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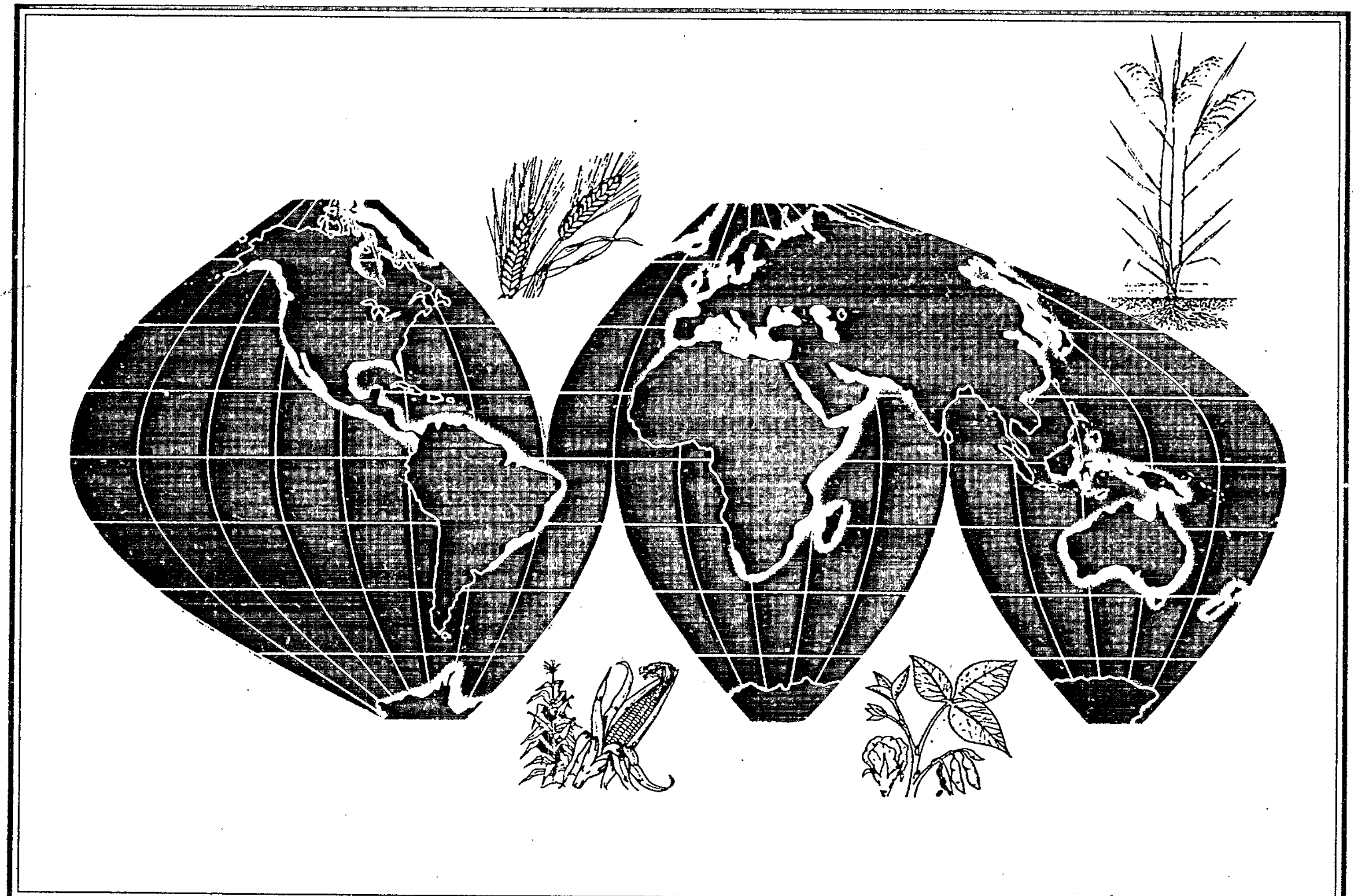

Implications Of Climate Change For International Agriculture:
Crop Modeling Study

Cynthia Rosenzweig and Ana Iglesias, Editors

United States Environmental Protection Agency
Office of Policy, Planning and Evaluation
Climate Change Division
Adaptation Branch

Ronald Benioff and Joel Smith, Project Officers

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IMPLICATIONS OF CLIMATE CHANGE FOR INTERNATIONAL AGRICULTURE: CROP MODELING STUDY

Editors

Cynthia Rosenzweig and Ana Iglesias

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PREFACE

This publication presents the crop modeling research conducted over the period 1989-1992 for the U.S. Environmental Protection Agency Climate Change Division project "Implications of Climate Change for International Agriculture: Global Food Production, Trade and Vulnerable Regions." Additional support was provided by the US Agency for International Development. Principal Investigators of the project were Cynthia Rosenzweig, of Columbia University and Goddard Institute for Space Studies, and Martin Parry, of the Environmental Change Unit at Oxford University.

