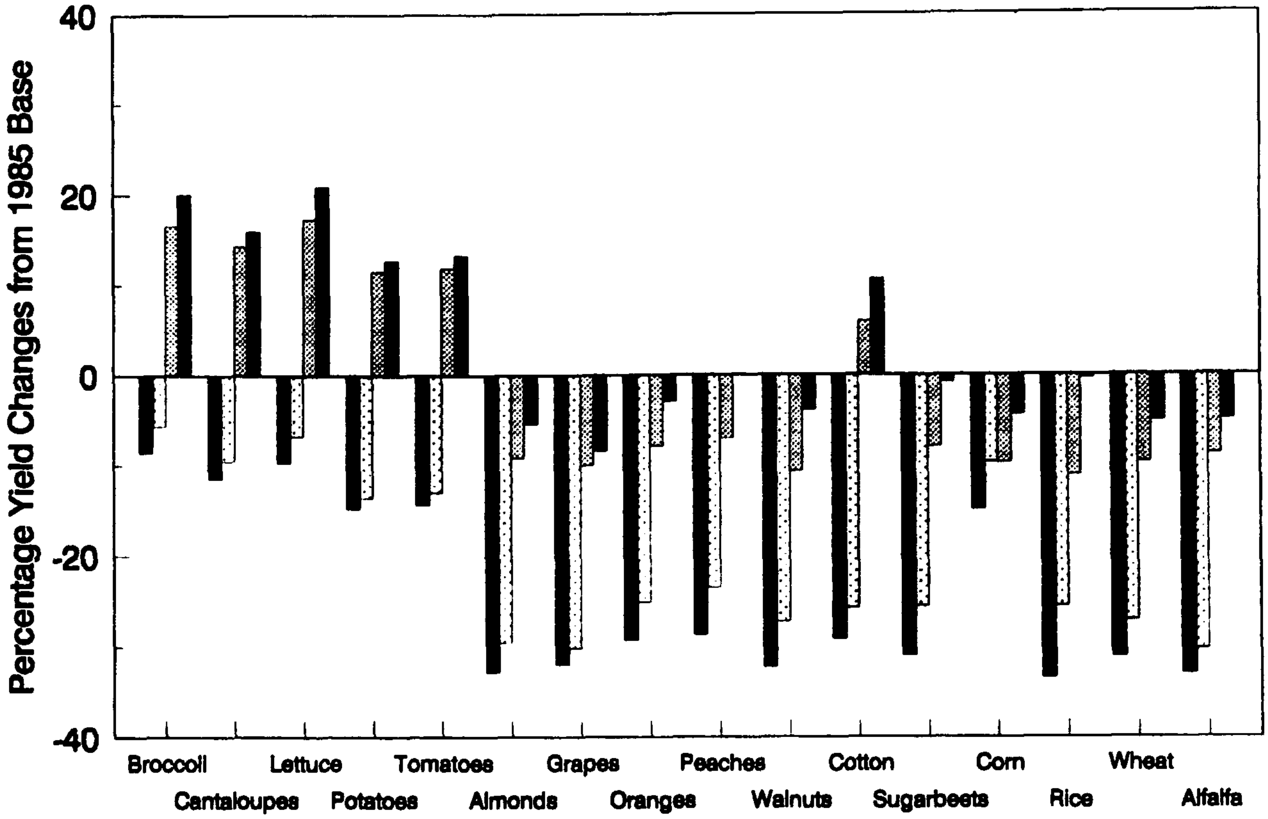


Figure 5. California Production Changes

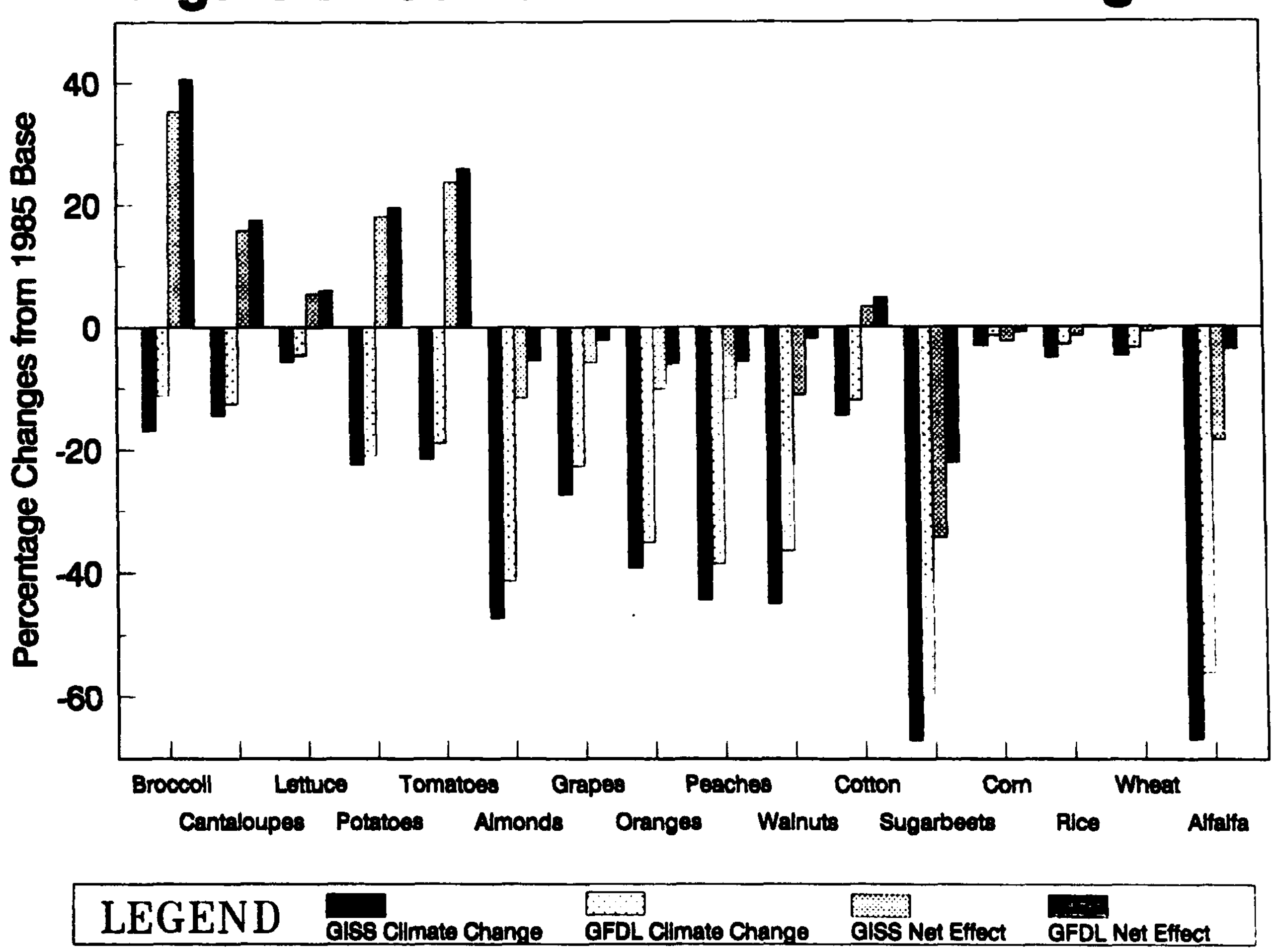


Figure 5 depicts the associated aggregate commodity production changes referenced to the 1985 base run. Production changes largely follow the pattern of underlying yield changes as modified by alternative production opportunities and price changes. Again, the trend in both climate change only scenario experiments was broadly similar. Almonds, peaches, walnuts, sugarbeets, and alfalfa hay are particularly large losers (productivity changes in these crops were represented by the sugarbeet effects listed in Table 4).

Figure 6 presents crop acreage changes in percentage terms. The pattern follows that discussed for average yields and production with the exception of increases in selected crops. The increases in grain crops are particularly noteworthy and stem from the use of national demand elasticities for these crops to reflect a national context of simultaneous stress across the national agricultural economy. The result is significant price increases for the grain crops as displayed in Figure 7. Figures 6 and 7 taken together are another measure of the homeostatic powers of market systems to modulate direct physical impacts. Overall, the results presented in Figures 5 and 7 are inversely related. Production declines are matched by price increases with the extent depending upon the magnitude of decline and the price elasticity of demand.

CARM measures aggregate economic values in terms of changes in values received by both producers and consumers, i.e., producers' and consumers' surplus (CPS). The changes described for the state as a whole under the GISS $2xCO_2$ scenario with climate change effects resulted in a 17% decline in CPS. Losses under the GFDL scenario were only slightly lower (see Figure 10). Total crop acreage was reduced by 6.7% under GISS and by 3% under GFDL. Given these acreage reductions and the water supply impacts, both ground and surface water use were reduced for the state as a whole under both scenarios. Groundwater use declined by roughly 20% in both GISS and GFDL scenario experiments. Surface water reductions, largely determined by hydrologic changes, that reduced state water project deliveries, were closely matched at close to 17% for the two GCMs.

Regional Results

While the statewide average results are useful to appreciate the overall impacts of the individual scenarios, one of the real strengths of CARM lies in its detail of regional production activities and resources. As the crop productivity results indicated, there are significant differences in the strength of impacts on crop yields in different locations. These impacts are further reinforced by water supply reductions which mainly affect the state water project service area in the San Joaquin Valley. Figure 8 presents some of the regional detail underlying the statewide changes. Crop acreage shifts for five major crop groups are displayed.

The greatest proportional changes under all scenarios occurred in the Delta and in the Imperial Valley. In the Delta region, strong price increases for grains encourages switching away from other field crops and fruits and nuts. Tree fruits and nuts move from the warmer interior valley regions to the cooler coastal production regions such as the Central Coast where productivity impacts are smaller, but still substantial. For the field crops, the large declines reflect the poor performance of cool season crops like sugarbeets, one of the principal field crops modeled. Vegetable crop acreage is the least affected of all crop groups since productivity was least affected under all scenarios. At the other extreme, hay is the most volatile crop, disappearing almost completely from some production regions under some scenarios (the climate change scenarios for the Central Coast and Imperial Valley regions). Hay is generally the marginal crop in irrigated regions and would be expected to decline under productivity declines or water shortages. Certainly, this decline would depend upon demand from the livestock sector and the availability of substitute feed from more distant regions.

In contrast, when viewed in absolute terms, the largest changes under the climate change scenarios occur in the northernmost production region, the Sacramento Valley. Under the GISS climate change scenario, ma acreage is reduced by 511,000 acres from base conditions. Increases in grain acreage make up for 337,000 acres of this loss. Nonetheless, the region overall loses 325,000 acres of previously cropped land. The shifts between hay and grain acreage in the southernmost Imperial Valley are second in size under the climate change scenarios with 293,000 acres of hay lost and 168,000 new grain acres. After CO_2 effects are included, the largest change still occurs as in hay acreage in the Sacramento Valley with a 235,000-acre loss under the GISS net scenario. Hay acreage reductions in the Imperial Valley remain the second greatest impacts despite the potentially beneficial direct effects of CO_2. These results illustrate the fact that although productivity impacts fall along a

Figure 6. California Acreage Changes

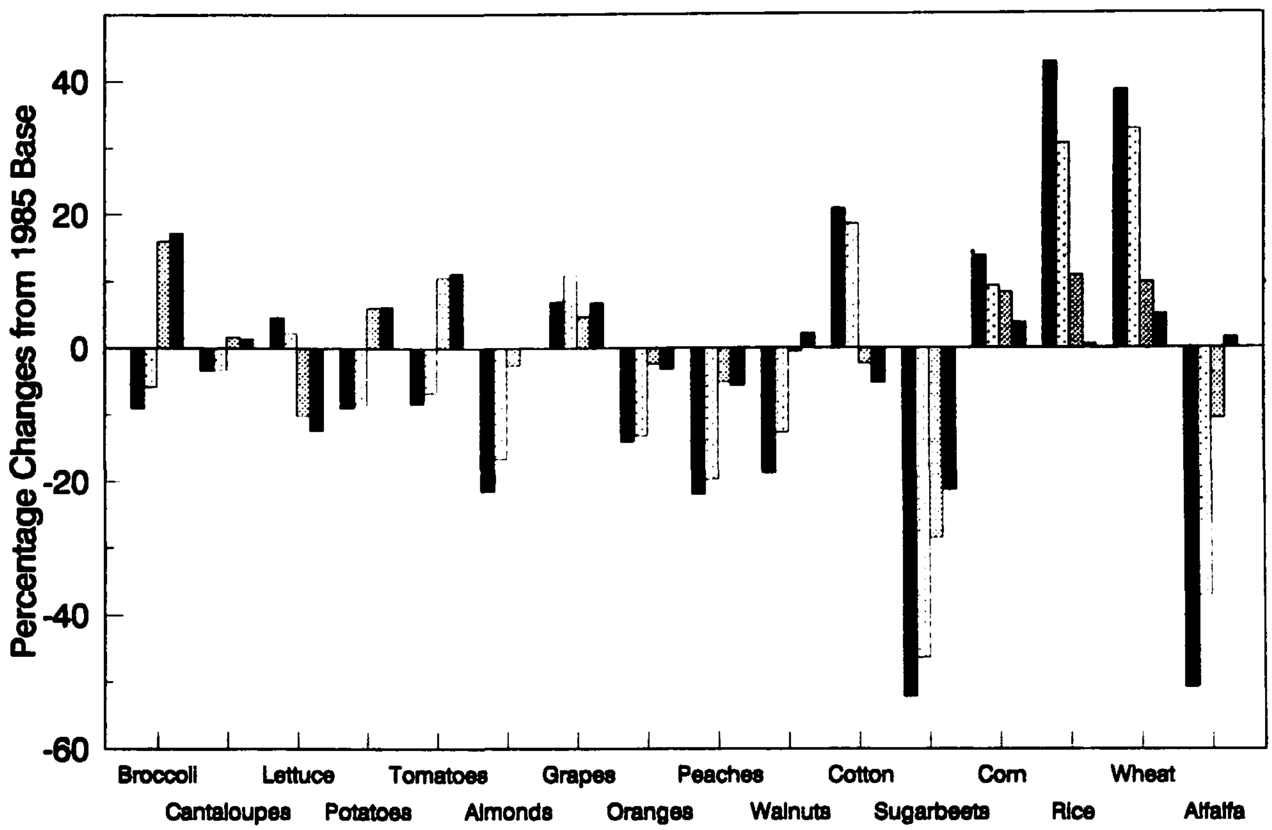


Figure 7. California Commodity Price Changes

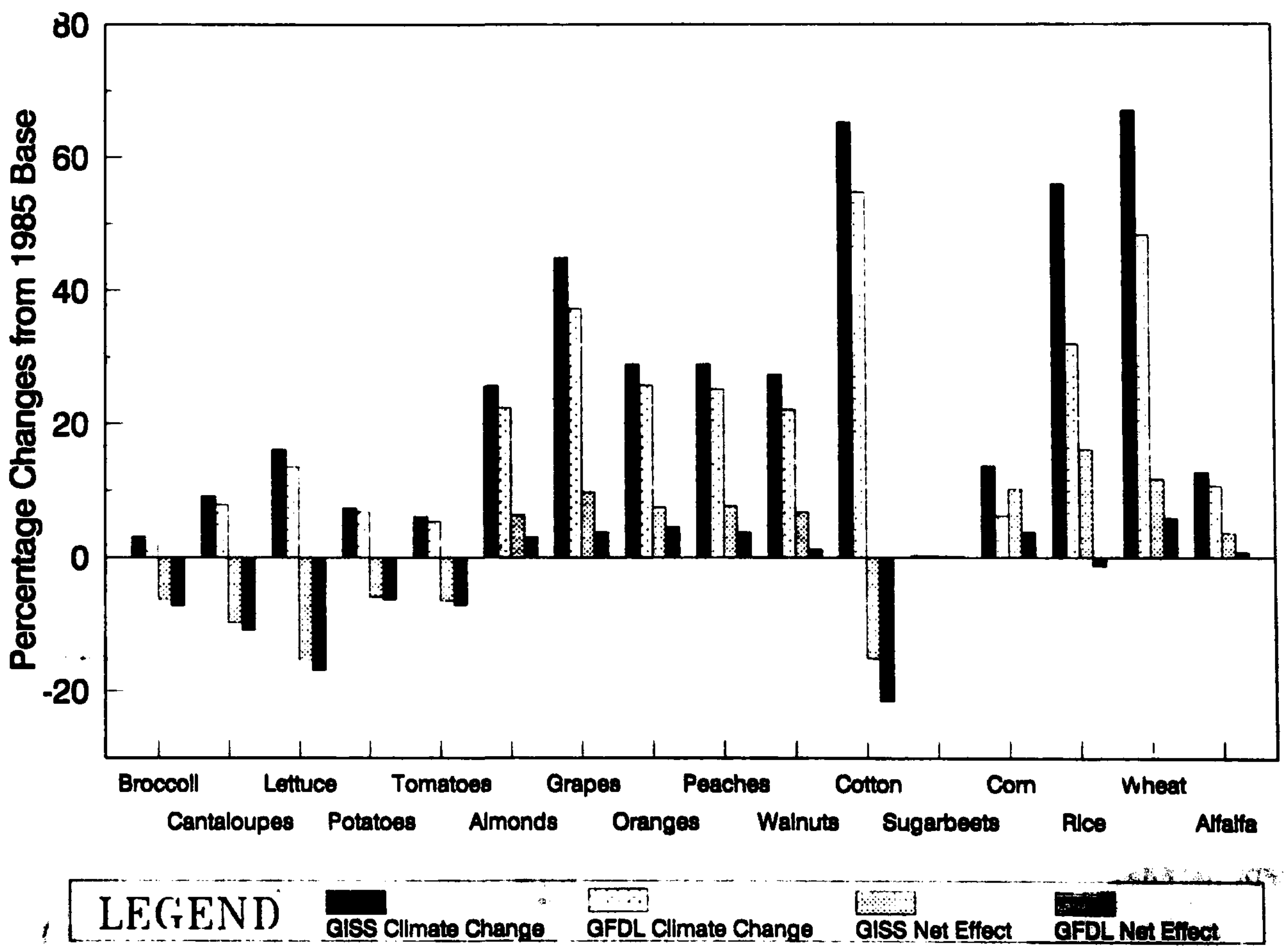
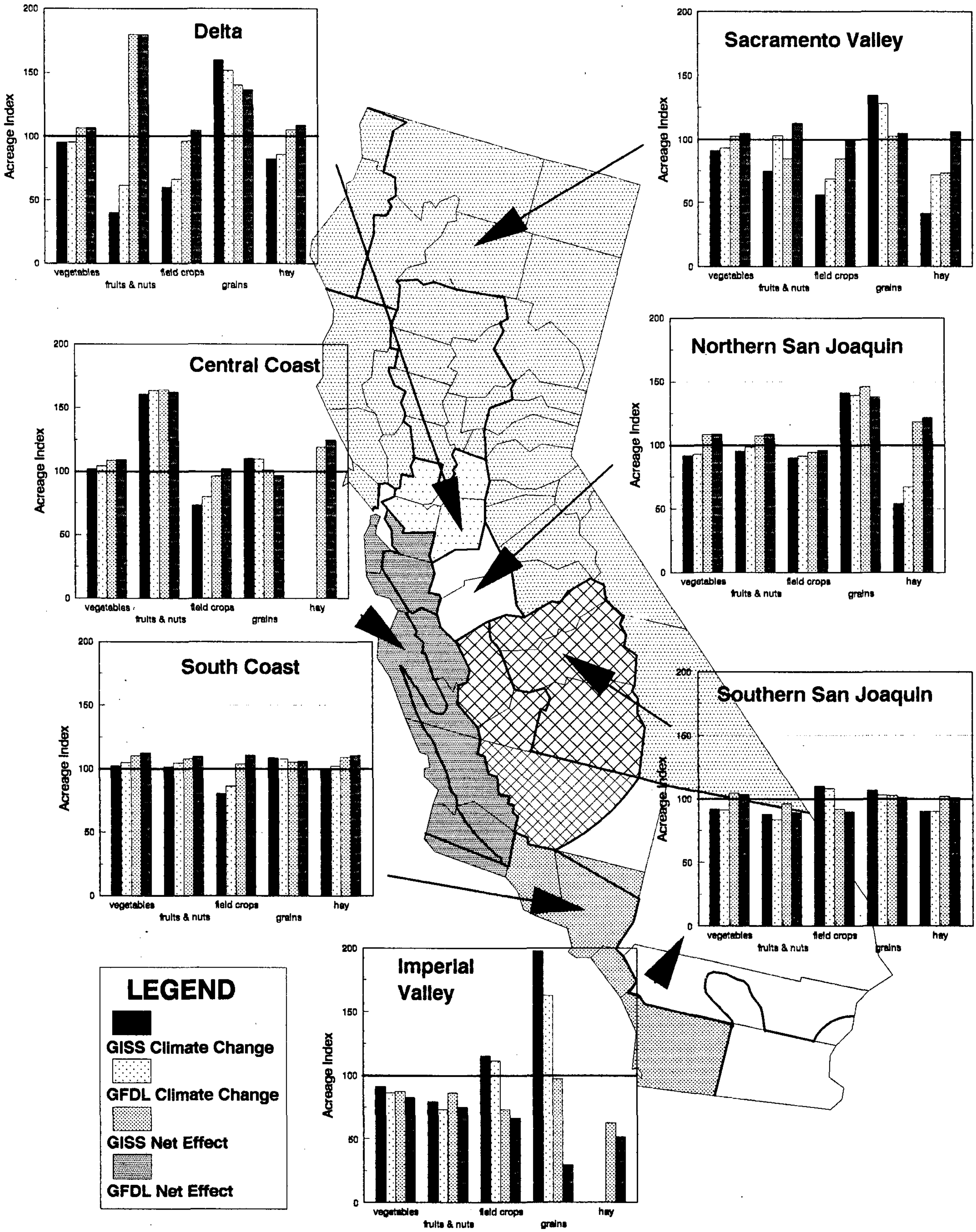


Figure 8. Regional Acreage Changes



south-to-north gradient, that fact is no cause to expect that northern regions will necessarily benefit in any way from climate change.