At U.S. EPA Climate Change Division, we thank Dennis Tirpak, Joel Smith, Ron Benioff, and Joel Scheraga; and at U.S. AID, Tej Gill. Dr. Roy Jenne provided the GCM climate change scenarios. At Columbia University, we thank Ruth Levenson, Chris Shashkin, and Rich Goldberg. We especially acknowledge the IBSNAT crop modeling team, Bruce Curry, Gerrit Hoogenboom, Jim Jones, Joe Ritchie, Upendra Singh, and Gordon Tsuji, for worldwide scientific and technical support.

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EXECUTIVE SUMMARY

The central aim of the study was to provide an assessment of potential climate change impacts on world crop production, including quantitative estimates of yield and water-use changes of major crops. Agricultural scientists in 18 countries estimated potential changes in water use and crop growth, using compatible crop models and consistent climate change scenarios. The crops modeled were wheat, rice, maize and soybean. Wheat, rice and maize account for approximately 85% of world cereal exports; soybean accounts for about 67% of trade in protein cake equivalent. Site-specific estimates of yield changes were aggregated to national levels for the modeled major crops for use in a world food trade model, the Basic Linked System.

The study assessed the implications of climate change for world crop yields taking into account:
(a) *Uncertainty in the level of climate change expected.* Sensitivity tests were conducted with arbitrary increases in temperature and changes in precipitation. The effects of three climate change scenarios were also tested using doubled CO_2 equilibrium climates from three general circulation models: the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL) and the United Kingdom Meteorological Office (UKMO) models. These climates are assumed to occur in 2060. Finally, a transient projection of climate change was tested, based on the GISS transient run A, for the 2010s, 2030s, and 2050s.
(b) *Physiological effects of CO_2.* The climate change scenarios were tested with and without the direct effects of CO_2 on crop growth and water use, as reported in experimental literature.
(c) *Different adaptive responses.* Climate change impacts on crop yields incorporating farm-level adaptation were simulated, based on different assumptions about shifts in crop planting dates, changes in crop variety, level of irrigation, etc.

The principal results that emerged from the study were:

Sensitivity tests. A 2°C temperature rise increased aggregated crop yields on a global basis, while a 4°C rise led to decreases in globally aggregated crop yields. Nevertheless, in semi-arid and subtropical regions, a 2°C temperature increase caused yield declines. The greatest yield decreases are caused by a 4°C temperature increase and 20% precipitation decrease.

GCM climate change scenarios without adaptation. Without physiological CO_2 effects, production of all three crops decreased compared to baseline climate conditions on a global basis. With CO_2 effects, yields were positive at middle and high latitudes, and negative at low latitudes for the scenarios with lower temperature increases (~4°C global surface air temperature increase). For the warmest scenario (~5°C temperature increase), crop yields declined almost everywhere. Thus, increases in potential yield depend strongly on full realization of the direct effects of CO_2 on crop growth.

GCM climate change scenarios with adaptation. Farm-level adaptation (shifts in planting dates, changes in crop variety, application of irrigation) reduces the negative effects of climate change. However, even when farmer adaptation is taken into account, climate change may decrease yields in semi-arid, subtropical regions. Successful adaptation often implies significant changes to current agricultural systems.

In order to minimize possible adverse consequences to climate change worldwide, the agricultural sector should continue to develop crop breeding and management programs for heat and drought conditions (these will be immediately useful in improving productivity in marginal environments today). Another important activity is to enlarge, maintain, and screen crop genetic resources at established seedbanks. Resilience of the agricultural production sector also depends on improved use of systems for monitoring weather, soil moisture, nutrient requirements, and pest infestations. Finally, strong communication links among the agricultural research, production, and policy sectors are essential.