Figure 9 portrays the spatial pattern of resource use changes that might result from climate changes depicted by the GISS and GFDL GCMs. The values depicted are an index constructed from the ratio of scenario results to the 1985 base period. Overall, the Imperial Valley is the region most severely affected, experiencing nearly uniform reductions in crop acreage and ground and surface water use across all scenarios. The Delta and South Coast regions exhibit the least amount of change, but they represent small proportions of the state's agricultural economy.

The most dramatic changes occur in groundwater use in the Northern San Joaquin Valley between the scenarios based upon climate change impacts only and those which include CO_2 effects. These shifts are driven both by crop acreage increases in general and by alfalfa hay acreage differences in particular (see Figure 8). Alfalfa is only exceeded by rice in its water requirements. For those regions relatively less disadvantaged by climate changes, in both productivity and water supply terms (northern and coastal regions), resource changes may be beneficial. For example, in much of central California groundwater aquifers are routinely overdrafted, i.e., pumped at a rate greater than recharge. In many of these regions, groundwater is more expensive than surface water and so groundwater pumping is reduced. These reductions are accomplished through a combination of cropping pattern and on-farm irrigation efficiency changes.

SOCIETAL RESPONSES TO CLIMATE CHANGE

Given the water supply stresses expected to be caused by climate change, this case study has focused additionally on an evaluation of mitigation measures. Several alternatives ranging from the construction of new reservoir capacity to improved on-farm irrigation efficiencies can be identified. This study examines the potential of both water marketing and on-farm irrigation efficiency improvements to reduce the impact of climate changes. Irrigation efficiency improvements are both technically and economically proven (Dudek and Horner, 1982). The obstacles to more widespread adoption of such methods have included the lack of market opportunities for conserved water (Willey, 1985). Specific barriers to water marketing and remedies are discussed in Chapter 4. This linkage between on-farm investments in improving irrigation and the reform to allow water tranfers prompts their joint consideration. Water market reform has already been identified as the single most cost-effective means of meeting water demands (Howitt et al., 1980).

Previous studies of water marketing have used more aggregate methods with less detail in the agricultural sector (Howitt et al., 1980). Since increases in urban demand are already factored into the WRMI model and results from Sheer and Randall, this case study focuses on water transfers between agricultural regions. As Howitt et al. note, there are substantial opportunities and gains possible from trading water between agricultural and urban users (see Chapter 4 as well). To accomplish this analysis, CARM was modified to include a range of alternative irrigation application systems as appropriate for each crop and location. The systems evaluated included hand move sprinklers, 1/4 mile furrow with recycling, 1/2 mile furrow with recycling, each of the furrow systems without recycling, drip irrigation, and a border system. Irrigation efficiencies were varied by application system and location. They ranged from a high of 80% for drip irrigation in the South Coast and Southern San Joaquin regions to 50% for some border systems and furrow irrigation with 1/2 mile runs (Sacramento Valley, Delta, and Imperial Valley). Capital and operation costs, net of water costs, varied by system as well from a low of $17 per acre for 1/2 mile furrow on some crops to a high of $80 for drip irrigation of grapes. For water marketing, publicly developed surface water supplies were offered for sale F.O.B. Sacramento Delta to the highest bidder.

Figure 10 portrays the statewide average changes for each scenario after water marketing is introduced. Note that a base model is included for comparison as well. The combination of water marketing plus irrigation efficiency improvements yields between 1.3 and 1.6% increases in consumers' and producers' surplus. Since the water market is geared to sales to agricultural users only, the equilibrium prices prevailing under each scenario reflect differing capacities to pay. Under base conditions, water marketing produced a price of $35.15 per acre-

Figure 9. Regional Resource Changes

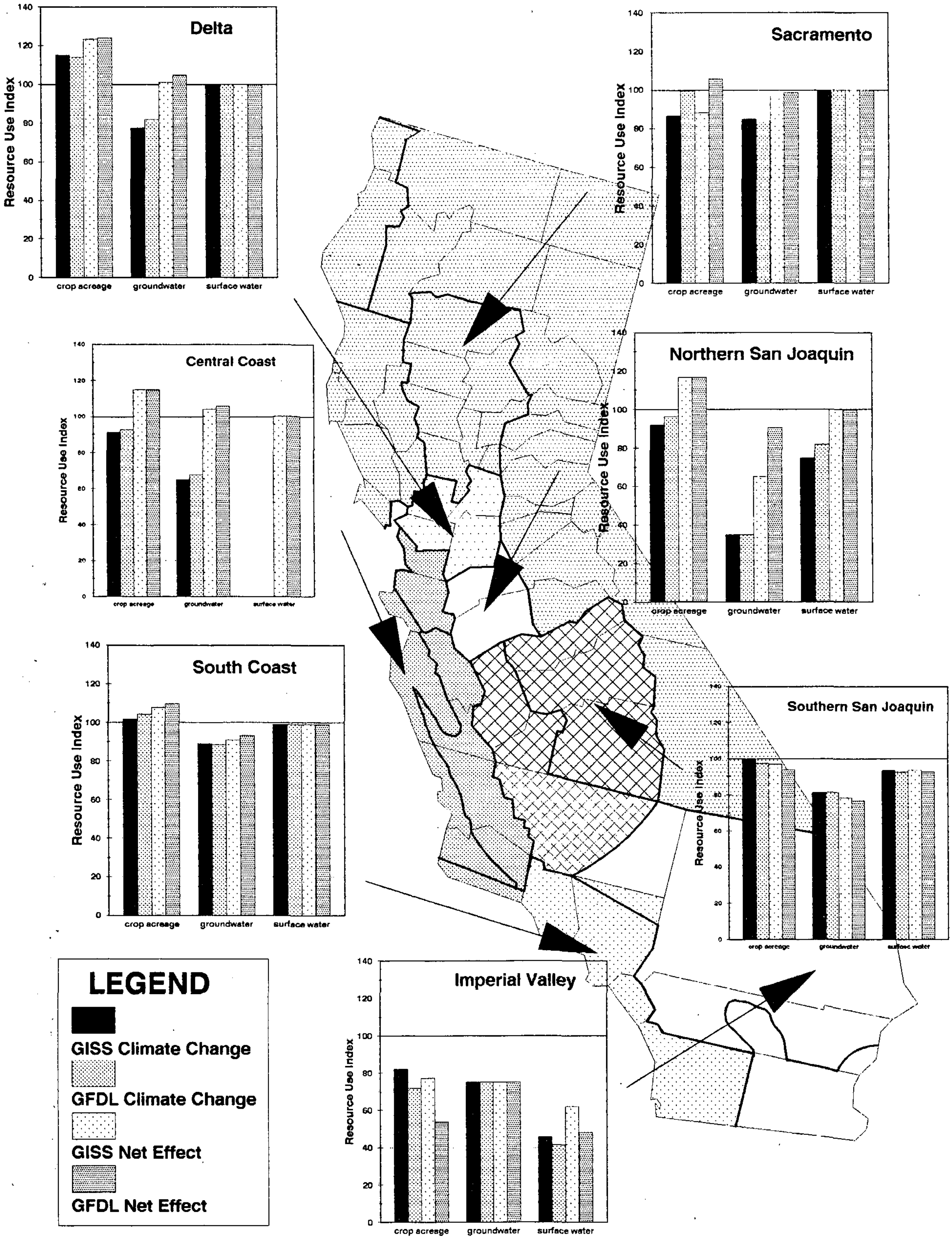
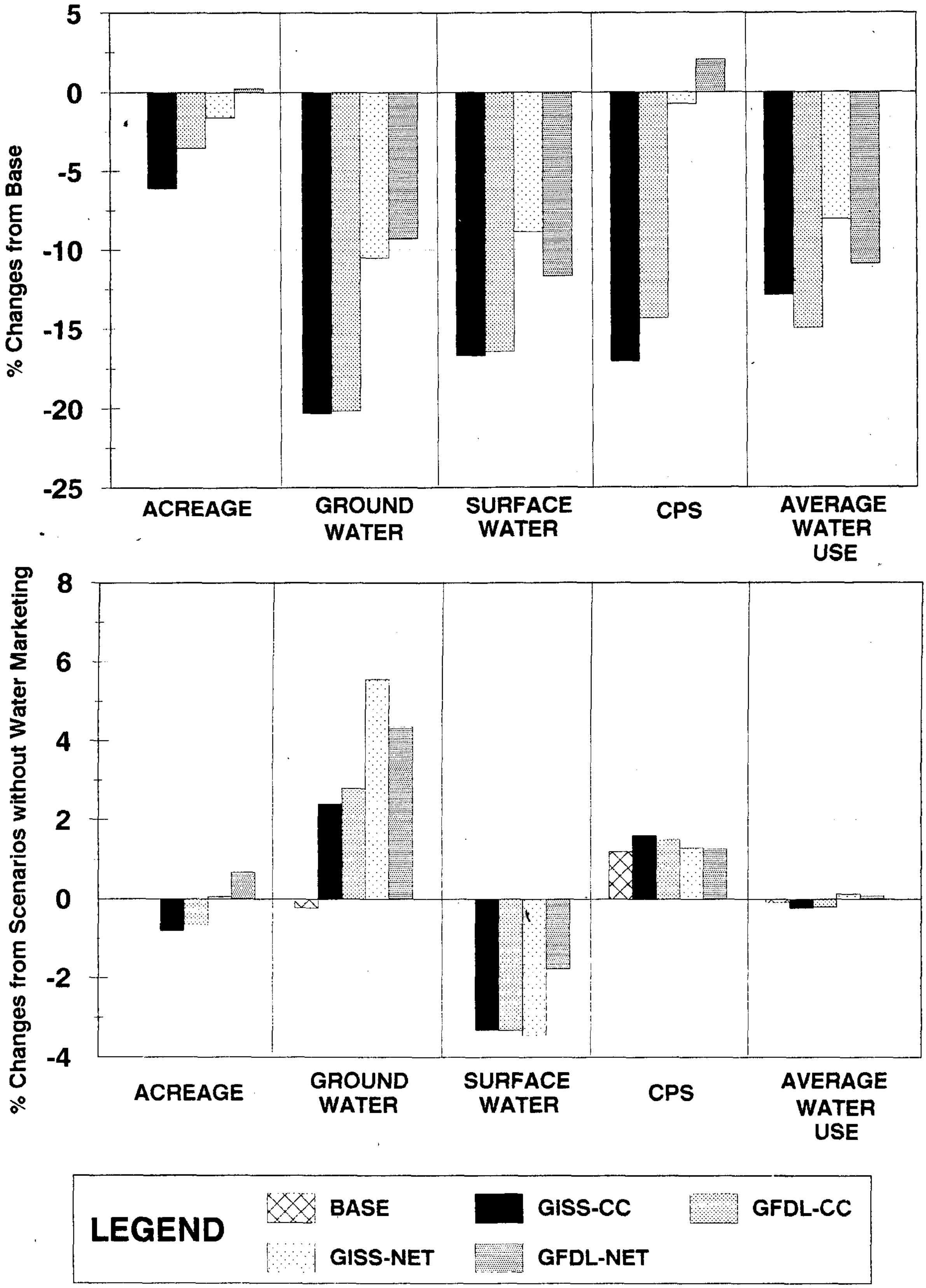


Figure 10. Overall Results



foot. Under the two climate change scenarios, water market prices declined to $27.35 For the scenarios which included CO_2 effects, prices rose to $31.78. It is important to note that these prices do not presume recovery of the substantial capital investments in the CVP or SWP. Further, these values are in sharp contrast to the costs of alternative new surface water supplies, which are estimated to range between $220 per acre-foot for an enlarged Shasta and $559 for Los Vaqueros in capital costs alone (Willey, 1985). These expansion projects have been typical of the suggestions offered by the traditional water supply agencies such as the U.S. Bureau of Reclamation and the California Department of Water Resources when confronted with the potential prospect of dealing with climate change. Water marketing alone would allow California's agricultural economy to increase the value it produces.

Overall, the results after water marketing are broadly similar: irrigated acreage decreases under climate change impacts and increases slightly with CO_2 effects, groundwater pumping is increased, and surface water use declines. Average water use per acre changes very little when comparing the marketing scenarios with those under which water is allocated by traditional means. These results are further amplified by the rough displacement of surface water supplies with increased groundwater pumping as the relative cost of these competing water supplies changes under water marketing.

Figure 11 displays the regional changes resulting from water marketing and irrigation efficiency investments. Again, both the Sacramento and Imperial Valleys show the greatest responses. In each case, crop acreage is increased, groundwater pumping is reduced, and surface water is increased. Trends in these two regions are clearly in opposition to the overall result. The Sacramento Valley is the region with the greatest potential for expansion of agricultural operations and it benefits from a market system of resource allocation which allows it to bid and acquire resources and forces others to pay higher prices for previously subsidized water supplies. The Imperial Valley benefits because it can substitute water purchased in the market, expensive though it is for more expensive groundwater, and so expand crop acreage profitably.

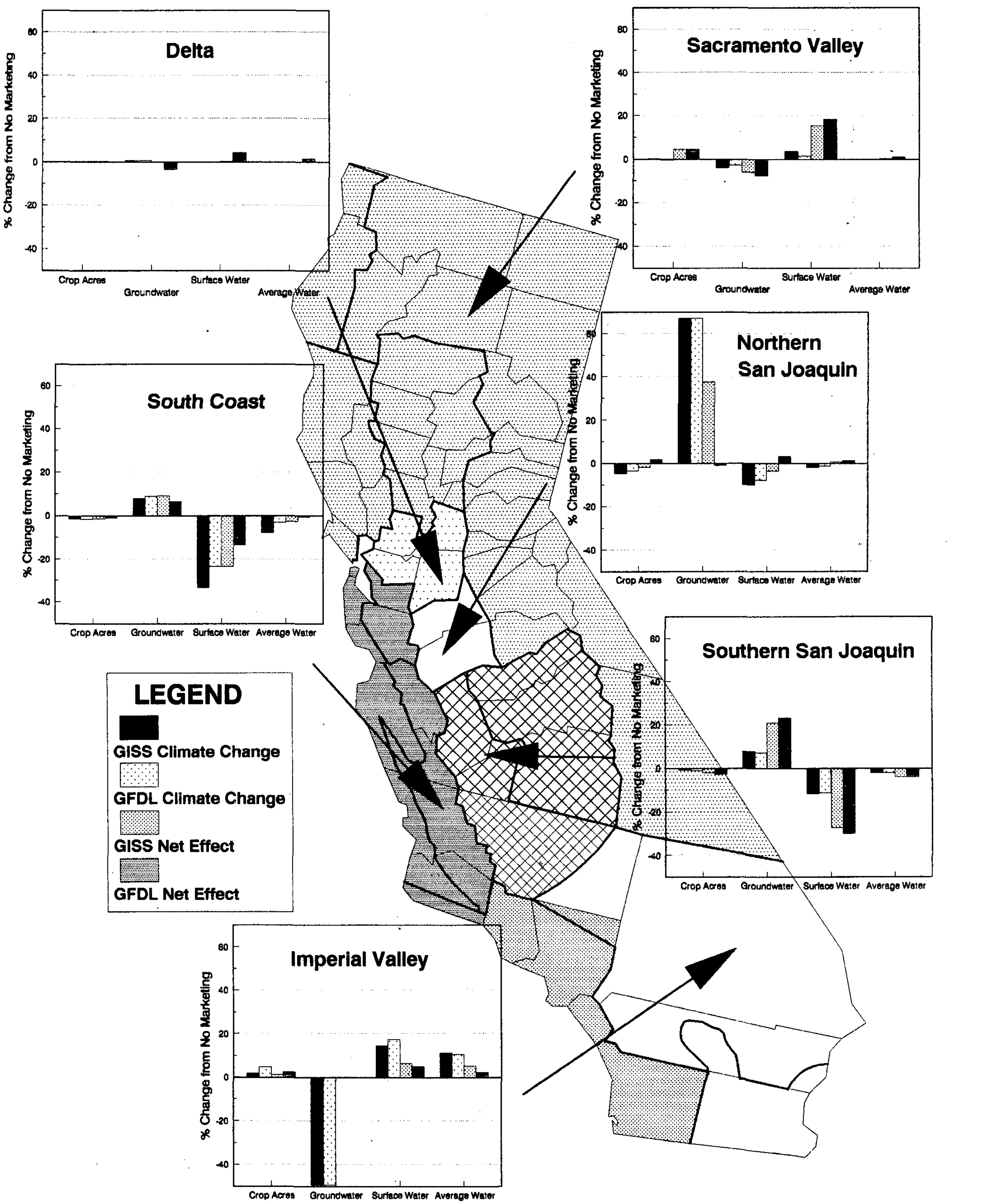
The Northern San Joaquin region experiences the greatest proportional changes of any region in its groundwater resources. Under the climate change scenarios with water marketing, groundwater pumping virtually doubles. This region of California is one which has benefited from extremely low surface water prices. When the region must suddenly face an economic competition for those supplies, it turns to groundwater and nearly doubles extraction. Nonetheless, final pumping levels are still only roughly 60% of base period levels after water marketing.

The Southern San Joaquin Valley has a pattern of changes which are the mirror image of those occurring in the Sacramento Valley. Crop acreage declines while groundwater pumping increases and surface water use decreases. This pattern reflects the region's diminished ability to compete for marketed public surface water supplies which were previously provided through substantial subsidies. Further, it highlights the importance of the future of groundwater resources in responding to the shifting resource potentials imposed by a changing climate. In the Southern San Joaquin, average water use is reduced due to cropping pattern shifts to less water-intensive crops and to more efficient irrigating methods. It is important to remember that the San Joaquin Valley suffers current severe drainage, salinity, and toxic trace element problems which are irrigation related. Improvements in irrigation efficiency would also have beneficial effects for these problems by reducing irrigation return flows (Dudek and Horner, 1982).

INCLUDING CARBON DIOXIDE EFFECTS

Throughout the preceding discussion reference has been made to the differences between scenarios evaluating climate change effects only and those which also included CO_2 (termed net). At the onset, it was clear that with two different sets of crop productivity impacts under the two general scenario types that the results would be different (see Figure 3). Most seriously divergent were the productivity results for vegetables. However, vegetables represented one of the most durable cropping patterns owing to the fact that the impacts were not as great in the first place. Overall, as illustrated in Figure 10, crop acreage was reduced for all scenarios.

Figure 11. Resource Changes Under Water Marketing



This case study highlights the importance of the accuracy of predicting crop responses to the set of simultaneous changes that will accompany the greenhouse effect. The methodology used in this study is an approximation developed from a model designed initially to assess irrigation needs. Its results seem to demonstrate substantial downside risk from either climate change effects or those which also include CO_2. These results further emphasize the need to assess any physiologic interactions between the set of stresses induced by climate change and the inadvertent fertilization provided by elevated CO_2 concentrations.

CHAPTER 4

POLICY IMPLICATIONS

AGRICULTURE

While technologic change has not been directly analyzed in this case study, it is clear that improved production techniques that reduce costs are critical. Clearly, improved irrigation application methods blunted some of the shocks analyzed with the model. Productivity improvements at a pace sustained in recent decades in agriculture would offset the impacts of even the more pessimistic climate change only scenarios. However, while some believe that new developments in biotechnology will aid in sustaining this pace of research, these gains have not been costless. Society has made huge investments in agricultural research and development and its dissemination through an elaborate extension service. Public willingness to continue this level of support has been questioned and is not assured, but climate change impacts require an invigorated and targeted research program. Also uncertain is public acceptance of new agricultural technologies. Bovine somatotropin (bst) has demonstrated the capability of boosting per animal milk output, yet it is not clear that consumers will accept this production technique. Similarly, management practices which rely upon increasing chemical use are likely to come under increased regulatory if not market pressure. Both the human health and environmental implications of chemical use are likely to weigh heavily in determining the feasibility of alternative production responses.

Of particular importance is research on water use efficiency under climate change, an area of active inquiry and controversy. Improvements in irrigation management are critical given the expected water supply reductions and the uncertainties surrounding groundwater availability. In addition, irrigation runoff is a primary source of environmental insults ranging from toxic trace elements to nutrients. Removing public subsidies to agriculture whether provided directly in the form of price supports or indirectly in the form of subsidized water would contribute to improved efficiency of water use. The improved responsiveness provided by market signals would also facilitate the regional transitions that are likely to occur. The challenge of this magnitude of policy reform looms large.

Further, agricultural operations do not have a benign impact on the environment (Dudek, 1987b). Policies to manage nonpoint sources of pollution such as sediment, fertilzer, and pesticide residues, and salinity and toxic trace elements have languished. Nonpoint source water quality problems have been identified as the single greatest impediment to achieving the nation's water quality objectives. The regional shifts in agricultural production intensity and cropping patterns described in this case study imply changes in the geographic distribution of nonpoint source loadings and resulting damages as long as current policies are pursued. Cross-compliance provisions requiring farmers to reduce off-farm loadings in exchange for the benefits provided by other public programs should be strengthened.

WATER RESOURCES

The water resource component of this study clearly demonstrates the need to question the long-term climate assumptions employed in water resource planning. Further, the results of this case study have illustrated the importance of the flexibility provided by market incentives as a means of buffering the effects of climate changes. They enable efficient reallocations of resources and provide growers with incentives for the adoption of more efficient irrigation techniques. The following sections explore these issues in the context of evolving California water conflicts.

Existing Legal and Institutional Setting

The California State Constitution states in Article X that the state's waters shall be put to "beneficial and reasonable" uses. The system of state water rights together with entitlement water for the State Water Project

(SWP) and contract water for the Federal Central Valley Project (CVP) is loosely regulated according to this criterion by the State Water Resources Control Board (WRCB) through its water rights permit system. Several types of usufructuary water rights have been established for waterfront property owners (riparian), groundwater pumpers (correlative), and diverters (appropriative). All state water rights, including those of the federal government for CVP appropriative rights south of the Delta, are governed by the Board.

There is a considerable history of support for adjustments in this system of state and federal water supply allocation to allow voluntary transfers and marketing. The Governor's Commission on Water Rights recommended in 1978 that legislative changes be made to facilitate such transfers. During the 1979-86 period, new legislation addressed, in a somewhat piecemeal fashion, various facets of state water law which had supported the "use-it-or-lose-it" status quo and fear of transfers among water rights holders. Individual legislative initiatives addressed such related topics as allowance of water rights maintenance with non-use resulting from water conservation; defining voluntary water transfers as "beneficial and reasonable"; directing the State Department of Water Resources (DWR) to facilitate water transfers through various supportive services for water rights holders; and requiring public water supply conveyance facilities to wheel transferred water with fair compensation where conveyance capacity exists.

At the same time, relevant policies supportive of water transfers have emerged elsewhere. The Western Governors' Association recommended in 1986 that water transfers should be facilitated as a means of encouraging efficiency of use. The U.S. Bureau of Reclamation recommended support for water marketing of reclamation contracts in a new policy document released in late 1987. Other states, such as Nevada and Colorado, have developed significant markets for water transfers in recent years.

<u>Status of Water Transfer Activities</u>

Despite recent legislative reforms, water transfer activities in California remain very limited. Inter-regional and inter-basin transfers, other than those already established by the operations of the CVP, the SWP, the Los Angeles Aqueduct, and the Colorado River Seven Party Agreement, remain in the planning/negotiation phase. The history of conflict between rural water supply sources and California's growing urban demands is one factor in this inactivity. The acquisition of "water ranches" in the Owens Valley by the Los Angeles Department of Water and Power during the 1920's and 1930's and ensuing depletion of the common property groundwater resources of the basin is perhaps the most representative episode in this conflict.

Despite this antagonism and other barriers to water trades noted below, there is an increasing amount of discussion and negotiation regarding specific potential water trades in several regions of the state. The following are some key examples:

- Imperial Irrigation District (IID) to Metropolitan Water District (MWD) of Southern California or others -- This is the first and potentially largest single transfer to be discussed during the legislative reforms enacted during the 1980's. As much as 400,000 acre-feet have been estimated as potential water supply availability in the Imperial Valley as a result of various irrigation system investments and management programs. The State Board processed a petition charging violation of "beneficial and reasonable use" in the IID in 1984, and required water conservation plans by the IID. Water marketing to the Los Angeles metropolitan area, most likely to the MWD, would provide the financial ability to invest in conservation facilities in the IID.

- Berrenda Mesa Water District (BMWD) to Marin Water District or others -- BMWD announced in 1987 that it intends to sell 50,000 acre-feet of its SWP entitlements. Marin has agreed to discuss this possibility, as have several other urban districts. Legal controversy regarding the respective rights to SWP entitlements of BMWD, the Kern County Water Agency, and the SWP Contractors surrounds this proposal.

- Kern County Water Bank -- This proposal is being pursued by the SWP to deliver surplus water to groundwater recharge areas in Kern County, thereby facilitating pumping of this stored water during dry years. Negotiations for acquisition by the SWP of a large area of land presently held by the Tenneco Corporation are underway. Issues of definition of surplus water and marketing rights to dry year pumping remain.

- o Los Angeles Department of Water and Power (LADWP) -- In an attempt to resolve longstanding disputes concerning its diversion of water from the Mono Lake Basin, a unique natural resource providing critical habitat for waterfowl and shorebirds, the LADWP and the Mono Lake Group (MLG) are seeking replacement water supplies of up to 100,000 acre-feet per year. A portfolio of water rights acquisition options is presently being developed by the Environmental Defense Fund for LADWP and the MLG, and negotiations with individual agricultural water rights holders began in 1988.

Barriers to Water Transfers and Prescriptions for Change

There are a number of reasons why a statewide market for water transfers is not developing rapidly in California. Some or all of the following sets of factors are often involved in protracted negotiation or failure of seemingly beneficial water transfers. Proposals for removal of these barriers are noted as well.

- o Groundwater rights -- With several important exceptions, such as the groundwater basins of the Los Angeles region, most groundwater in California has not been adjudicated. Since the resource remains in a quasi-common property status in these areas, the interface between rights to sell private rights to surface water on the one hand and to pump unadjudicated groundwater on the other is a problem which can hinder approval of some water transfer proposals. Adjudication of groundwater rights in areas selling water rights may be the ultimate answer to this problem, but this involves expensive and time-consuming procedural and technical processes. In the interim, it may be necessary to include stipulations about groundwater usage as part of an application for transfer of water rights before the State Board. As indicated in this case study, this could be an issue of increasing contention under climate change.

- o State and federal water projects -- Along with the complexities of the private water rights system in California, the state's water system is also heavily influenced by the operations of two large public water supply and distribution systems. The State Water Project (SWP) allocates its water supplies according to a scheme of entitlements established nearly three decades ago. That scheme has remained fairly rigid, and can be altered only under a consensus arrangement among the SWP contractors and the California Department of Water Resources. Although entitlement holders have been repaying the costs of SWP facilities, their legal right to sell their entitlements to the highest bidder has been questioned by state water bureaucrats and influential contractors, most notably the MWD. The resistance to the Berrenda Mesa Water District's proposal noted above is a case-in-point. The introduction of marketing flexibility into the SWP entitlement scheme will probably require some combination of legislative reforms and litigation.

  The Federal Central Valley Project (CVP) is also a system based on fixed contractual rights of the reclamation districts which it was originally intended to serve. The right of these districts, and/or of the individual farmers which they serve, to market federal contract water is an unsettled issue. While there are a number of individual irrigators within reclamation districts who are interested in leasing or outright sales of their contractual rights, there is often resistance from others within the district or from outside political and bureaucratic forces. The U.S. Bureau of Reclamation would have to agree to such transfers, and policies pronounced by the Department of Interior in 1987 are favorable to voluntary transfers of reclamation water. Such transfers have occurred in other states, with approval of the Secretary of the Interior. The barriers here appear to be political and not legal.

  The state and federal systems reached an agreement in 1986 called the Coordinated Operating Agreement (COA) which was ratified by Congress (H.R. 3113). The COA allows the SWP to purchase up to 250,000 acre-feet per year from the CVP for about 20 years. The CVP is also allowed to sell additional water, which subsequently has been determined to be up to 1 million acre-feet per year.

Since the water transfers and sales allowed by the COA will occur at rates which are consistent with the financial requirements of the CVP, those rates will be cost-based and subsidized and, therefore, will be considerably lower than water prices which would result from a value-driven market setting. The COA water transfers will be based upon bureaucratic as opposed to market allocations. While this will have beneficial effects for those fortunate enough to be able to acquire this cheap water, it will also have the effect of stifling the development of market-based transfers for a considerable period of time. A combination of allocation of some COA water for mitigation of the environmental costs of the CVP together with a bidding process for COA water would alleviate this problem. This issue is now under active discussion in the context of the U.S. Bureau of Reclamation's Environmental Impact Statement process for its COA water marketing program.

- Third-party issues -- Most proposed water trades involve impacts on other water users within the seller's region. Surface return flows or groundwater recharge which in turn supplies other water uses are often affected. Legal rights of these third parties are variable, but their political power is sometimes significant. Transfers of consumptive uses only may be the solution.

- Local economic impacts -- Fear of adverse impacts on some elements of the local economies of potential water-selling areas is frequently an additional political barrier. In addition, county property tax revenue deterioration could result if agricultural lands are retired from production as part of a water transfer. In-lieu taxation of retired lands -- continued payment to the county of these taxes -- and establishment of rural economic trust funds are often proposed as compensation for these impacts. This amounts to a severance tax placed on water transfers, and would result in reduced amounts of such transfers.

- Public trust issues -- Court rulings during the 1980's have opened the possibility that existing water rights may be usurped at least in priority of right by what are often undefined public rights to water for a variety of uses. Important cases involving public trust rights for Mono Lake and the Delta have become a consideration in defining and negotiating the transfer of private water rights. Public trust protection based on acquisitions, as opposed to taking, may resolve this apparent inconsistency.

- Uncertainty of water rights and of transfer contracts -- Water rights do not have the status of private property rights in California. Appropriative rights, which are the prime candidates for transfer, are evidenced by permits for time, place, and amount of diversion and manner and place of use which are issued and enforced by the State Board. These permits are not equivalent to real estate deeds as they are in other states, such as Nevada. Legislation or judicial findings defining water rights permits as real property may be the only solution to these uncertainties.

Water policy reform is an active element of California's contemporary political scene. It offers substantial benefits for many environmental and resource problems plaguing the state. The benefits that water marketing offers in mitigating climate change impacts is only one more reason to expedite these reforms.

THE ENVIRONMENT

Changes in surface water supplies and the location of water use in California were highlighted in the results. These changes are likely to have two main environmental impacts. One would be the demand for more dams and reservoirs. The few remaining free-flowing rivers support natural ecosystems and recreational opportunities increasingly prized for their scarcity. Thus, we would expect increased conflict over the allocation of water resources to maintain ecosystem values and wildlife. Temperature increases will affect both managed and unmanaged watercourses with possible impacts on cold water species distribution.

While changes in crop productivity, soil moisture availability, precipitation patterns, and water resource availability are expected to have profound impacts upon the location of agricultural production, these impacts may be even larger upon ecological systems. Areas currently devoted to wildlife habitat due to their marginal potential for agricultural development may come under pressure as climate changes alter favorably their suitability for crop production. The basic carrying capacity of existing habitats may be substantially altered.

We do not yet fully comprehend the consequences of all of the potential environmental changes taken together. For example, natural systems will be stressed simultaneously by increased ultraviolet radiation which is harmful to almost all life forms (Teramura), a changed climate with increased temperatures and altered rainfall and weather patterns, as well as more traditional pollutants such as photochemical oxidants and acid deposition. We have made huge investments in the conservation of natural environments and the species that they are designed to protect in this country. We have committed vast sums for the maintenance of ecological reserves, wildlife refuges, and national parks. Wild plant and animal species heavily dependent upon protected areas may be severely disrupted as these biospheric changes cause ecological shifts. Land-use patterns outside these protected areas may prevent species from "retreating" to other suitable habitats. Taken together, these effects may mean that the considerable sums already "sunk" in conservation efforts will be lost. This is but a single measure of the severity of the problem and the resources at risk. Shifts in the location of agricultural production could play a substantial role in the future viability of these natural systems.

CHAPTER 5

CONCLUSIONS

The conclusions from this case study are best presented against the backdrop of an overview of the results of the scenario experiments. Figure 10 summarized these results with reference to the base period. From the preceding sections, it is clear that the results differ in magnitude only depending on the basis of the treatment of carbon dioxide effects. Each of the scenarios analyzing climate change productivity impacts alone (labeled CC) show acreage, water use, and economic values reduced. Those which include CO_2 effects (termed net) have less severe economic impacts. Water use reductions persist since reduced SWP surface water deliveries are unaffected by the treatment of CO_2. Consequently, in all scenarios water use is affected with resulting regional impacts which may be amplified by California water politics. These results demonstrate the importance of integrating agricultural impact assessments with studies of changes in the availability or suitability of critical agricultural resources.

This study also investigated the potential of changes in both on-farm management and public policy to mitigate the impacts of climate changes. As Figure 10 illustrates, scenarios which incorporate water marketing produce greater economic surpluses and thus blunt the force of climate change impacts. As that analysis indicates, the benefits of current reform would not be inconsequential. However, in each case groundwater pumping also increases. For regions such as the San Joaquin Valley which already have overdraft problems, the economic feasibility of continuing current trends is uncertain. Water marketing and irrigation efficiency improvements are not a panacea for climate change impacts upon agriculture. Nonetheless, proposed conservation investments such as those described for the Imperial Irrigation District could be right on the mark given potential impacts on that region.

This study has demonstrated that economic feedback is a critical element of impact assessment. In addition, the introduction of markets can facilitate adjustments and reduce costs. However, the scope of resources at risk in California from climate change is narrowly construed in this study and there are a diversity of values not captured in market processes. The potential for increased stress on natural systems and species is a likely outcome and one for which market mechanisms are poorly developed.

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EFFECTS OF PROJECTED CO_2-INDUCED CLIMATIC CHANGES ON IRRIGATION WATER REQUIREMENTS IN THE GREAT PLAINS STATES (TEXAS, OKLAHOMA, KANSAS, AND NEBRASKA)

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FINDINGS[1]

In general, based on averages of the two general circulation model (GCM) $2xCO_2$ climatic scenarios and the likely occurrence of only moderate CO_2-induced increases in bulk stomatal diffusion resistances of crop canopies of about 20%, seasonal irrigation requirements for a mixture of alfalfa, corn, and winter wheat in the Great Plains region will likely increase by about 15% under the $2xCO_2$ scenario. The following findings illustrate the causes and effects of these changes.

1. Lengths of potential growing seasons were increased in all parts of the Great Plains region, with magnitudes of increases ranging from 0 to 28%. Increases were less in the lower latitudes (less than 30 degrees latitude), as much of this region currently has an almost all-year growing season. Although the two general circulation models (GISS and GFDL) predicted different climatic scenarios, projected changes in potential growing season lengths were not significantly different.

2. Changes in season lengths were heavily influenced by the timing of planting dates. Growing season lengths for corn were projected to shorten in regions where current planting dates are in April and May (northern latitudes). However, regions with corn planting dates in February and March are expected to experience increases in the lengths of growing seasons. These increases will likely occur when planting dates under the GCM climatic scenarios shift to January and early February periods, during which air temperatures and solar radiation levels are low. Crop development rates will be slower during these planting periods than under current climatic conditions where crops are planted later when solar radiation levels are higher.

3. Growing seasons for winter wheat will likely be shortened under the GCM scenarios owing to later planting dates in the fall when temperatures will be cool enough to eliminate moisture stress to seedlings, and in most instances, owing to earlier harvest dates resulting from more rapid growth and earlier spring green-ups resulting from higher air temperatures.

4. Major changes in irrigation water requirements were predicted at all 17 stations. The most significant changes will be the persistent increases in seasonal net irrigation water requirements for crops that take advantage of longer growing seasons such as alfalfa. These increases will be driven by projected increases in air temperature, wind, and solar radiation, and the lengthening of growing seasons. Decreases in seasonal net irrigation requirements were predicted for winter wheat and corn in most regions, especially if water vapor diffusion resistances of crop canopies increase, as is postulated by some recent research. Decreases were also caused by the shortening of growing seasons caused by projected increases in air temperature and solar radiation, which accelerated crop phenologies.

5. Adaptation of a longer-season variety of winter wheat having a 20% greater growing season solar radiation/degree day requirement would likely increase growing season lengths by 15 to 20 days in the Great Plains and would increase seasonal irrigation requirements by about 10% in Nebraska, Kansas, and Texas and by about 20% in Oklahoma as compared to current cultivars under the $2xCO_2$ settings. Thus, if farmers adapted to crop varieties with higher seasonal environmental energy requirements to more fully utilize increased levels of available solar radiation and temperature by changing to longer season crop varieties and/or increasing cropping intensity, irrigation water requirements would increase.

6. Irrigation water requirements during peak periods increased in almost all areas. These increases may require larger capacity irrigation systems and peak energy demands, but may not necessarily increase total

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seasonal water and energy requirements. Annual drafts of the Ogallala aquifer may also increase by 15% based on projected increases in seasonal irrigation water requirements.

7. Predicted increases in peak and seasonal irrigation water requirements would be ameliorated somewhat by postulated increases in values for bulk stomatal diffusion resistances resulting from elevated atmospheric CO_2 concentrations.

8. Plant canopy (leaf) temperatures were predicted to increase above current baseline values for all crops and sites studied. Projected increases in leaf temperatures may have detrimental effects on photosynthetic activities and crop yields. They also make crops more sensitive to moisture stress.

CHAPTER 1

INTRODUCTION

Carbon dioxide concentration in the atmosphere has been increasing and is expected to double by the year 2015 (Gribbin, 1981). Increase in carbon dioxide concentration will likely have a profound effect on the climatic energy balance, as carbon dioxide (CO_2) is fairly transparent to solar radiation but is largely opaque to thermal radiation, causing an increase in net radiation (Kimball and Idso, 1983). The increase in atmospheric CO_2 is predicted to result in an increase in air temperature, net solar radiation, and humidity. Amounts and distribution of wind and precipitation may also be affected. This modification of the plant environment is expected to increase photosynthetic activities and influence stomatal regulation of water use. These changes are likely to have a major effect on irrigation water requirements.

Irrigation is a major consumer of discretionary water in the United States. Any increase in irrigation water consumption due to increased evaporative demands may accelerate depletion of limited ground and surface water resources. In addition, in water-short areas or in areas under rainfed agriculture, increased evaporation may increase differences between precipitation amounts and evaporative demands, thereby reducing available water supplies in aquifers and streams and increasing crop water stress and decreasing yields.

OBJECTIVES AND SCOPE OF THE STUDY

The purpose of this study was to provide information for assessing environmental and socioeconomic impacts of increasing CO_2 concentration on the agricultural sector in general and water management in particular. The objective of this study was to determine the effect of projected climatic and bulk stomatal diffusion resistance changes on irrigation water requirements in Texas, Oklahoma, Kansas, and Nebraska. Specific tasks undertaken included:

1. Computation of daily estimates of reference and crop evapotranspiration (E_t) over a 30-year period (1951-1980) using weather data collected from 17 locations in the region.

2. Computation of daily soil moisture-E_t water balances for each weather station location for three crops (alfalfa, corn, and winter wheat), three typical soil types representative of soils in the surrounding areas, and for center pivot and surface irrigation methods.

3. Determination of baseline (current CO_2 level) seasonal and peak monthly evapotranspiration and net irrigation requirements for each of the site-soil-crop system combinations assuming irrigation on demand, no leaching requirements, and 100% irrigation water application efficiency.

4. Repetition of tasks 1, 2, and 3 for the same period of record with adjustments in climatic parameters (air temperature, humidity, solar radiation, windspeed and precipitation) based on projected climatic scenarios and conditions as provided by the National Center for Atmospheric Research (NCAR), from General Circulation Models (GCMs) operated by the Goddard Institute for Space Studies (GISS), and by the Geophysical Fluid Dynamics Laboratory (GFDL).