SECTION 1: INTRODUCTION

THE USE OF CROP MODELS FOR INTERNATIONAL CLIMATE CHANGE IMPACT ASSESSMENT: STUDY DESIGN, METHODOLOGY, AND CONCLUSIONS

Cynthia Rosenzweig

Columbia University and Goddard Institute for Space Studies
New York, USA

and

Ana Iglesias

Inst. Nacional de Investigaciones Agrarias (INIA)
Madrid, Spain

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SUMMARY

The methodology for an assessment of potential climate change impacts on world crop production, including quantitative estimates of yield and water use changes for major crops, is described. Agricultural scientists in 18 countries estimated potential changes in crop growth and water use using compatible crop models and consistent climate change scenarios. The crops modeled were wheat, rice, maize and soybean. Site-specific estimates of yield changes for the major crops modeled were aggregated to national levels for use in a world food trade model, the Basic Linked System. The study assessed the implications of climate change for world crop yields for arbitrary and GCM equilibrium and transient climate change scenarios. The climate change scenarios were tested with and without the direct physiological effects of CO_2 on crop growth and water use, as reported in experimental literature. Climate change impacts on crop yields incorporating farm-level adaptation were simulated, based on different assumptions about shifts in crop planting dates, changes in crop variety, and level of irrigation.

INTRODUCTION

Scientists predict significant global warming in the coming decades due to increasing atmospheric carbon dioxide and other trace gases (IPCC 1990a; 1992). Substantial changes in hydrological regimes are also forecast to occur. Understanding the potential effects of these changes on agriculture is an important task, because agriculture provides food for the world's population, now estimated at 5 billion and projected to rise to 10 billion in the coming century. Despite technological advances such as improved crop varieties and irrigation systems, weather and climate are still key factors in agricultural productivity. For example, weak monsoon rains in 1987 caused large shortfalls in crop production in India, Bangladesh, and Pakistan, contributing to reversion to wheat importation by these countries (World Food Institute 1988). Despite adequate supplies elsewhere, the 1980s also saw the continuing deterioration of food production in Africa, caused in part by persistent drought and low production potential. This resulted in international relief efforts to prevent widespread famine. These examples emphasize the close links between agriculture and climate, the international nature of food trade and food security, and the need to consider the impacts of climate change in a global context.

Recent research has been focused on regional and national assessment of the potential effects of climate change on agriculture (IPCC 1990b). The methodology for regional and national climate impact studies has thus been developed and tested. However, the studies have, for the most part, treated each region or nation in isolation, without relation to changes in production in other places. The purpose of this study was to increase understanding of potential simultaneous changes in production in all major food-producing regions, because such changes may lead to altered world supply and demand (and prices), and hence competitiveness in any given region. Such understanding should aid in the meaningful interpretation of regional climate change impact studies.

The study[1] was an international collaborative effort of agricultural scientists in 18 countries. A suite of dynamic process models, climate change scenarios, and simulation experiments was assembled, comprised of climate sensitivity tests and climate change scenarios devised from global climate models (GCMs), dynamic crop growth models, and a world food trade model (Figure 1). Common methodology was developed for the

[1]The study was commissioned by the U.S. Environmental Protection Agency Climate Change Division. The U.S. Agency for International Development provided support and additional funding for the crop modeling simulations.

simulation of climate change impacts on major agricultural crops and for the analysis of the results. The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT 1989) compatible crop growth models were utilized at over 100 sites (Figure 2). The crop models can simulate the direct physiological effects of increased atmospheric CO_2 on crop growth and water use. They allow for the simulation of both rainfed and irrigated agricultural systems and other potential farmer adaptations to climate change. Results of the dynamic crop growth simulations were then used to estimate global changes in crop yields for use in a world food trade model, the Basic Linked System (Fischer et al. 1988). Results of the entire study are described in Rosenzweig and Parry (1994).

BACKGROUND AND PREVIOUS STUDIES

Research on the effects of climate on agriculture has been extensive for many years. Much of the previous research on climate impact assessment sought to isolate the effects of climate on agricultural activity, whereas lately there has been a growing emphasis on understanding the interactions of climatic, environmental, and social factors in a wider context (Parry et al. 1988). An example of the earlier approach is the U.S. Department of Transportation's study on the possible effects of atmospheric ozone depletion which (in part) used regression models to determine statistical relationships between climate and agriculture, a method which does not explain the processes underlying the relationships. The National Defense University also studied long-term effects of climate change on crop yields and agricultural production with a relatively simple cause-and-effect approach (NDU 1980).

More integrated approaches to climate change impact assessments have been described by Callaway et al. (1982), the Carbon Dioxide Assessment Committee, Nix (1985), and Warrick et al. (1986). These studies and reviews advocate comprehensive research methods that integrate economic and political factors as well as biophysical ones. Some integration has been achieved in national impact studies completed in the United States (Adams et al. 1990; Smith and Tirpak 1989), Canada (Smit 1989), Australia (Pearman 1988), the UK (UK Department of the Environment 1991), and New Zealand (Martin et al. 1990), and in regional studies including high-latitude and semi-arid agricultural areas (Parry et al. 1988) and the U.S. Midwest (Rosenberg and Crosson 1991).