5. Repetition of task 4 using four levels of increased plant bulk stomatal vapor diffusion resistance that may result from increased atmospheric carbon dioxide content.

DESCRIPTION OF THE ECOLOGICAL SYSTEM

Geographic Area Covered

This study covers four states of the Great Plains Region, namely Nebraska, Kansas, Oklahoma, and Texas. This area is immense and varies in topography, soil, water resources, and climate. Although most of the region is sparsely populated, its agricultural production is significant as it produces approximately 40% of the nation's sorghum, 25% of cotton, and 17% of wheat (Schaffer and Schaffer, 1984).

Nebraska. The landscape of Nebraska changes from gently rolling prairie in the east to rounded sandhills in the north-central part. The elevation rises from less than 300 meters in the south to 400 meters in the northeast. The elevation also increases westwards to about 900 meters in the southwest and 1500 meters in the northwest. The climate of the area is characterized by light rainfall, low humidity, hot summers, cold winters, great variation in temperature and rainfall from year to year, and frequent changes in weather from day to day. The precipitation of the state decreases from about 850 mm in the southeastern corner to about 350 mm near the western border (Stevens, 1959). The economy of the state is dependent heavily on agriculture. The principal crops are corn, soybeans, sorghum, hay, winter wheat, and oats. Approximately 8 million acres are now irrigated in Nebraska.

Kansas. The elevation across Kansas gradually rises from 240 to 300 meters above sea level in the eastern counties to approximately 1100 meters at the Colorado line. Precipitation ranges from 1000 mm in southeastern counties to 750-900 mm in the northeast, and decreases gradually westward to about 400 mm at the Colorado line. The distribution of precipitation favors crop production with about 75% of the year's total occurring during the crop growing season (Robb, 1959). The principal crops are wheat, corn, and sorghum.

Oklahoma. The terrain of Oklahoma is mostly rolling plains, sloping downward from west to east. The climate is characterized by long and occasionally hot summers and short and less rigorous winters. Precipitation decreases sharply from east to west, about 1400 mm in the southeastern corner of the state, to 380 mm in the extreme western areas (Curry, 1970). The principal crops are wheat, cotton, corn, and sorghum.

Texas. The changes in climate across Texas are considerable but gradual. The average annual rainfall ranges from 1400 mm in the eastern border to about 200 mm in the western extremity of the state. Rainfall occurs most frequently in late spring. East of 95 degrees longitude, the rainfall is fairly evenly distributed throughout the year and exceeds average potential evapotranspiration, whereas west of this meridian, potential evapotranspiration exceeds precipitation (Orton, 1969). The principal crops are cotton, sorghum, winter wheat, and rice. Other important crops are corn, oats, peanuts, soybeans, potatoes, alfalfa, citrus, and vegetables.

Irrigation and Water Issues

Irrigated agriculture is the lifeblood of much of the Great Plains region. Researchers have shown that whereas climatic, crop, and soil factors may limit crop productivity, availability of water is the most critical factor in determining crop development, survival, and productivity (Dale and Shaw, 1965; Musick et al., 1976; Rosenberg et al., 1983). In many locations, irrigated agriculture has replaced native vegetation, low-value crops and dryland farming, thereby improving the productivity of land and strengthening the regional and local economies. Table 1 shows the extent of irrigated agriculture in the region.

The depletion of the water in the Ogallala aquifer threatens irrigated agriculture in this region. Schaffer and Schaffer (1984) projected that Texas, New Mexico, and Oklahoma may experience annual water use declines of 53% by the year 2020 due to aquifer depletion, and that annual water use may increase 33% in the more northern states of Kansas, Colorado, and Nebraska.

Table 1. Irrigated Land by State

State	Irrigated crop land as a percent of total cropland harvested	Irrigated land as a percent of US total irrigated land
Nebraska	34	11
Kansas	less than 15	5
Oklahoma	less than 15	less than 1
Texas	31	14

Source: USDA, 1982.

Water issues in the region are complicated by socioeconomic and environmental factors. The development and exploitation costs of surface and groundwater have soared over the last few decades making many technically feasible projects unaffordable. In some areas deteriorating water quality brought about by increasing pollution and diminishing flows is threatening recreation, wildlife, and fishery habitats.

LITERATURE REVIEW

Crop water use, irrigation water requirements, and precipitation adequacies are governed largely by the evaporative process in which energy from radiative and convective heat sources is converted into the latent form of energy through conversion of water from the liquid to vapor state. The modification of the atmospheric environment by human activities can affect the evaporative process by varying amounts of energy available for evaporation. This may occur through increased air temperatures resulting from increased levels of carbon dioxide and, to a lesser extent, through changes in humidity levels and turbulent mixing (windiness) of the lower atmosphere and through increases or decreases in solar radiation at the earth's surface as a consequence of CO_2 increase.

Studies of the sensitivity of the evaporation or evapotranspiration (E_t) processes to changes in net radiation, air temperature, dew point temperature, and windspeed have been conducted by Saxton (1975), Brockway et al. (1985), and Rosenberg et al. (1988). Brockway et al. (1985) found that estimates of E_t increased by 4.5 to 5.0% per degree Celsius increase in average air temperature, depending on which E_t estimating equation was used. Estimates of E_t decreased by about 1.5% per degree Celsius increase in dew point temperature, and increased by about 2.3% per kilowatt per square meter increase in solar radiation intensity. Estimated E_t increased from 6 to 12% per m/s increase in windspeed. Results of the Brockway study are specific to climatic conditions in southern Idaho, but indicate relative sensitivities of E_t to changes in climate or local environment. Rosenberg et al. (1988) observed increases of about 4 to 8% in estimated E_t from a Kansas grassland per degree Celsius for high and low values of Et demand and about 8% per degree for forests. They also used the Penman-Monteith (Monteith, 1965) E_t equation and predicted the following relationships:

1. One percent increase in net radiation increased E_t by 0.6%;

2. One percent increase in air vapor content increased E_t by about 0.2 to 0.8%;

3. Increasing temperature by 3°C and net radiation by 10% and decreasing vapor content by 10% increased E_t by 20 to 40%;

4. Increasing LAI by 15% increased E_t by 5%; and

5. Increasing stomatal resistance by 40% decreased E_t by 15%.

ORGANIZATION OF THE REPORT

The remainder of this report describes the evapotranspiration environment, the model used to estimate the potential impacts of climate change and increased stomatal diffusion resistance on irrigation water requirements in the southern and central Great Plains, the results and limitations of the study, and the environmental and socioeconomic implications of the results.

CHAPTER 2

METHODOLOGY

This section is divided into three parts. The first part is a review of material pertinent to the development of the irrigation water requirement model. The second part describes the model development. The last part describes data used.

THE ENVIRONMENT AND EVAPOTRANSPIRATION

Climatic Factors

Climatic variables which have a direct bearing on irrigation water requirements are evaporative energy, temperature, windspeed, relative humidity, and precipitation. Identification of these variables, assessment of their relative importance, and an appreciation of the interrelationship among the variables is essential in predicting irrigation water requirements.

Evaporative Energy. The energy that is consumed by the evapotranspiration process is supplied mainly from radiation energy and advective energy. The energy budget analysis method attempts to account for major heat exchange processes and is represented by the equation:

$$R_n = H + LE + G + P \qquad [1]$$

where R_n is net radiation, H = vertical sensible heat flux to or away from the surface, LE = evapotranspiration energy flux, G = heat flux into or out of the soil, and P is miscellaneous energy consumed by photosynthesis and associated activities (usually negligible).

According to Eq. 1, energy reaching an evaporative surface by way of radiation is dispersed through evapotranspiration, or is convected from the surface to the atmosphere or is conducted into the soil. Net radiation is typically the major source of energy for evapotranspiration in humid regions. In more arid regions, sensible heat flux to vegetation can provide as much energy for E_t as R_n. Advection is the process by which heat is transported horizontally by the mass motion of the atmosphere. The origin of sensible heat in advective air depends on surface conditions, especially the availability of water for evapotranspiration. The availability of water determines the partitioning of the available energy among sensible, latent, and soil heat fluxes. For moist surfaces, almost all net radiative energy is consumed as latent heat, whereas under dry surface conditions, latent heat is reduced and sensible heat is generated. This sensible heat can then be advected to downwind areas, thereby increasing evaporative demands there. Rosenberg (1969) noted that sensible heat advection was a major component of energy balance in the Great Plains region. Rosenberg and Verma (1978) reported that during the extended drought of 1976, E_t from an irrigated alfalfa field at Mead, Nebraska, ranged from 5 to over 14 mm day^{-1} even though R_n provided sufficient energy for only 7 mm day^{-1}.

Air Temperature. Air temperature affects the evapotranspiration process as follows:

1. The amount of water vapor that the air can hold increases exponentially with temperature. As air temperature increases, the vapor pressure deficit of the air increases, consequently increasing evapotranspiration demand;

2. Higher leaf temperatures increase saturation vapor pressure inside leaf stomatal cavities, thereby forcing more vapor out of the leaf and increasing evapotranspiration;

3. Warm, dry air blowing toward the evaporative surface may supply advected sensible heat energy to the evapotranspiration process;

4. Slightly less energy is required to evaporate water at higher temperatures;

5. Increased temperature is accompanied by an increase in stomatal openings, indicating attempts by some plants in some environments to increase evaporative cooling of plant tissues (Hofstra and Hesketh, 1969);

6. Increased air temperatures will generally increase the rate of crop growth and phenology, thereby decreasing the length of time between plant emergence and maturity for annual crops.

All the above phenomena increase the evaporative demand. The following phenomena would tend to moderate evaporative demand:

1. Higher surface and air temperatures increase the net outgoing longwave radiation at the evaporating surface, thereby decreasing net radiation; and

2. Decrease in season length resulting from increased rate of crop growth will tend to reduce the magnitude of the increase in seasonal E_t requirement.

Wind. The presence of wind-induced atmospheric turbulence plays an important role in the evapotranspiration process by facilitating the movement of moist air away from plants and the transport of sensible heat from dry regions into the plant canopy. Air turbulence is by far the major transfer mechanism for both sensible and latent energy exchange within and above the plant canopy.

Humidity. The humidity of the air near the plants is a rough indicator of the drying power of the atmospheric air under a given condition. The inclusion of the air humidity effect in the Penman type of evapotranspiration equation is typically as a saturation vapor pressure deficit (e_a - e_d) at a standard height above the ground surface.

Effects of Changing Climates

Weather is an extremely stochastic process with many complexities and interactions among parameters. This complicates farmers' decision-making and management strategies. Farmers of the Great Plains frequently cope with variations in growing season precipitation of more than 60 mm and variation in length of season of two weeks or more.

Climatic variability also plays an important role in selection of specific plant varieties and genotypes. In 1920, hard-red winter wheat production ranged from northern Texas to central Nebraska and from eastern Colorado to central Illinois. Since then, production has been adapted to regions with lower mean annual precipitation, lower average air temperature, and changes in growing season lengths as it has spread north-westward to the Canadian border and southward to central Texas (Rosenberg, 1982). Rosenberg (1982) noted that equivalent yields were obtained in western Nebraska and central Texas, the latter having 300 mm more precipitation but an average annual temperature that is 8.5°C warmer. This example demonstrates agriculture's capacity to cope with changes in climatic conditions by adapting genotype and crop husbandry.

Increased CO_2 in the air is expected to increase photosynthetic activities and to decrease transpiration, especially in C_3 species (Allen et al., 1985). These changes will increase the water-use efficiencies[2] (WUE) of

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[2]Water-use efficiency is defined as the ratio of mass of usable biomas produced to mass of evapotranspirated water (Allen, 1986a and Kimball and Idso, 1983).

most agricultural crops. Increases in WUE will be beneficial from agronomic and economic points of view, as less precipitation or irrigation water is required to produce normal yields. However, yield increases resulting from increased photosynthetic activities may be partially offset by shortened growing seasons having less solar radiation energy owing to accelerated crop phenologies.

Plant Factors

Leaf area index (LAI) is the ratio of leaf surface area (one side only) to the area of underlying ground, and is an indicator of the amount of foliage in a stand of plants. Generally, as leaf area increases, the number of stomata increase and evaporation increases because the bulk stomatal resistance of the canopy to vapor diffusion decreases. Crop height has a direct influence on evaporation because tall plants are more aerodynamically rough, thereby promoting more mixing of air in and above the plant canopy and causing increased transfer of momentum, heat, and latent energy from or to the atmosphere. Broad-leafed crops may transpire more than grasses of the same height and leaf area, as the size of the broad leaves tends to be less efficient in dissipating heat thorough convective transfer and may therefore retain more energy for evapotranspiration than does the size of leaves (Rosenberg et al., 1983).

Increases in atmospheric CO_2 content are also likely to have pronounced effects on plant growth, yield, stomatal regulation, and water-use efficiencies. The magnitudes of the effects may depend to some part on the type of photosynthetic pathway regulating CO_2 uptake. C_3 plants (including small grains, such as wheat and leguminous species, such as alfalfa) have been found to be more responsive to elevated CO_2 levels in the atmosphere than C_4 plants (corn, sorghum, millet, sugarcane) (Allen et al., 1985).

Stomatal resistance (r_s) is a primary determinant of the transport of water vapor from plants to the atmosphere. Any increase in r_s due to elevated CO_2 levels will likely decrease evaporation from plant leaves. However, several feedback mechanisms in the plant's microclimate partially offset the increase in r_s (Allen et al., 1985), including the following:

1. Elevation of internal leaf temperatures due to decreased conversion of net radiation into latent heat causes increased vapor pressure inside leaves and increases the diffusion of water vapor through the partially closed stomata;

2. Increases in air temperature due to transfer of sensible heat from the leaf surface to air result in an increased vapor pressure deficit causing increased E_t demand; and

3. Increased LAI from elevated levels of CO_2 results in lower bulk stomatal resistance (r_c) to water vapor diffusion.

Kimball and Idso (1983) estimated that doubling CO_2 concentrations would increase stomatal resistances and would reduce transpiration an average of 34%. They also noted that decreases in plant evapotranspiration (if occurring) would enable wheat production to spread into more arid areas.

MODEL DEVELOPMENT

Governing Equations

Evapotranspiration. Estimates of evapotranspiration in this study were made using a Penman-Monteith resistance model with variable bulk stomatal (canopy) and aerodynamic resistances. This model had been found, during previous studies, to provide reliable and consistent daily estimates of alfalfa and grass reference E_t when proper heights and leaf areas of the evaporating surfaces are considered (Allen, 1986b; Allen et al., 1988).

The form of the Monteith version of the Penman equation used in this study for estimation of reference E_t on a daily average basis is:

$$E_t = \frac{\Delta(R_n - G) + 0.0864\rho c_p (e_a - e_d)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \quad [2]$$

where E_t is the evaporation flux (MJ m^{-2} d^{-1}), R_n is net radiation flux to the plant canopy (MJ m^{-2} d^{-1}), G is soil heat flux (MJ m^{-2} d^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), ρ is the density of the air (kg m^{-3}), c_p is specific heat of the air (J kg^{-1} °C^{-1}), e_a is the mean saturation vapor pressure of the air at the current air temperature (kPa), e_d is the saturation vapor pressure of the air at the dew point temperature (actual vapor pressure of the air) (kPa), r_a is the aerodynamic resistance to vapor and heat diffusion (s m^{-1}), γ is the pyschrometric constant (kPa °C^{-1}), and r_c is the bulk stomatal (canopy) resistance (s m^{-1}).

Aerodynamic Resistance. The aerodynamic resistance (r_a) is the aerial resistance to the flow of sensible and latent heat and describes the external factors that affect evapotranspiration. Aerodynamic resistance depends on windspeed and geometry and roughness of the plant community and can generally be derived from a logarithmic wind profile when the change in temperature with height is close to the dry adiabatic lapse rate (the surface is only slightly hotter or cooler than the air at screen height). The aerodynamic resistance to heat transfer from the surface to height z was approximated for neutral stability conditions as suggested by Garratt and Hicks (1973) and Brutsaert and Stricker (1979) as:

$$r_a = \frac{\left[\ln\frac{z_m - d}{z_{om}}\right]\left[\ln\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \quad [3]$$

where r_a has units of s m^{-1}, z_m is the height of the wind measurement (m), and z_h is the height of the temperature and humidity measurements above the ground surface (m). Variable d in equation 3 is the zero plane displacement height of the measurement surface (m), and z_{om} is the roughness length for momentum transfer (m), z_{oh} is the roughness length of the vegetation for vapor and heat transfer (m), k is the von Karman constant for turbulent diffusion (0.41), and u_z is windspeed (m s^{-1}) at the z_m height. For most agricultural crops and wind conditions, the aerodynamic resistance typically lies between 20 and 50 s m^{-1}.

The roughness parameters for aerodynamic transfer of momentum and heat to a crop were estimated as (Brutsaert, 1975):

$$z_{om} = 0.123 h_c \quad [4]$$

and

$$z_{oh} = 0.0123 h_c \quad [5]$$

where h_c is the mean height of vegetation (m). Zero plane displacement height was estimated as (Plate, 1971; Monteith ,1981 and Brutsaert, 1982):

$$d = 0.67 h_c \quad [6]$$

where d and h_c have units of meters.

The value of h_c used in equation 6 for zero plane displacement height was set equal to that of the weather measurement surface, rather than that of the reference crop being estimated, so that the calculated value of r_a would better reflect the logarithmic wind, vapor, and temperature profiles occurring over the measurement surface (Allen, 1986). This adjustment partially compensates for differences that commonly occur between roughnesses and canopy heights of weather measurement surfaces and roughnesses and canopy heights of the alfalfa reference crop. A crop height of 50 cm was used in this study to predict E_t from the alfalfa reference (E_{tr}).

Canopy Resistance. Direct measurement of canopy resistance is difficult and therefore methods of estimating canopy resistance have been developed (Szeicz and Long, 1969; Federer, 1979; Allen et al., 1988). Canopy resistance for a well-watered, actively growing reference crop was approximated by dividing the minimum stomatal resistance per single leaf area by the effective leaf area index of the canopy. Szeicz and Long (1969) recommended considering only one-half of the leaf area index as being effective in evaporation from a fully developed crop, since typically the upper half of the canopy of a dense crop absorbs the majority of net radiation and is therefore more active in vapor and heat transport than is the lower half. In addition, Wright and Lemon (1966), Tanner and Fuchs (1968), and Lemon and Wright (1969) observed that the majority of carbon dioxide exchange occurred within the top half of a dense crop canopy. Vapor exchange through stomata within the canopy is governed by processes similar to carbon dioxide, with similar flux gradient profiles (Wright and Brown, 1967; van Bavel and Ehrler, 1968). The one-half factor agrees with observations of effectiveness of leaf area in transpiration as summarized by Allen et al. (1985). The assumption that only one half of the total leaf area is effective in evaporation of water also helps to correct for the use of 24-hr averages of weather and resistance parameters (Allen, 1986b).

Average daily values for canopy resistance, r_c, of alfalfa under current levels of CO_2 were estimated as (Allen et al., 1988):

$$r_c = \frac{r_l}{0.5\ LAI} \quad [7]$$

where r_l is an average minimum daytime value of stomatal resistance for a single leaf, approximated as 100 s m^{-1} for alfalfa and grass canopies (Monteith, 1965; Monteith, 1981; Sharma, 1985). LAI is the leaf area index and r_c has units of s m^{-1}. Equation 7 does not consider effects of temperature or net radiation on the value of r_c, as reported relationships have been contradictory. Equation 7 is best used for daily average values of r_c rather than for shorter time periods. Average daily values of r_c for well-watered alfalfa or grass canopies generally range between 40 and 70 s m^{-1}.

Leaf Area Index. Leaf area indices (LAI) vary with time, crop height, and cultural practices. In estimating potential evapotranspiration from grass or alfalfa reference surfaces, the major variable affecting leaf area is height, although many types of grasses can differ significantly in physiological composition and structure. For a clipped grass, less than 15 centimeters in height, LAI was approximated (Allen et al., 1988) as

$$LAI = 0.24 \cdot h_c \quad [8]$$

where h_c is mean grass height (cm).

For alfalfa, LAI was approximated as

$$LAI = 1.5 \cdot \ln(h_c) - 1.4 \quad [9]$$

where h_c is mean canopy height (cm), and h_c was greater than 3 centimeters. The logarithmic relationship in Eq. 9 results from stem extension with less leaf development with increasing height. Equation 9 predicted an LAI of 4.5 for 50 centimeters tall alfalfa.

Water Balance-Irrigation Requirements Model

A computer model was developed, verified, and calibrated to compute daily evapotranspiration (E_t), soil moisture balances and irrigation water requirements (IR).

Predicting Evapotranspiration. Evapotranspiration by an alfalfa reference crop (E_{tr}) was computed using the Penman-Monteith and supporting equations (equations 2 through 9). Intermediate parameters required to complete the Penman-Monteith calculation (net radiation, air density, etc.) were computed as described by Allen et al. (1988). Net radiation was estimated from vapor pressure, air temperature, and solar radiation as suggested by Wright (1982).

Daily values of global, short wave solar radiation (R_s) were estimated by transforming the percent sky cover values into percent sunshine (n/N) estimates according to procedures suggested by Doorenbos and Pruitt (1977), and then estimating solar radiation (R_s) as:

$$R_s = (0.25 + 0.5n/N)\,R_a \qquad [10]$$

where R_a is extraterrestrial radiation (MJ $m^{-2}d^{-1}$), which was estimated according to procedures by Duffie and Beckman (1980).

Soil heat flux was estimated using the temperature gradient and thermal conductivity method. Average daily temperature gradient was estimated using the current day's average temperature and the mean temperature of the previous three days and a constant soil thermal conductivity of 0.38MJ/m^2/day/°C was used (Wright, 1982).

Crop Evapotranspiration. The alfalfa E_t reference crop is commonly used in the agricultural community to represent potential evapotranspiration[3], and has been defined as a well-watered, actively growing alfalfa crop with aerodynamically rough surface, and with at least 30 centimeters of top growth (Jensen et al., 1970). The alfalfa reference differs from an alfalfa hay crop, in that the reference is always actively growing and is always more than 30 cm in height because it is never harvested. Use of an E_t reference crop allows E_t from other crops (E_{tc}) to be estimated as simple ratios of reference E_t. These ratios, termed "crop coefficients" (k_c) are essentially lumped parameters that include differences between characteristics of specific crops and alfalfa (or grass) reference parameters, including differences in height, roughness, stomatal resistance, leaf area, row spacing, and albedo. Values of crop coefficients generally change with phenology and time through the growing season. Crop coefficients allow the use of a standard reference that can be both verified and/or calibrated for specific areas. The assumption of consistency and transferability in crop coefficients (ratios of E_{tc} to E_{tr}) allows estimation of E_{tc} without the need to verify and/or calibrate equations for every crop of interest.

Crop coefficients used in the model were "basal" crop coefficients developed by Wright (1982) at Kimberly, Idaho, for an alfalfa reference. The term "basal" indicates that the coefficients approximate the ratio of crop E_t to reference E_t when direct evaporation from the soil surface is small, e.g., for periods that are more than 5 to 7 days after rainfall or irrigation. Values of the basal coefficients were increased to reflect evaporation from soil surfaces for periods of 1 to 7 days following precipitation or irrigation using exponential decay functions for specific soil types as suggested by Wright (1982). In addition, the cumulative sum of evaporation from the soil surface was limited to specified values that were also a function of soil type.

The crop coefficient curves reported by Wright (1982) express basal k_c values as functions of time through a growing season. These curves were converted from the time base to an energy unit base by which to "clock" crop development and change in value of k_c. The energy unit (EU) selected for the k_c base was a solar radiation-air temperature interaction term represented by a form of the Jensen-Haise evapotranspiration equation (Jensen and Haise, 1963):

$$EU = (0.025T_a + 0.078)R_s \qquad [11]$$

where units of EU and R_s are in mm d^{-1} of equivalent evaporation. Values for EU were limited to zero when mean daily air temperature (T_a) was less than -3.1°C. Selection of this particular energy unit to "drive" crop

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[3]Potential evapotranspiration is defined as the evapotranspiration from an extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water (Rosenberg et al., 1983).

and k_c development follows from observations of both solar radiation and air temperature as having direct and interactive influences on crop growth. Use of both radiation and temperature were felt to improve the transferability of crop coefficient curves to areas throughout the Great Plains region and to more readily simulate the compression of growing season lengths brought on by higher air temperatures and perhaps greater levels of solar radiation. The use of the Jensen-Haise E_t equation as a clock for k_c development was first adapted by the U.S. Bureau of Reclamation (Buchheim and Brower, 1981) and has been used elsewhere. Threshold values of EU were used to trigger the occurrence of effective full cover and maturity (harvest) for wheat and corn and dates of anticipated cuttings for alfalfa hay.

Cropping Calendar. Average dates of planting for corn and spring wheat for specific years were assumed to occur when the 10-day running average of mean daily air temperature increased to 13 and 5°C, respectively. Fall planting of winter wheat was assumed to occur when the 10-day running average of mean daily air temperature decreased to 17°C or December 1, whichever came first. A maximum threshold temperature for winter wheat was used to represent conditions when air temperatures (and E_{tr}) would be low enough to maintain sufficient soil moisture after planting to ensure germination and healthy crop development before winter. The temperature thresholds used for corn, wheat, and alfalfa follow from observations by local county extension agents and agree with values recommended by the USDA-SCS (1967).

Alfalfa hay was assumed to "greenup" in the spring after the last occurrence of a minimum temperature of -5.5°C or lower (very hard frost). The alfalfa crop was also assumed to become dormant in the late fall after the first occurrence of a minimum temperature below -5.5°C. These thresholds follow from those observed and used in Idaho by Allen and Brockway (1982). If there were no occurrences of minimum daily air temperatures below -5.5°C within a year, then the alfalfa crop was assumed to remain green throughout the winter months for that year. Winter wheat was assumed to remain on a "standby" status during winter months, responding to periods of warm temperatures with some growth advance.

Soil Moisture Balance. Beginning soil moisture at planting for all crops were assumed to be at points halfway between field capacity (upper limit of soil retained moisture) and allowable depletion at irrigation.

The portion of precipitation infiltrating the soil during each rainfall event was estimated using the SCS curve number method. The curve number method provides estimates of the portion of daily precipitation depths that run off from the soil surface. The difference between precipitation and runoff includes interception and infiltration. Since evaporation of interception reduces transpiration demands of crops, the total difference between precipitation and runoff was assumed to infiltrate into the soil. The curve number method is a very approximate method. However, it was selected for use since information on specific rainfall storm durations was unavailable. Specific curve numbers were selected for each crop and soil type from tables presented by Hjelmfelt and Cassidy (1975). In addition, the values of curve numbers were adjusted according to soil moisture levels to reflect capacities of dry soils to infiltrate more precipitation than similar moist soils.

A portion of precipitation infiltrating the soil was assumed to drain below the root zone when the sum of soil moisture before the precipitation event and infiltration exceeded the drainable upper limit of soil moisture within the root zone. Drainage below the root zone -- deep percolation -- was assumed to be lost to the system and to be unavailable for fulfilling E_t requirements. The effective root zone for annual crops was assumed to increase in depth proportional to the increase in the basal crop coefficient. This assumption follows from the assumption that rooting depth and density are proportional to height and density of the crop canopy. Because the value of the basal crop coefficient relates to the height and density of the crop canopy, it serves as a good approximation of root growth from planting until a maximum rooting depth is reached at full canopy cover.

Plant Surface Temperatures. Fall-offs in plant growth rates and yields when plant canopy (surface) temperatures exceed certain threshold values have been noted (Hatfield, et al., 1987). Because of possible physiological implications of increases in plant canopy temperatures, estimates of an "apparent" daily average surface temperature, T_s, were made from a combination of the energy balance and sensible heat equations using equation 12:

$$T_s = \frac{[(R_n - G) - E_{tc}]r_a}{\rho c_p} + T_a \qquad [12]$$

where E_{tc} is the estimated value of daily evapotranspiration from crop "c."

MODEL DATA

The model inputs are climatic data, controllable variables, and system parameters. Seventeen locations in the Great Plains, five in Nebraska, three in Kansas, two in Oklahoma and seven in Texas were selected based on the availability of long periods of climatic data.

Climatic Data

The climatic parameters used in this study included maximum and minimum air temperature, windspeed, mixing ratio, cloud cover, and precipitation. The 1951-1980 weather data set for the 17 first-order NOAA stations was assembled for this study by R. Jenne and W. Springer at NCAR. Data set parameters included percent sky cover for both opaque and total clouds for the period from 9 a.m. to 3 p.m., 24-hr windspeed, and 24-hr average mixing ratios. Daily maximum and minimum air temperatures and precipitation were obtained from separate temperature-precipitation data sets also furnished by NCAR.

Adjustment of Air Temperature. Irrigation of a local area or region affects the characteristics of the lower boundary layer of the atmosphere. These effects typically include cooling of the air (reduced air temperature), increased moisture content, and reduced wind (less macro-scale buoyancy mixing due to reduced sensible heat transfer). The elevation of air temperatures at dryland settings relative to air temperatures at adjacent irrigated setting commonly exceeds 5°C during summer months in areas of southern Idaho (Allen et al., 1983; Allen and Pruitt, 1986). Changes in the lower boundary layer include changes in absolute values and shape of the vertical profiles of air temperature, humidity, and windspeed. Values of air temperature and vapor pressure deficits at measurement heights imply information concerning the value of surface temperature and the relative partitioning of radiation energy into sensible and latent heat at the evaporating surface. Therefore, inclusion of air properties measured over non-irrigated surfaces having less than full crop canopies or sufficient soil moisture to fulfill E_t demands into an E_t estimating equation will cause overestimation of E_t. The majority of modern reference E_t equations, including equation 2, assume that weather measurements are made over a well-watered crop with characteristics similar to the reference crop for which E_t is being estimated. These assumptions are usually embedded in empirical constants in the equations and in the underlying theory.

Because weather data used in this study were collected from station located in airport settings, and because these settings were typically surrounded by nonirrigated, rainfed agriculture, air temperatures and windspeeds recorded at these locations lie above levels and air humidities below levels that would have occurred over an irrigated reference crop. Because it was desirable to obtain reasonably accurate estimates of current, baseline evapotranspiration and irrigation water requirements, a method was developed to make adjustments to maximum and minimum recorded air temperatures at all weather sites. No adjustment was made to humidity and wind data, as insufficient information and adjustment techniques were available and differences in these parameters between irrigated and dryland settings are likely to be less pronounced.

The background, theory, and validation of the air temperature adjustment procedure is described in more detail by Allen (1988). As a starting point in the adjustment procedure, an apparent, average daily temperature of the evaporating surface of the rainfed region around the weather site (T_{sa}) was estimated as:

$$T_{sa} = \frac{((R_n - G) - E_{ta})r_a}{\rho c_p} + T_a \qquad [13]$$

where E_{ta} is the estimated, actual daily evapotranspiration from the rainfed region. Equation 13 is a solution of the sensible heat transport equation, where H, the sensible heat flux, has been replaced with the other three major components of the energy balance equation, namely, R_n, G, and E_{ta}. It should be noted that the value of T_{sa} has no direct physical equivalent, e.g., it cannot be measured in the field, as it is the product of using daily averages of E_t, windspeed and air temperature. However, it does function as an index of average surface temperature properties that would be required to "drive" the amount of sensible heat transfer from the crop surface to the atmosphere to close the energy balance.

Actual daily evapotranspiration, E_{ta}, was computed with a daily soil water balance with precipitation as the only moisture input. The value of E_{ta} was calculated as:

$$E_{ta} = \left[\frac{\Theta_i - \Theta_L}{\Theta_U - \Theta_L}\right] [0.8 E_{to}] \qquad [14]$$

for $\Theta_i - \Theta_L < R \cdot (\Theta_U - \Theta_L)$ and

$$E_{ta} = 0.8 \cdot E_{to} \qquad [15]$$

for $\Theta_i - \Theta_L > R \cdot (\Theta_U - \Theta_L)$

where Θ_i is the root zone soil moisture on day i, Θ_L is the lower limit of plant extractable water in the root zone, Θ_U is the drainable upper limit of plant extractable water in the root zone, and R is a stress threshold indicator, set equal to 0.5 in this study. Equation 13 has been used successfully in relatively simple crop yield simulation models to predict the effect of soil moisture on E_t (Hill et al., 1982a). E_{to} represents evapotranspiration from a grass reference crop. This parameter was calculated using the Penman-Monteith equation with a roughness height of 12 cm and an LAI value of 2.9. The product of $0.8 \cdot E_{to}$ in equations 14 and 15 was used to represent the average potential E_t of the region (integrated over all crops and surface types) surrounding the airport weather sites under conditions of adequate soil moisture. The daily soil moisture balance for the rainfed area was of the form:

$$\Theta_i = \Theta_{i-1} - E_{ta_i} + P_i - SR_i - DP_i \qquad [16]$$

where P_i is precipitation on day i, SR_i is estimated surface runoff on day i, computed using the curve number method, and DP_i is deep percolation, which was assumed to occur when soil moisture exceeded the drainable upper limit. Initial values of Θ_i at the beginning of the season were assumed to be at levels that lay 75% of the way between the lower limit of plant extractable moisture and the drainable upper limit.

The second step in the adjustment procedure was to calculate an additional apparent, average surface temperature, T_{si}, for an adequately watered, irrigated reference crop, which in this case was alfalfa. This crop is the type of evaporating surface over which the E_t reference equation assumes that weather data were measured. The value of T_{si} was computed by numerically searching for the value that solved the following energy balance equation:

$$R_n - G = \frac{(e^o[T_{sl}]-e^o[T_d])\rho c_p}{\Upsilon(r_a+r_c)} + \frac{\rho c_p(T_{sl}-T_a)}{r_a} \quad [17]$$

where $e^o[T]$ is the saturation vapor pressure at temperature T and T_d is average daily dew point temperature. The values of r_a and r_c in equation 17 represent resistances for an alfalfa reference.

If E_{ta} and E_{tr} were equivalent (the region surrounding the airport was an irrigated alfalfa reference), then the values of T_{sa} and T_{sl} would be equivalent. Deviations between T_{sa} and T_{sl} then indicate differences between E_{ta} and E_{tr} resulting from lack of precipitation and/or to differences in characteristics of the evaporating surface. These differences are largely due to differences in sensible heat fluxes from the rainfed and irrigated surfaces. Because the implied values of sensible heat are numerically "anchored" to the same value of air temperature, T_a, in equations 16 and 17, differences in implied levels of sensible heat are manifested as differences in apparent surface temperatures.

The actual adjustments to maximum and minimum values of air temperature measurements were made following a concept similar to the theory of "complimentary" relationships between actual and potential estimates of evapotranspiration as formulated by Bouchet (1963), where any deficit between potential evaporative demand and actual evapotranspiration in an area would manifest itself in nearly equivalent magnitude as an increase in predicted potential evaporation by a Penman type of equation. In other words, the increased sensible heat flux generated by a moisture-stressed surface would provide positive feedback to the atmosphere, thereby increasing the evaporative demand by a like amount. One of the manifestations of the increased sensible heat flux would be elevated air temperature, as previously discussed. Because the sensible heat fluxes and corresponding apparent surface temperatures computed for the rainfed and irrigated conditions "bracketed" the actual sensible heat flux and surface temperatures that would have occurred over an irrigated surface with a boundary layer at equilibrium (similar to the bracketing of the complimentary E_t theory), adjusted temperatures were computed as follows:

$$T_{xa} = T_x - 0.3(T_{sa} - T_{sl}) \quad [18]$$

$$T_{na} = T_n - 0.2(T_{sa} - T_{sl}) \quad [19]$$

Values of T_{sl} were almost always less than values for T_{sa} owing to predicted downward transfer of sensible heat to the irrigated surfaces (T_{sl} - T_a was negative). The coefficients 0.3 and 0.2 (in contrast to a coefficient of 0.5 indicated by the complementary theory) were found to best predict the necessary adjustment to air temperatures to represent conditions over an alfalfa reference surface. This procedure was evaluated and calibrated using irrigated and airport or rangeland weather data from southern Idaho and Scotts Bluff, Nebraska, as described by Allen (1988). Results of the adjustment were found to be quite good, with adjusted temperatures closely approximating air temperatures above an irrigated alfalfa surface on a daily basis. The deviation from the theoretical 0.5 value are due to other effects, assumptions, and numerical idiosyncrasies lumped into equations 13 through 17. Minimum daily air temperatures were adjusted less than maximum temperatures owing to lower values of sensible and evaporative heat fluxes at night and the proximity of minimum daily air temperatures to dew points in many areas even when regional E_t was less than potential values.

GCM Climatic Scenarios. Daily values of adjusted air temperature, estimated solar radiation, mixing ratio, and precipitation from the baseline 1951-1980 data sets were multiplied by monthly ratios generated by the GISS and GFDL models to reflect long-term, steady-state relative increases or decreases in the 30-year period for a $2xCO_2$ atmosphere.

Absolute changes were necessary for modifying windspeeds, because applying ratios of monthly windspeeds from the GCMs on windy days predicted winds that were unrealistically high. Daily values of windspeed from the baseline data sets were modified by adding or subtracting absolute changes in windspeeds as projected by the GCM models.

Trends in changes in the climatic parameters air temperature, humidity (mixing ratio), solar radiation, wind, and precipitation were similar between the GISS and GFDL scenarios, with the GFDL scenario having more extreme changes than the GISS scenario. Averages of GCMs projected percent change in parameters for stations within each of the four states are listed in Table 2. In general, air temperatures were projected to increase during all months, with the increases averaging 1 to 2% of a Kelvin scale (approximately 3 to 6°C), with the GFDL model projecting temperatures during summer months which were about 1.5°C higher than the GISS (5.3°C versus 3.8°C above baseline (1951-1980) temperatures). Changes in projected precipitation were widely scattered under both scenarios, with an average 2.9% increase in annual precipitation projected by the GISS model and a 5% increase by the GFDL model. Changes commonly alternated in sign from month to month under both scenarios and the magnitudes of monthly fluctuations were quite high. Projected changes in air movement (wind) fluctuated widely from month to month in both models, with some months projected to have increased windspeeds and some projected to have lower. Vapor content of the air (humidity), expressed in the GCMs as mixing ratios, was projected to increase. One effect of increased humidity would be to reduce the evaporative demand of the air and consequently evapotranspiration, all other factors being constant. Solar radiation was predicted to increase. Higher changes in solar radiation were projected in the winter months, especially in the northern states. This increase was most likely due to projected decreases in cloudiness.

Control Variables

Cropping System. Corn, winter wheat, and alfalfa were selected to represent typical crops grown in the Great Plains region. Corn represents row crop production, winter wheat represents a drilled, overwinter crop, and alfalfa represents a perennial crop that is able to take full advantage of extended growing seasons.

Bulk Stomatal Resistances. Leaf area indices and stomatal resistances of single leaves are the major determinants in values of bulk stomatal resistance. These two parameters are also both felt by many researchers to be affected by elevated CO_2 levels. Rosenberg et al. (1988) hypothesized that values of LAI may increase by about 15% and single leaf stomatal resistances by 40% for doubled CO_2 levels. Allen et al. (1985) and Allen (1986a) summarized evidence that LAI may increase by about 20 to 75% and stomatal resistances may increase by about 75% for doubled CO_2 levels. According to the relationship presented in equation 7, equivalent increases in LAI and r_l would effectively cancel each other out. Because of uncertainties in the literature concerning the nature and magnitudes of increases in both LAI and r_l, the water balance model was rerun several times for four levels of increased bulk stomatal resistance, r_c. These levels represent increases of 20, 40, 60, and 80% in the values of r_c.

System Parameters

Soil Types. Three soil types were considered in the water balance model for each weather location to evaluate the effect of soil type on evapotranspiration (primarily wet soil evaporation), rooting depth, effectiveness of precipitation, and irrigation water requirements. Particular soil types at each site were selected according to information furnished by local county extension agents and other agricultural personal. This information was collected by C. Rosenzweig (1988, personal communication). Soil type information in the model was for "generic" soil types ranging from shallow, medium, and deep silty clays to shallow, medium, and deep sands. Parameters describing attributes of these soils were obtained from the IBSNAT data base. The three parameters in the IBSNAT data base that were used directly in the water balance model were the lower limit of plant-extractable water (wilting point), the drainable upper limit of soil moisture (field capacity), and upper limit of stage 1 evaporation. The lower and upper limits of plant-extractable water were significantly reduced for the IBSNAT silty clay soil before use in the water balance model to better reflect observed field data.