These regional and national studies have been summarized in the Intergovernmental Panel on Climate Change (IPCC) Working Group II Report (IPCC 1990b), but integrated global assessments of climate change impacts have been few to date. Kane et al. (1991) have analyzed the sensitivity of world agriculture to potential climate changes and found that the overall effect of moderate climate change on world and domestic economies may be small as reduced production in some areas is balanced by gains in others. These estimates did not consider the agricultural impacts of climate change associated with the higher end of the predicted IPCC-predicted range of warming (1.5 to 4.5°C mean global surface air temperature rise) (IPCC 1990a). Leemans and Solomon (1993) found that climate change would affect the yield and distribution of world crops for one GCM doubled CO_2 climate change scenario, leading to production increases at high latitudes and production decreases in low latitudes.

CLIMATE CHANGE SCENARIOS

Because of the uncertainties surrounding prediction of climate change, it is common to employ climate scenarios (Wigley 1987; Lamb 1987), in order to estimate the impacts of climate change on a system (in this case agricultural production, both potential and actual, and world food trade). Climate scenarios are sets of climatic perturbations which are used with impact models to test the sensitivity of the system to the projected changes. The design of an impact study should include more than one scenario, so that a range of possible effects may be defined. Realism is augmented when the climate change scenarios are internally consistent, i.e., the climate variables within the scenario should vary in a physically realistic way (Wigley 1987). Common doubled CO_2 GCM climate change scenarios and sensitivity tests were devised for the global crop modeling analysis.

Sensitivity Tests

An approach to analyze the possible impacts of different climate on crop yield is to specify incremental changes to temperature and precipitation and to apply these changes uniformly to the baseline climate. Arbitrary climate sensitivity tests were conducted to test crop model responses to a range of temperature (+2° and +4°C) and precipitation changes (+/- 20%). The scenario, +2°C with a precipitation decrease of -20%, is interesting because it assumes a possible temperature increase combined with a large decrease in the amount of rain, which is not simulated under the GCM climate scenarios. Sensitivity studies allow the consideration of the question: "What type, magnitude, and rate of climate change would seriously perturb the agricultural system in question?"

GCM Equilibrium and Transient Scenarios

Scenarios are often devised by changing an original set of climatological data by prescribed anomalies. These anomalies may be derived from historical climate or from global climate models. GCMs provide the most advanced tool for predicting the potential future climatic consequences of increasing radiatively active trace gases in a consistent manner. However, climate models have not yet been validated to project changes in climate variability, such as changes in the frequencies of drought and storms, even though these could affect crop yields significantly.

Mean annual changes in climate variables from doubled CO_2 simulations of three GCMs—Goddard Institute for Space Studies (GISS, Hansen *et al* 1983), Geophysical Fluid Dynamics Laboratory (GFDL, Manabe and Wetherald 1987), and United Kingdom Meteorological Office (UKMO, Wilson and Mitchell 1987)—were applied to observed (baseline) daily climate to create climate change scenarios for each site (Table 1). GCMs were used to create climate change scenarios because they produce climate variables that are internally consistent; thus they allow for comparisons between or among regions.

The method used the differences between $1xCO_2$ and $2xCO_2$ monthly GCM temperatures, and the ratio between $2xCO_2$ and $1xCO_2$ monthly precipitation and solar radiation amounts ($1xCO_2$ refers to modeled current climate conditions and $2xCO_2$ refers to the modeled climate that would occur with an equivalent radiative forcing of doubled CO_2 in the atmosphere). Temperature ranges of the three GCMs are near the high end of the IPCC range of predicted warming for doubled CO_2 (IPCC 1990a). In general, the GCMs predict increases in global precipitation associated with warming because warmer air can hold more water vapor.

Most of our knowledge concerning the climate response to greenhouse-gas forcing has been obtained from equilibrium response GCM experiments. These are experiments which consider the steady-state response of the model's climate to step-function changes in atmospheric CO_2. Recent evidence from a few GCM experiments incorporating time-dependent greenhouse-gas forcing suggest that there may be important differences between the equilibrium and transient responses (Hansen et al. 1988, Bryan et al. 1988; IPCC 1992).

This study also considered a set of transient climate scenarios (as opposed to the atmospheric equilibrium scenarios), derived from the GISS transient climatic simulations (Hansen et al. 1988) for the 2010s, 2030s, and 2050s, and assuming CO_2 concentrations of 405, 460, and 530 ppm, respectively. Transient scenarios for each site were developed by using the same procedure as that used for the equilibrium scenarios.