Table 2. Percentage Changes from Baseline Weather Parameters during the growing season

	Temperature		Precipitation		Windspeed		Mixing Ratio		Solar Radiation	
	GISS	GFDL	GISS	GFDL	GISS	GFDL	GISS	GFDL	GISS	GFDL
Nebraska										
Mar	2.2	1.9	32.7	5.0	-11.0	-9.0	53.1	45.3	7.0	23.9
Apr	1.7	1.6	10.1	37.7	12.3	-15.5	28.1	38.4	4.4	-9.4
May	1.3	1.4	15.0	1.3	-76.1	-8.8	32.1	27.7	1.0	7.1
Jun	1.3	2.8	-2.6	-51.6	3.4	-13.8	33.8	26.1	3.3	21.0
Jul	1.2	2.7	-11.0	-30.6	10.5	22.2	15.4	6.4	-0.4	9.6
Aug	1.5	2.3	21.3	-39.1	-1.9	20.0	29.6	15.8	8.7	7.1
Sep	1.9	2.1	-4.8	4.9	-2.0	-8.1	34.0	10.1	11.8	5.3
Oct	1.5	1.8	-30.4	-15.6	15.9	-15.8	32.5	43.0	36.0	23.7
Kansas										
Feb	1.6	1.9	11.4	38.7	-5.0	-27.6	43.9	49.2	2.1	6.4
Mar	2.0	1.6	-9.3	17.8	3.1	-9.6	48.7	34.3	6.1	7.1
Apr	1.7	1.7	-7.9	48.8	-3.0	1.5	34.4	34.5	6.8	-1.0
May	1.1	2.0	-2.8	-4.5	-9.3	-10.4	23.8	29.0	3.2	12.2
Jun	1.2	2.1	-13.7	-50.7	10.3	15.9	20.0	8.2	4.3	9.5
Jul	1.4	2.1	-16.7	-35.8	3.7	25.3	22.0	4.6	4.9	-0.5
Aug	1.6	1.5	33.4	-31.8	-1.0	7.2	32.8	19.9	7.8	8.1
Sep	1.4	1.6	85.0	7.1	-5.0	0.9	31.5	11.6	2.8	2.2
Oct	2.0	1.7	-6.2	-5.1	4.2	-4.1	38.4	42.4	10.9	8.0
Nov	2.0	1.7	-15.6	48.3	8.9	-10.7	40.8	46.7	6.9	10.4
Oklahoma										
Feb	1.4	1.7	7.3	24.0	-8.5	-27.8	35.6	42.3	3.1	-4.3
Mar	1.9	1.6	-28.2	39.9	10.7	-10.4	46.5	33.4	12.2	0.7
Apr	1.7	1.6	-15.1	16.0	-11.2	8.7	37.7	30.3	10.8	2.3
May	1.0	2.0	-9.2	-10.0	23.0	-5.0	19.7	23.6	4.7	11.0
Jun	1.1	1.5	-18.1	-33.2	16.4	18.2	13.1	0.8	4.3	2.1
Jul	1.5	1.6	-20.3	7.9	1.5	35.9	25.3	4.8	7.7	0.1
Aug	1.6	1.2	35.5	8.0	-0.8	15.6	34.4	22.3	9.3	5.4
Sep	1.2	1.6	130.4	-16.6	-8.1	-7.0	30.3	13.3	2.9	4.6
Oct	2.2	1.7	4.1	-12.5	-1.0	2.3	41.4	39.7	11.2	10.2
Nov	1.9	1.6	-37.4	35.0	9.0	-13.6	35.1	47.2	10.5	7.1
Texas										
Jan	1.8	1.4	-19.7	-5.9	-1.0	-0.9	44.2	31.6	4.1	8.4
Feb	1.3	1.9	8.9	13.2	-1.3	-15.8	33.4	46.3	5.2	2.0
Mar	1.8	1.6	-21.9	17.6	10.9	-3.2	44.4	30.3	11.1	3.3
Apr	1.7	1.5	-3.5	-20.7	-24.3	0.4	38.6	25.4	8.8	7.4
May	1.0	2.1	10.5	-31.2	12.9	-2.8	24.0	21.0	3.6	16.4
Jun	1.3	1.4	-15.8	70.1	8.2	19.1	20.8	6.8	4.7	-1.7
Jul	1.4	1.6	-4.6	-1.0	-4.4	20.6	26.2	12.8	5.9	3.1
Aug	1.6	1.3	21.2	26.4	-3.0	12.7	33.0	24.5	8.3	4.8
Sep	1.3	1.5	67.0	-34.2	-6.3	-0.6	29.3	19.7	2.9	9.8
Oct	2.0	1.7	-8.4	-3.8	3.6	2.6	38.0	30.1	9.2	10.9
Nov	1.9	1.5	-29.5	8.4	3.5	2.1	35.7	36.7	10.6	4.7
Dec	2.1	1.8	-2.7	-14.6	5.8	2.4	51.4	41.1	13.0	15.3

Irrigation System Types. The frequency of irrigation affects the portion of time during which the soil surface is wet and is contributing moisture to fulfill the evapotranspiration demand. Center pivot systems, which are quite common in the Great Plains region, typically irrigate every 2 to 3 days during the peak of the growing season, whereas periodically moved sprinkler systems such as wheel lines and hand-moved systems and surface irrigation systems such as furrow, basin, and border are generally managed to maximize the time periods between irrigations in order to minimize irrigation labor. Therefore, crops grown under center pivot systems generally have increased evapotranspiration rates due to increased wet soil evaporation. However, center pivots may provide for higher values of effective precipitation (that precipitation entering and remaining in the root zone), since the soil moisture is generally maintained at levels below the drainable upper limit so that root zones under center pivots have more capacity, more of the time, to retain infiltrated precipitation and thereby limit deep percolation losses. Periodic systems (other types of sprinklers and surface systems) generally have lower evapotranspiration demands than do center pivots because the soil surface is likely to be dry over a larger portion of time.

Two system types were simulated in the water balance model. The first type represented center pivot systems where net irrigation depths of 15 mm were applied whenever soil moisture in the root zone was depleted by E_t to a point halfway between the upper limit of plant-extractable moisture and the allowable depletion level. This level was generally when 25% of the soil moisture between the drainable upper limit and lower limit of plant-extractable moisture had been depleted. The second system type represented the periodic systems, where irrigation water was assumed to be added when soil moisture was depleted to the allowable depletion level. The allowable depletion level was defined as the level to which soil moisture can be depleted by E_t before the lower availability of remaining soil moisture would cause E_t to decrease from its potential amount. This level ranged from 50 to 55%, depending on the soil type.

CHAPTER 3

RESULTS AND DISCUSSION

The Water Balance-Irrigation Requirements model was run for a 30-year period (1951-1980) of baseline climatic data and under GISS and GFDL scenarios for the same period with $2xCO_2$ concentrations. Additional simulation runs were made to evaluate the effects of increased growing season for annual crops under the GISS and GFDL scenarios. These additional analyses were made to evaluate potential changes in crop cultivars that would take advantage of longer potential growing seasons. For each of the GISS and GFDL scenarios, effects of five hypothetical levels of bulk stomatal resistance values on irrigation water requirements were evaluated.

CHANGES IN LENGTHS OF GROWING SEASONS

The growing seasons for alfalfa were used as general indicators of maximum lengths of potential growing seasons for most crops. Significant shifts in green-up and frost-induced dormancies of alfalfa were observed at higher latitudes owing to earlier occurrences of last killing frosts in the spring and later occurrence in the fall. The lower latitudes (less than 30°) experienced more modest changes in season lengths, as many of the regions currently have an almost year-round growing season. Although the two general circulation models (GISS and GFDL) predicted different climatic scenarios, the changes in lengths of growing seasons for alfalfa obtained for the two scenarios were not significantly different.

The following regression equations were found to predict growing season lengths:
Baseline scenario ($R^2 = 0.98$)

$$S_l = 377 - 1.74d \quad \text{for} \quad 16 < d < 106 \qquad [20]$$

GISS Scenario ($R^2 = 0.88$)

$$S_l = 400 - 1.43d \quad \text{for} \quad 24 < d < 106 \qquad [21]$$

GFDL Scenario ($R^2 = 0.86$)

$$S_l = 402 - 1.47d \quad \text{for} \quad 25 < d < 106 \qquad [22]$$

where S_l = season length and d is the day of year when alfalfa regrowth begins under current climatic conditions (last occurrence of -5.5°C). For regions where alfalfa regrowth began before January 25th, year-round growing seasons were predicted under both GCM scenarios.

Increased air temperatures predicted by the GCM model scenarios increased rates of crop development according to phenology, solar radiation, and air temperature relationships used in the water balance-E_t model. These increases resulted in increased numbers of hay cuttings per growing season for alfalfa and reductions in the lengths of growing seasons for other annual crops. Figure 1 shows the changes in lengths of growing seasons from the baseline values.

The changes in season lengths for corn were heavily influenced by the occurrence of planting dates. Decreases in the season lengths were observed in regions where planting dates were in April and May (northern latitudes). However, regions with corn planting dates in February and March experienced modest increases in the lengths of the growing seasons. The longer growing seasons for February and March planting dates occurred because planting dates under the GCM climatic scenarios shifted to January and early February

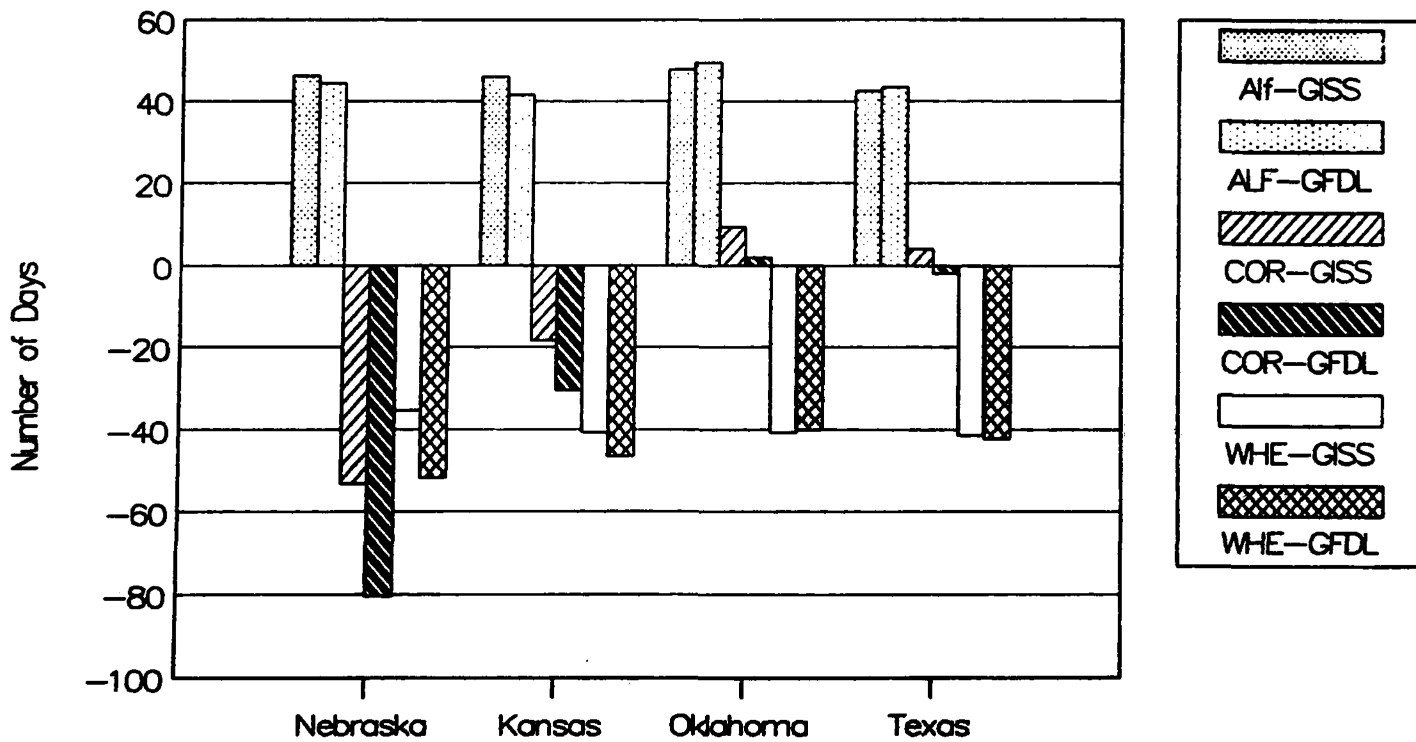


Figure 1. Changes in season lengths (days) from baseline values.

periods, during which air temperatures and solar radiation levels were low. Thus, crop development rates were slower during these periods than under current climatic conditions where crops are planted later when solar radiation levels were higher. The large decreases in season lengths for corn in Nebraska were due to more rapid maturing of the crop, thereby eliminating extension of the season into the months of October and November when levels of temperature and solar radiation are low.

The growing seasons for winter wheat were always shortened under the GCM scenarios owing to the later planting dates in the fall when temperatures were cool enough to eliminate moisture stress to seedlings, and in most instances, to earlier harvest dates due to more rapid growth and earlier green-up resulting from higher air temperatures and higher solar radiation levels.

EVAPOTRANSPIRATION

The combined effects of the changes in climatic conditions and in lengths of growing seasons influenced peak and seasonal evapotranspiration demands as shown in Figure 2. Conditions under the GFDL scenario predicted larger changes in both seasonal and peak month evapotranspiration than did the GISS scenario, mainly owing to the higher air temperature changes predicted by the GFDL scenario. The increases in seasonal evapotranspiration of alfalfa were due to the increases in the lengths of the growing seasons coupled with the effects of climatic changes. Seasonal evapotranspiration requirements of corn and winter wheat crops were reduced primarily because of decreases in lengths of growing seasons and because of changes in cropping calendars. Winter wheat was predicted to have been planted later in fall and harvested earlier in the summer under the GCM scenarios (late September to early June), the period in which climatic changes were generally modest. Increases in seasonal evapotranspiration from corn were predicted in these regions where GCM scenarios predicted increases or only slight decreases in lengths of growing seasons (around 30 to 40° latitude).

Estimates of peak monthly evapotranspiration increased under the GCM scenarios for all crops and all sites evaluated, except in Brownsville, Texas (see Table 3). The increases in peak monthly E_t are attributed mainly to the increase in evapotranspirative demand of the atmosphere under the GCM scenarios (higher air temperatures, wind, and solar radiation in most months). In Brownsville, Texas, the peak evapotranspiration of corn and winter wheat decreased by 11 and 2%, respectively, under the GISS scenario with no increase in bulk stomatal diffusion resistance. The decrease was attributed to the fact that under the modified climate, crops were predicted to be grown in relatively cooler months with lower solar radiation (January to June), thereby avoiding months with higher evaporative demands.

The upper ranges in Table 3 represent increases in peak monthly E_t predicted if there were no changes in bulk stomatal diffusion resistance of plant leaves (no change in LAI or stomatal resistance). The lower ranges represent changes predicted if bulk stomatal diffusion resistances of plant canopies were increased by 80%.

Sensitivities of both peak and seasonal E_t to projected changes in bulk stomatal diffusion resistance are very pronounced. Results indicate that increases in evapotranspiration due to changes in climate may be moderated or even negated by increases in bulk stomatal diffusion resistances under the high CO_2 scenarios. The increases in bulk stomatal resistances required to nullify any projected increases in seasonal evapotranspiration due to climatic change vary with GCM scenario, geographic location, and the type of crop as evidenced in Figure 2. Trends in increases in peak E_t requirements were very similar to those for peak irrigation requirements shown in Figure 5, with the largest changes occurring for the GFDL scenario and in the northern latitudes.

IRRIGATION REQUIREMENTS

Irrigation requirements were computed by incorporating the effects of climate, cropping patterns and planting schedules, soils, and irrigation methods with estimated evapotranspiration and precipitation. A summary of the ranges of change in net irrigation requirements resulting under the GISS and GFDL scenarios are shown

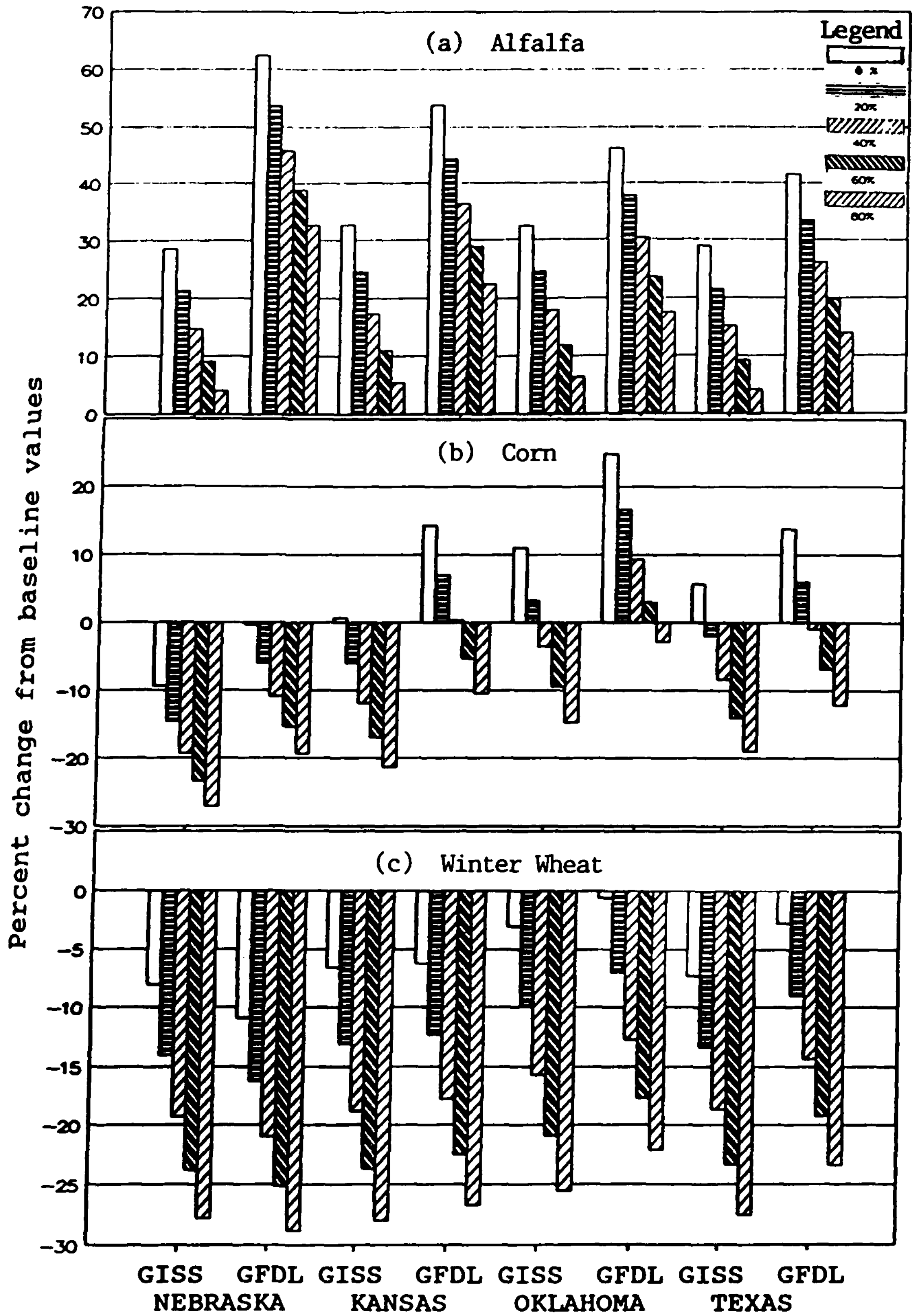


Figure 2. Percent change in seasonal evapotranspiration from baseline values for alfalfa, corn and winter wheat vs. postulated increases in bulk stomatal diffusion resistance.

Table 3. Ranges of percent change in peak evapotanspiration from baseline values over the 17 stations.

Crop	GISS			GFDL		
	Alfalfa	Corn	Wheat	Alfalfa	Corn	Wheat
Nebraska	-10 - 17	-5 - 29	-20 - 10	38 - 72	29 - 80	1 - 31
Kansas	-10 - 17	-11 - 19	-21 - 8	21 - 58	12 - 55	-15 - 18
Oklahoma	-1 - 19	-11 - 14	-11 - 15	11 - 66	0 - 41	1 - 35
Texas	-10 - 20	-28 - 17	-23 - 16	3 - 46	4 - 47	-7 - 37

in Figure 3. Predicted changes in seasonal irrigation water requirements were consistently higher under the GFDL than GISS scenarios, with estimated increases in seasonal irrigation requirements for alfalfa under the GFDL scenario averaging about 90% greater than under the GISS scenario.

Net seasonal irrigation water requirements increased with the increased temperature and decreased precipitation during growing seasons predicted under the GCM model scenarios. The predicted increases in net irrigation requirement were generally higher than predicted increases in evapotranspiration. This is attributed to the effect of lower rainfall during growing seasons predicted by the GCMs. Computed changes in irrigation water requirements were greatest in central Nebraska, Kansas, Oklahoma, and northern Texas. Percent changes in irrigation requirements were greatest in eastern Nebraska since baseline values were lower owing to higher precipitation.

Shortened growing season lengths reduced predicted irrigation water requirements for corn under the GISS scenario, even with small changes in bulk stomatal diffusion resistances. Under the GFDL scenario, however, the effects of reduction in growing season lengths of corn were negated by larger increases in evaporation demands and decreases in growing season precipitation. Seasonal requirements of winter wheat were decreased under both GCMs scenarios owing to shortening and advancement of growing seasons, although changes would be very slight if bulk stomatal diffusion resistances were to remain constant.

The effect of bulk stomatal diffusion resistance on net seasonal irrigation water requirements is dramatic. Projected net seasonal irrigation requirements decreased as projected bulk stomatal diffusion resistances were increased as shown in Figure 3. Under the GISS scenario, the effect of expanded growing seasons for alfalfa would be nearly balanced by increases in bulk stomatal diffusion resistances of 80%. Under GFDL scenario, seasonal irrigation requirements of alfalfa would increase by an average of 20% even with an increase in bulk stomatal diffusion resistance of 80%. The increase would be about 85%, otherwise.

The predicted variations between stations were dramatic, especially for alfalfa and corn, primarily owing to the larger variations in season lengths. The decreases were almost linear for the incremental values of bulk stomatal diffusion resistance evaluated in this study. These decreases varied with latitude, longitude, altitude, local conditions, soil, and crops. The decreases were, however, persistent in all cases. Isograms of net seasonal irrigation water requirements of alfalfa are presented in Figure 4. Only the results for baseline, zero, and 40% increases in bulk stomatal resistance for scenarios for GISS and GFDL are presented. In almost all cases, the water requirements increased from east to west, which is consistent with recognized precipitation patterns for the region.

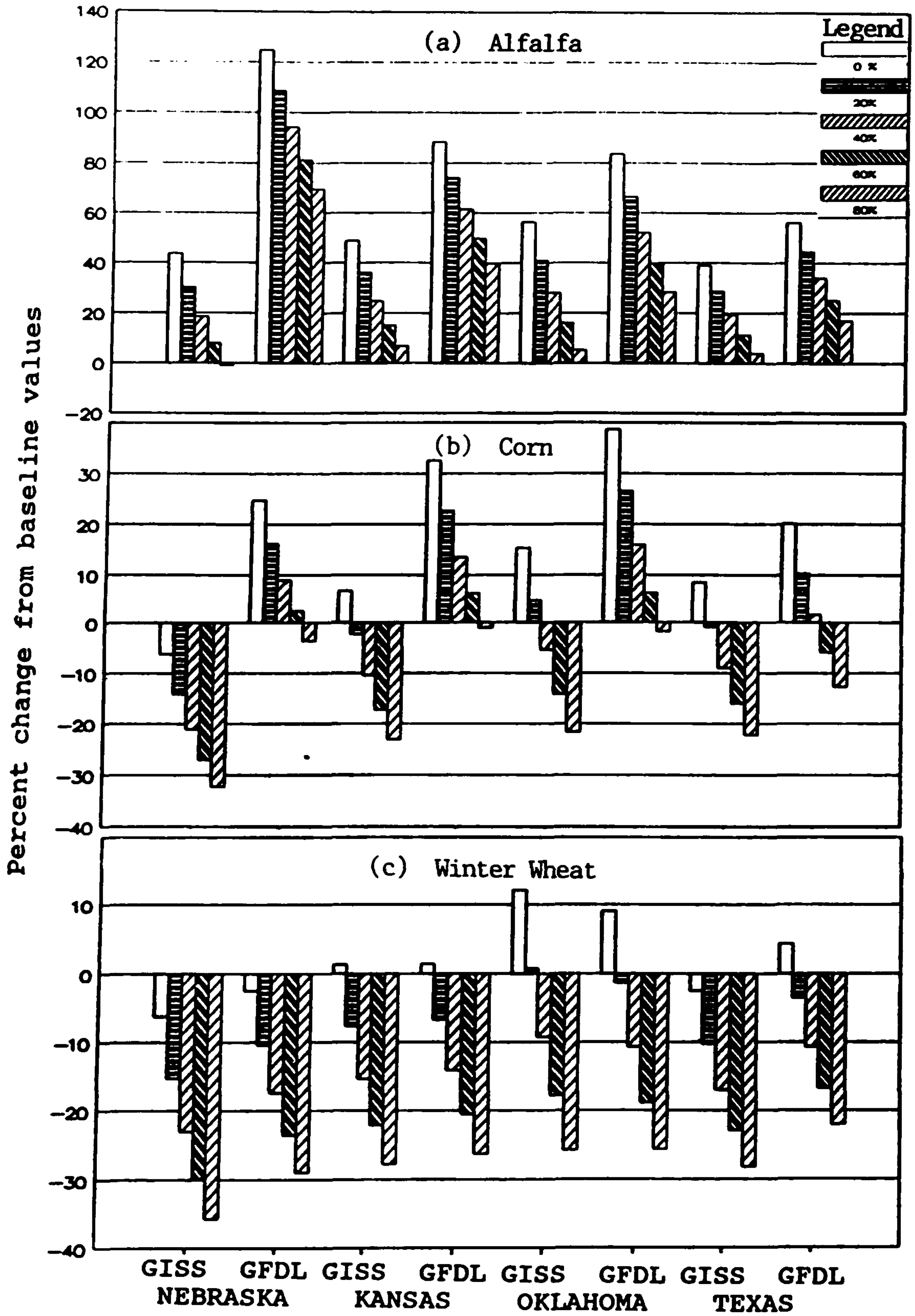
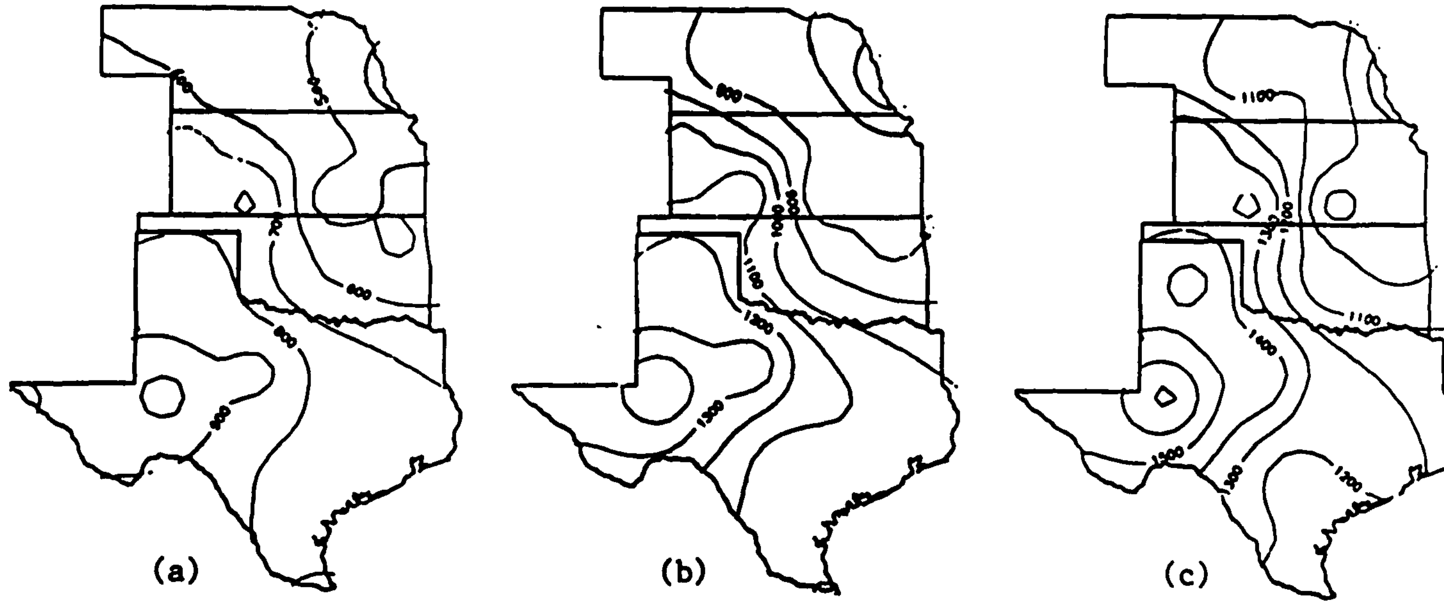


Figure 3. Percent change in net seasonal irrigation requirement from baseline values for alfalfa, corn and winter wheat vs. postulated increases in bulk stomatal diffusion resistance.



Isogram of Seasonal Irrigation Requirements (Alfalfa).

a) baseline
b) GISS with no increase in bulk stomatal resistance
c) GFDC with no increase in bulk stomatal resistance
d) GISS with 40% increase in bulk stomatal resistance
e) GFDL with 40% increase in bulk stomatal resistance

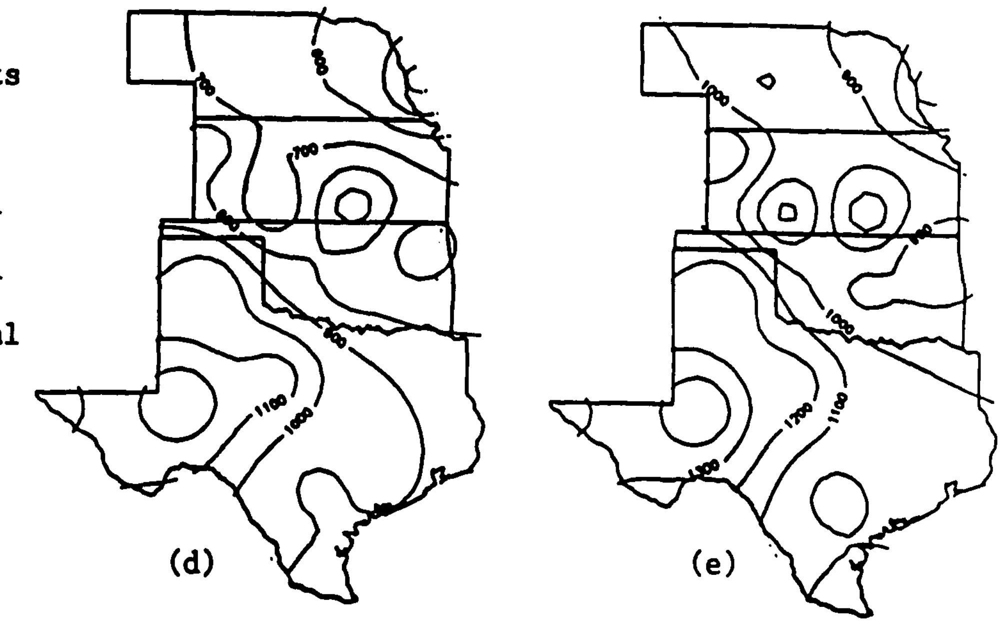


Figure 4. Isograms of seasonal net irrigation water requirements for Alfalfa.

Figure 5 show changes in peak monthly irrigation water requirements. These trends are similar to trends in change in peak monthly E_t requirements, with projected increases under the GFDL scenario being more than double those projected under the GISS scenario due primarily to higher projected increases in air temperatures and in general, smaller projected increases in humidities under the GFDL scenario. Trends in peak irrigation requirements for corn and wheat under the GISS scenario would be close to zero if bulk stomatal diffusion resistances were increased to about 40%. Otherwise, peak requirements for these two crops would be expected to increase by 5 to 20% under GISS scenario if bulk stomatal diffusion resistance values did not change.

SURFACE TEMPERATURE

Plant temperature is a major component of the plant energy balance and provides an indication of the energy exchanges between the plant and the atmosphere. Temperature exerts a profound influence on plant metabolic activities (Hatfield et al., 1987). Predicted plant surface temperature (T_s) represents only an index of the actual average plant canopy temperature, owing to the use of averages of daily parameters R_n, G, E_{tc}, r_a and T_a, and incompleteness of plant canopies during parts of the growing season. However, differences between T_s and T_a and relative changes in the value of T_s for different climatic scenarios and values of canopy resistance may reveal information that will be helpful in assessing crop productivity in the changing climatic environments. Values of T_s and $T_s - T_a$ were computed for the month of each year having the highest value of E_{tc}, as this would likely be a period when the plant canopy is nearest full development (T_s more closely represents canopy temperature than an integration of canopy and soil surface temperature). Also, the peak E_t month is likely to coincide with a period when the effects of temperature stress on crop growth and yield are most pronounced.

Surface temperatures were predicted to increase above baseline (current climatic conditions) values for all crops and sites studied. It is reasonable to speculate that surface temperatures would increase for all irrigated crops as the atmosphere warms up. Higher surface temperatures and higher variations between study sites were predicted for the GFDL scenario. Linear increases in surface temperatures over baseline values were predicted to occur with increases in bulk stomatal diffusion resistances under both scenarios (GISS and GFDL) as shown in Figure 6.

The increases in surface temperatures as bulk stomatal diffusion resistances increase were due to reductions in E_t and corresponding increases in sensible heat fluxes where sensible heat fluxes were positive (away from the crop) and to decreases in sensible heat where sensible heat fluxes were negative (advection of heat into the crop). Increases in surface temperature were greatest for alfalfa. The variability among locations in the changes in surface temperatures over the baseline values were greatest for wheat, followed by corn, and were least for alfalfa. These variations may be explained by the spatial (geographic) variations in the months in which peak evapotranspiration occurred and in climatic differences and projected changes in air temperatures for each GCM cell for peak months. The increases in surface temperatures agree with effects projected by Slatyer and Bierchuizen (1964) and Polyakoff-Mayber and Gale (1972).

Projected increases in plant canopy temperatures were fairly constant between the two GCMs scenarios for alfalfa and corn crops (see Figure 6). However, projected increases in canopy temperature for winter wheat were 2 to 6°C greater under GFDL scenario as compared to the GISS scenario. These increases in canopy tempreature were likely due to later projected fall plantings of winter wheat under the GFDL scenario due to higher fall temperatures and extension of the growing seasons into hotter summer months as compared to the GISS scenario.

The air-surface temperature differences serve as sensible heat transfer indices. The air-surface temperature differences predicted for the scenarios decreased with increases in bulk stomatal resistance. The

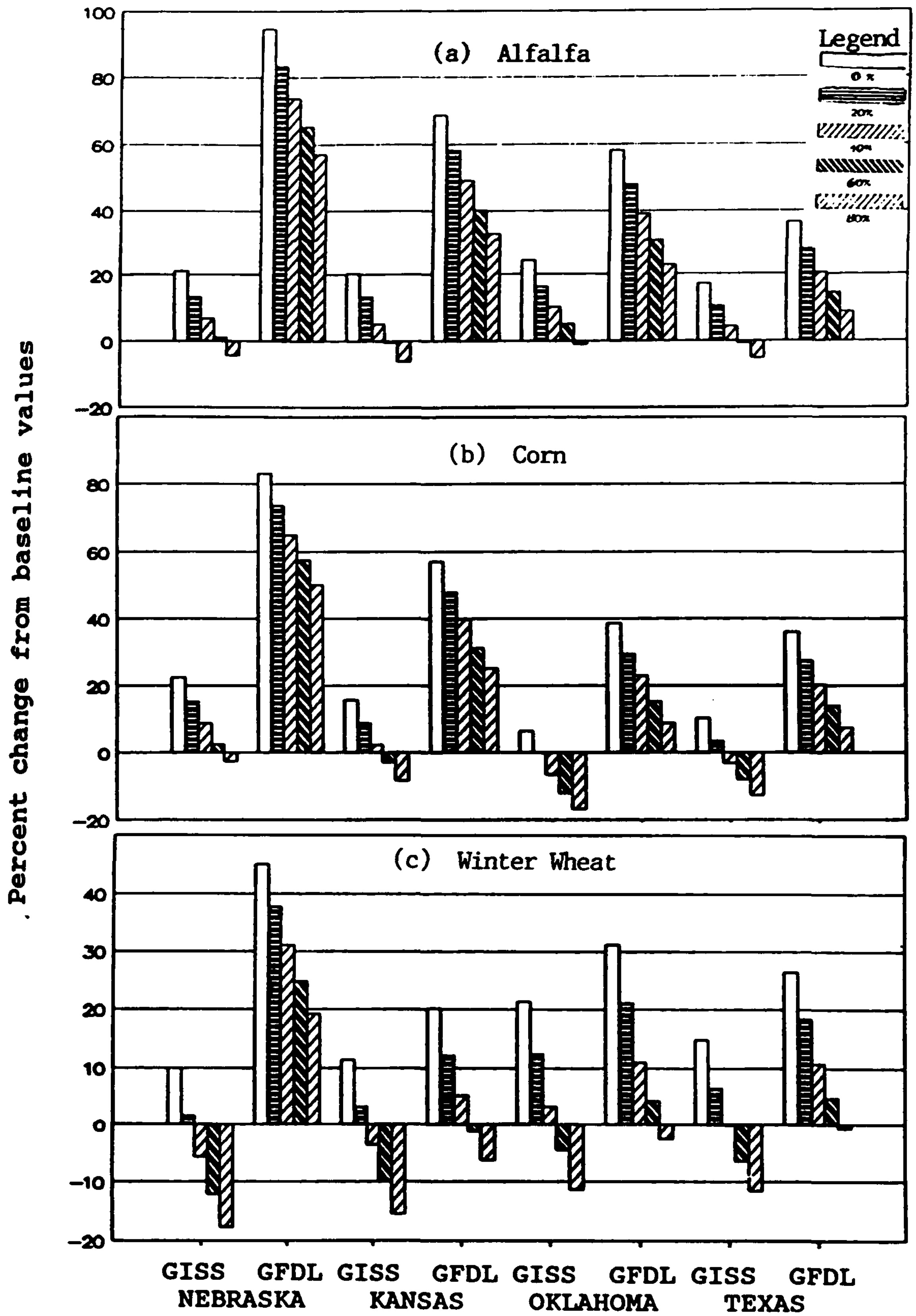


Figure 5. Percent change in net peak monthly irrigation requirement from baseline values for alfalfa, corn and winter wheat vs. postulated increases in bulk stomatal diffusion resistance.

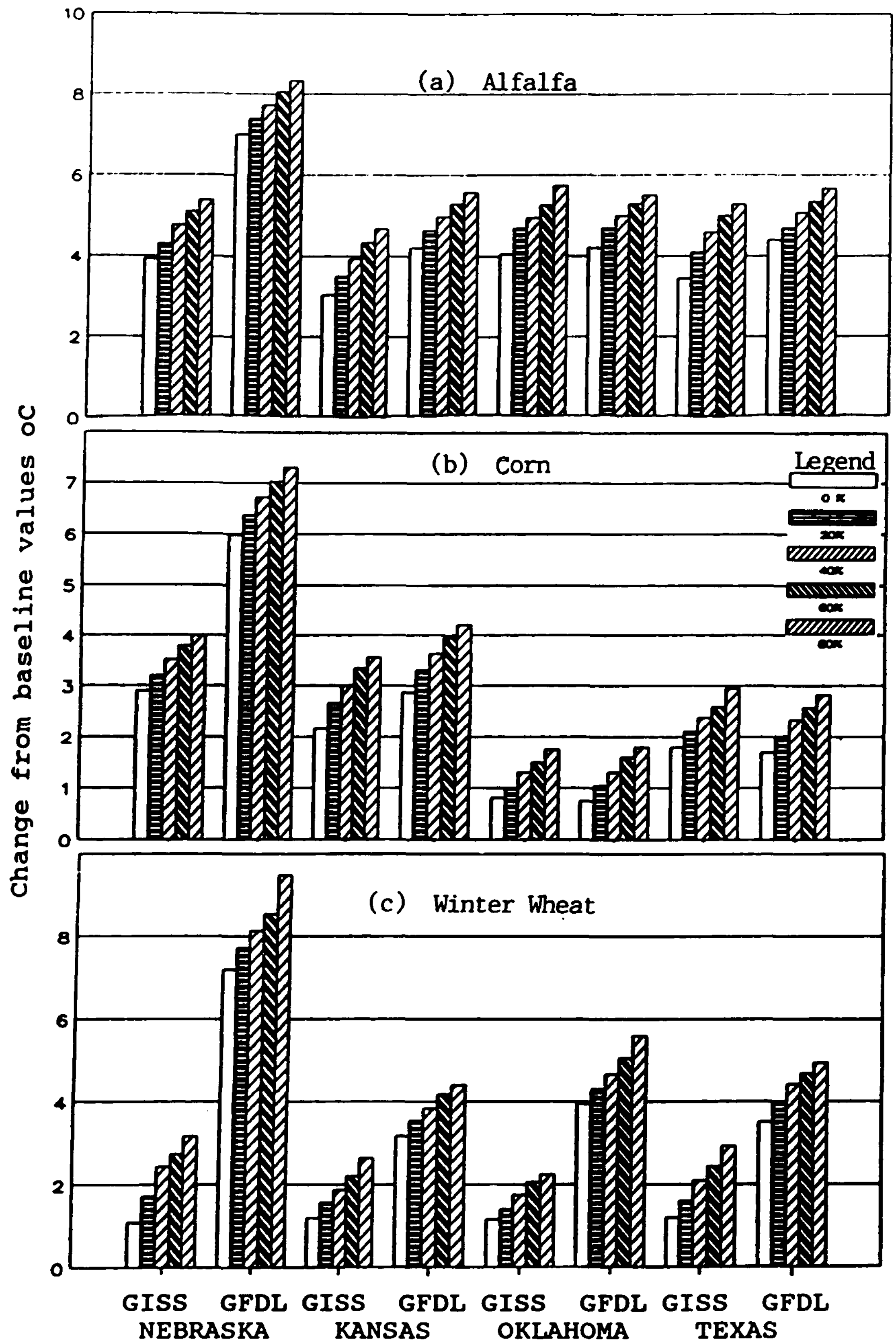


Figure 6. Change in surface temperature from baseline values for alfalfa, corn, and winter wheat vs. postulated increases in bulk stomatal diffusion resistance.

decreases indifferences were due to increases in surface temperatures, which resulted from increased bulk stomatal diffusion resistances. These decreases reduced the transfer of sensible heat from the air to plant surfaces. Plant canopies were estimated to be cooler than air temperatures because of evaporative cooling and the extraction of sensible heat from the air.

POTENTIAL AGRONOMIC ADJUSTMENTS

The postulated climatic change scenarios were predicted to increase potential growing season lengths by approximately 40 days and to compress actual growing seasons for current cultivars of corn and wheat by 0 to 80 days and 30 to 40 days, respectively (see Figure 1). Irrigators are likely to make changes in their cropping systems to take advantage of the new climate regimes. This may take the form of either growing longer season cultivars or by increasing cropping intensities.

Winter wheat was selected to study the effects of substituting longer season varieties in place of current cultivars. This simulation was accomplished in the model by increasing the phenology energy units of winter wheat by 10 and 30% for the crop development and crop maturation stages, respectively. The resulting mean differences in season lengths between the current cultivars and longer season cultivar were 19 and 17 days for the GISS and GFDL models, respectively (see Figure 7). Results indicate that growing season lengths for winter wheat would still be shortened, as compared to current baseline conditions, even when phenology-energy (growing degree radiation) requirements were increased by about 20%. It should be noted that some of this reduction for winter wheat was caused by the reduction in lengths of dormant periods during winter months, rather than by compression of growing periods.

Seasonal irrigation water requirements for winter wheat were predicted to increase by about 8 to 33% across the region under the GISS scenario and by about 15 to 35% under the GFDL scenario as compared to baseline values when longer season varieties were used (assuming a 20% increase in value of bulk stomatal diffusion resistance). Increases in seasonal irrigation water requirement in Figure 8 for extended wheat cultivars contrast with predicted reductions in seasonal irrigation water requirements for current cultivars as shown in Figure 3.

Increases in potential growing seasons and compressed season lengths for annual crops may encourage farmers to grow a second crop in regions with sufficient water supplies. This would result in increased irrigation water requirements as evidenced in the alfalfa case study.

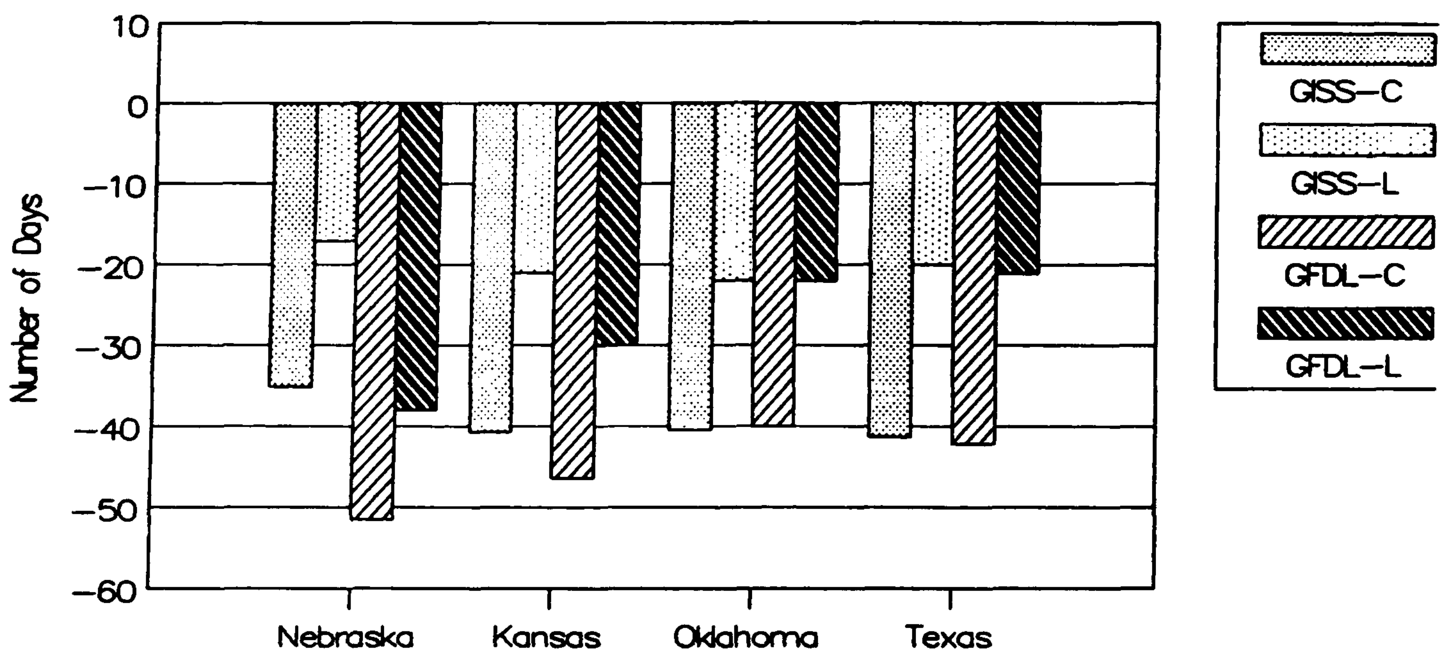


Figure 7. **Changes in season length (days) from the baseline values for current (C) and postulated longer-season (L) varieties of winter wheat.**

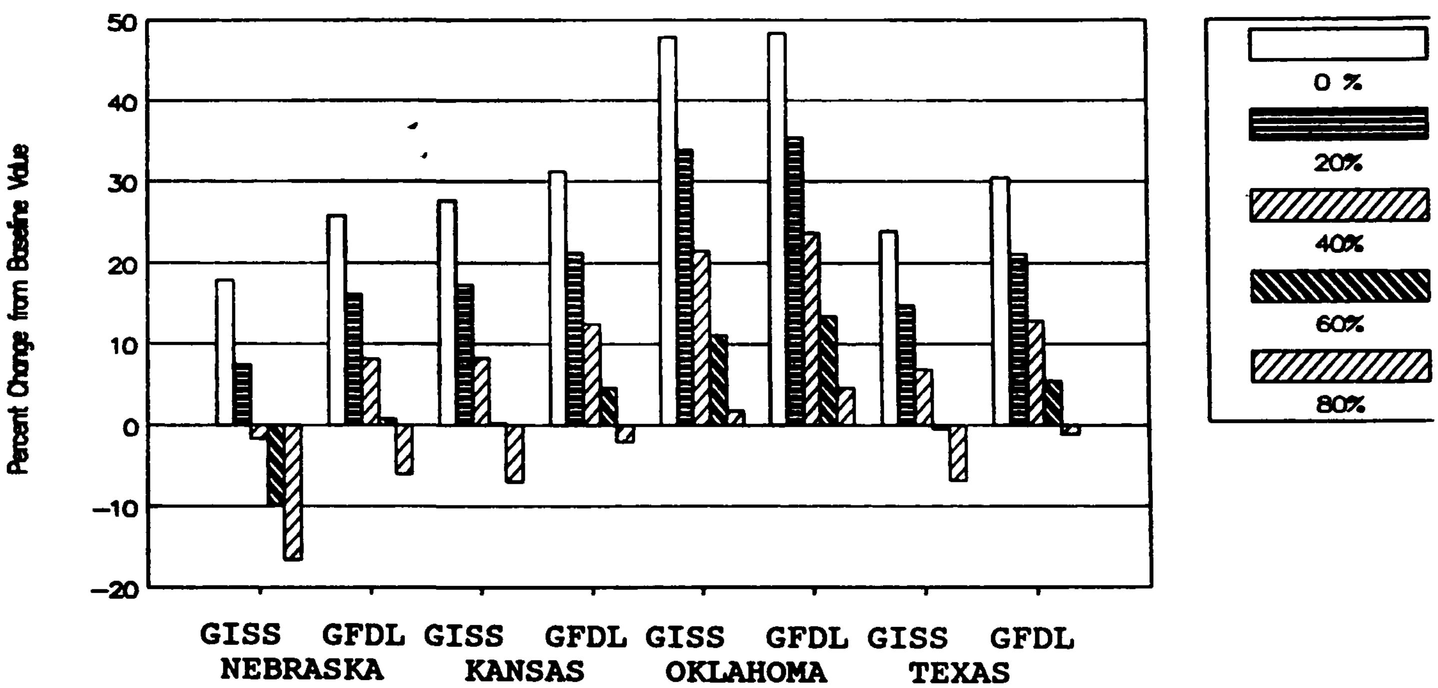


Figure 8. Percent change in net seasonal irrigation requirements from baseline values for longer-season varieties of winter wheat vs. postulated increases in bulk stomatal diffusion resistance.

CHAPTER IV

INTERPRETATION OF RESULTS

CLIMATIC AND STOMATAL RESISTANCE EFFECTS

The water balance-E_t model was applied to baseline and GCM data to evaluate effects of a series of climate change scenarios and variations in bulk stomatal diffusion resistances on irrigation water requirements. Major changes in irrigation water requirements were observed in all 17 stations with requirements for alfalfa significantly increasing and requirements for corn and wheat decreasing, depending on the climatic scenario and projected increases in bulk stomatal diffusion resistances used. It should be noted that exact magnitudes of changes cannot be predicted with complete accuracy owing to uncertainties in model input (GCM predictions and projected cropping systems), the simplifying assumptions inherent in the model development, and the complexities in the interactions of crops, farmers, and the environment. Results do, however, show definite trends and relative changes in water requirements and local plant environment.

Climate-Induced Change

The results of the model indicate that the postulated climatic changes would have a significant effect on seasonal net irrigation water requirements. The increases in irrigation requirements were mainly due to increased evaporative demands driven by increased magnitudes of climatic parameters and changes in lengths of growing seasons and in precipitation patterns.

Increases in temperatures, solar radiation, and windspeeds under the GCM scenarios provided the major impetus for increased evaporative demands. Predicted increases in humidity and shifts in growing seasons to months with lower levels of solar radiation ameliorated the majority of increase for annual crops. The lengths of growing seasons have a major impact on irrigation water requirements. The largest increases in net seasonal irrigation water requirements occurred in alfalfa owing to increased lengths of growing seasons and higher evaporative demands. Decreases or modest increases in seasonal irrigation requirements for corn and winter wheat are attributed to the shortening of growing seasons and lower evaporative demands during growing seasons due to earlier planting dates.

Stomatal Resistance-Induced Changes

Projected increases in bulk stomatal diffusion resistances brought about by increased levels of atmospheric CO_2 had tremendous effect in ameliorating the impacts of climatic change on irrigation water requirements. In all cases, irrigation water requirements were predicted to decrease with increasing levels of bulk stomatal resistance. The levels of increase in bulk stomatal resistances required to negate the effect of climatic change varied with location and crop. Surface temperatures were predicted to increase by one to two degrees as bulk stomatal resistances increased by 80%. The increases in surface temperatures resulting from the climatic and bulk stomatal resistance changes could have significant effects on crop metabolism. They may also make crops more sensitive to moisture stress.

Because of uncertainties in the literature concerning the nature and magnitudes of increases in both LAI and r_l, no specific conclusions are drawn concerning the probable magnitude of changes in bulk stomatal diffusion resistances or amelioration of climatic impacts on irrigation water requirements. Any increases in stomatal resistance are likely to increase water-use efficiencies. If the values of bulk stomatal diffusion resistance do not change, then values of water-use efficiency for most crops will likely decrease, because of increased E_t demand resulting from advection of sensible heat.

CAVEATS AND LIMITATIONS OF THE STUDY

1. Air temperature data measured at airport locations were adjusted to reflect temperature profiles expected to have occurred over irrigated crops. However, wind and humidity data still contain effects of airport settings (nonirrigated). Therefore, humidity levels are probably lower than those over irrigated crops and wind levels are probably higher. These two effects have likely caused an overestimation of true baseline crop E_t by about 3 to 10 %. However, relative changes due to GCM scenarios are probably only slightly affected by this bias.

2. Air temperature and humidity profiles in the boundary layer above a cropped surface are a reflection of the energy balance at the surface, with higher positive fluxes of sensible heat generating steeper temperature profiles for fixed levels of wind. Therefore, weather measurements are indicative of specific evaporative and energy balance conditions at the ground or canopy surface. Any change in the condition of the surface will cause a change in the temperature and vapor profiles and will change corresponding weather measurements. The Penman and energy balance equations utilize logarithmic characteristics of temperature, vapor, and wind profiles in estimating evaporative fluxes from crops. As the hypothesized values of canopy resistances are increased, less energy at crop surfaces is converted into latent heat, with more energy converted into sensible heat. Consequently, when sensible heat transfer is from crops to the air, both the leaf temperatures and steepness of temperature profiles above crops will increase with increasing canopy resistance, and air temperatures and vapor pressures at weather measurement heights will be affected. This modification will provide a type of feedback control affecting energy balances at leaf surfaces, much the same as the feedback of increased leaf temperature due to increased stomatal resistance, which increases the vapor pressure inside the leaf, thereby increasing the evaporative flux out of the leaf and reducing the effect of the increased resistance. The magnitudes and signs of the effects of increased canopy resistance on air temperatures and vapor contents at weather measurement heights are unknown, as the changes in surface temperatures and profile slopes are generally of opposite signs. Therefore, there is some uncertainty embedded in the E_t and irrigation water requirement estimates owing to "mismatching" of weather profiles and crop characteristics.

3. The evapotranspiration analyses in this study assumed that alfalfa (used as a reference E_t crop) and corn and wheat would all respond in similar manners to changes in carbon dioxide contents of the atmosphere, primarily in changes in canopy resistance and leaf areas. This assumption permitted the use of "basal" crop coefficients to estimate corn and wheat E_t from reference estimates for alfalfa.

4. Soil evaporation constitutes about 10 to 30% of the total evapotranspiration requirement of crops, depending on the frequency of precipitation and irrigation and crop canopy development. The estimates in this study are for a mixture of 50% center pivots with 2- to 3-day irrigation frequencies and 50 % other system types with generally 7- to 28-day irrigation frequencies. Therefore, estimates in this study are average values for a mixture of various system types.

5. The portion of daily rainfall infiltrating the soil and becoming available to reduce irrigation requirements was estimated using values of surface runoff predicted by the SCS Curve number method. This method is approximate. Therefore, estimations of effective precipitation, especially for large rainfall events, may have significant error.

6. This study assumed that crop development was a function of the product of solar radiation and air temperature ($R_s \cdot T$). Therefore, season lengths were shortened either by increased radiation (decreased cloudiness) or by increased mean daily air temperature.

7. Bulk stomatal diffusion resistance (r_c) includes both r_s and LAI components. Therefore, results of the sensitivity analyses reflect integrated changes in these two parameters.

8. The effect of elevated CO_2 concentrations on phenological development (times of flowering, maturity, root development, etc) or yield were not evaluated.

9. Planting dates were significantly earlier and growing seasons for corn and winter wheat were shorter under the 2xCO_2 global climatic scenarios. However, phenological or morphological changes or yield increases or decreases due to changes in photoperiod lengths and/or increased vulnerability to spring frosts were not evaluated.

10. Farmers may shift to crop varieties with higher environmental energy requirements to more fully utilize increased amounts of solar radiation and temperature available. The majority of results presented in this study assumed that varieties would not change, resulting in "compressed" growing seasons due to more rapid crop growth and phenology. Two reasons why farmers may be reluctant to shift to longer season varieties are the common lack of precipitation during later summer months, which would increase irrigation water requirements or moisture stress for dryland crops, and elevated leaf temperatures during late summer months, which may exceed optimum temperatures required for high productivity.

CHAPTER V

IMPLICATIONS OF RESULTS

The postulated climatic changes imply future increased peak demands and potentially increased seasonal demands on water resources in the Great Plains region. Because irrigated agriculture is the largest water user in this region, policies and strategies for stretching water supplies will be required.

ENVIRONMENTAL IMPLICATIONS

Increases in irrigation water requirements for full-season crops such as alfalfa or for improved annual cultivars that will be developed to take advantage of longer growing seasons will result in increased extraction of water for irrigation purposes (assuming that the irrigated acreages remain the same or increase as dryland farming gives way to irrigated agriculture). Increased extraction of groundwater may pose serious environmental and economic problems, especially in areas where groundwater "mining" is currently being practiced. Reduced streamflows resulting from increased extraction of surface and groundwater may aggravate water quality problems which may in turn affect fish, wildlife, and recreational activities.

Water shortages brought on by increased water requirements by some crops may lead to increased salinity problems if leaching requirements are not met. Recharge from irrigation seepage may also be diminished. Some positive impacts may result from improved farming practices allowing for better control of water, soil, fertilizer, and pesticides, thereby reducing agricultural pollution.

If irrigation requirements are reduced for corn and winter wheat, as indicated for some locations, especially if bulk stomatal diffusion resistances increase, then the changes will tend to benefit water resources and economics as less water and energy will be required. Groundwater drafts from the Ogallala aquifer will likely decrease, barring expansion of irrigated acreage, shifting to cultivars having longer growing seasons, or implementation of double cropping under irrigation.

Water-use efficiencies may decrease if bulk stomatal diffusion resistances remain constant and advection of sensible heat within the region increases. Water-use efficiencies may increase if bulk stomatal diffusion resistances increase, thereby reducing the ratio of E_t to photosynthetic activities.

SOCIOECONOMIC IMPLICATIONS

Socioeconomic impacts are difficult to assess because of the numerous external factors that influence the supply and demand for agricultural produce. It is, however, obvious that increases in evaporative demands and greater variability in rainfall will result in the following:

1. Potential reduction in crop yields due to reduced lengths of growing seasons for some annual crops. However, some or all of the reduced yield from less radiation may be offset by increased photosynthesis due to higher CO_2 levels.

2. Increase in the need for irrigation in present dryland farming regions owing to increases in peak monthly E_t and irrigation water requirements. Thus, the amount of capital invested in the irrigated sector may increase as irrigated areas are increased, even though seasonal irrigation water requirements for some crops may be less than at present.

3. Sizes of farm irrigation systems may need to be increased to meet increased peak demands. These increases will also require larger peak drafts of groundwater and electric supplies.

4. Increased competition for water and energy among users and uses during peak irrigation months. This may spur the development of technologies that promote water and energy conservation practices (technical and not technical) and breeding of crop varieties better adapted to the climatic conditions.

5. Increased yields for full-season crops such as alfalfa owing to longer growing seasons.

6. Decreased lengths of growing seasons for corn may reduce energy costs for grain drying, since the corn crop will have more opportunity to dry in the fields after reaching an earlier maturity.

7. Farmers may shift to crop varieties with higher seasonal environmental energy requirements to more fully utilize increased levels of available solar radiation and temperature. Two reasons why farmers may be reluctant to shift to longer season varieties are the common lack of precipitation during later summer months, which would increase irrigation water requirements or moisture stress for dryland crops, and elevated leaf temperatures during late summer months, which may exceed optimum temperatures required for high productivity. However, other economic considerations are the possibility of lower yields due to reduced lengths of growing seasons for some annual crops. Some, or all, of the yield reductions due to lower amounts of solar radiation may be offset by increased photosynthesis due to increased CO_2 levels.

Based on the assumption that the effects of climatic change will be spread over space and will occur gradually through time, we can expect modern agriculture to learn how to cope with the changes from the experiences gained in regions earlier impacted. During the transition stage, irrigators, planners, policy-makers, and research communities could develop strategies to cope with the transient and final steady-state conditions.

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