Limitations

Current global climate models which have been used for CO_2 studies employ grids on the order of 4° latitude by 5° longitude, or greater. At this resolution, many smaller scale elements of climate are not properly represented, such as warm and cold fronts and hurricanes, as well as the diversities of ecosystems and land-use. Accurate modeling of hydrological processes is particularly crucial for determining climate change impacts on agriculture, but GCM simulation of infiltration, runoff, and evaporation, and other hydrological processes is highly simplified. Precipitation, in particular, is sometimes poorly represented in GCMs results.

There is also uncertainty in the prediction of rate and magnitude of climate change. Ocean heat transport is a key, but not well understood, process that affects how fast the climate may warm. The doubled CO_2 climate change scenarios used in this study have assumed an abrupt doubling of the CO_2 concentration in the atmosphere and then have allowed the simulated climate to come to a new equilibrium. This step change in the atmosphere is unrealistic, since trace gases are increasing gradually. The transient scenario does simulate the response of gradually increasing radiatively active gases and is more realistic in this regard.

CROP MODELS

Description

The crop modeling study estimated how climate change and increasing levels of carbon dioxide may alter yields and water use of world crops in both major production areas and vulnerable regions. The crops modeled were wheat, rice, maize, and soybeans. Table 2 shows the percentages of world production modeled in this study for wheat, rice, maize, and soybean. Even though only two countries (Brazil and USA) simulated soybean production, their combined output accounts for 76% of world total. Less of the total world rice production was simulated than total production of the other crops. This is because India, Indonesia, and Vietnam have significant rice production not included in the study. Together, these crops account for more than 85% of the world traded grains and legumes, although only approximately 4% of rice produced is traded compared to about 20% of wheat. Rice is included in the study because of its importance to the food security of Asia.

The IBSNAT models employ simplified functions to predict the growth of crops as influenced by the major factors that affect yields, i.e., genetics, climate (daily solar radiation, maximum and minimum temperatures, and precipitation), soils, and management (IBSNAT 1989). The models used were CERES-Wheat (Ritchie and Otter 1985; Godwin et al. 1989), CERES-Maize (Jones and Kiniry 1986; Ritchie et al. 1989), CERES-Rice (both paddy and upland) (Godwin et al. 1993), and SOYGRO (soybean) (Jones et al. 1989).

The IBSNAT models were selected for use in this study because they have been validated over a wide range of environments (e.g., Otter-Nacke et al. 1986) and are not specific to any particular location or soil type. Thus they are suitable for use in international studies in which crop growing conditions differ greatly. The validation of the CERES and SOYGRO models over different environments also serves to enhance predictive capability concerning the climate change scenarios, in cases when predicted climates are similar to existing climates in other regions. Furthermore, because management practices, such as cultivar, planting date, plant population, row spacing, and sowing depth, may be varied in the models, they permit experiments that simulate management adjustments by farmers to climate change.

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 and SOYGRO models also have the capability to simulate the effects of nitrogen deficiency and soil-water deficit on photosynthesis and pathways of carbohydrate movement in the plant.

Physiological CO_2 Effects

Most plants growing in atmospheric CO_2 that is higher than ambient levels exhibit increased rates of net photosynthesis (i.e., total photosynthesis minus respiration). High CO_2 also reduces the stomatal openings of some crop plants. By so doing, CO_2 reduces transpiration per unit leaf area while enhancing photosynthesis. Thus it often improves water-use efficiency (the ratio of crop biomass accumulation or yield and the amount of water used in evapotranspiration). Experimental effects of CO_2 on crops have been reviewed by Acock and Allen (1985) and Cure (1985). In a compilation of greenhouse and other experimental studies, Kimball (1983) estimated a mean crop yield increase of 33 +/- 6% for a doubling of CO_2 concentration from 300 to 600 ppm for a range of important agricultural crops.

In order to project the impact of increasing CO_2 on agricultural production, these beneficial direct effects should be considered along with the climatic effects of the radiatively active trace gases. The assessment of the relative contributions of the direct effects of CO_2 and the predicted climate changes to agricultural crop responses remains a crucial research question. GCM predictions show that climate warms in virtually all regions, while hydrologic regimes may become either wetter or drier. Thus, the climatic effects on crop yields may thus be either negative or positive depending on location; this study tested whether the beneficial direct effects (as estimated from experimental studies) may compensate for negative climate change impacts in a variety of crop-growing environments around the world.

The IBSNAT models have been modified to simulate the changes in photosynthesis and evapotranspiration caused by higher levels of CO_2. These modifications (based on methods derived from Peart et al. (1989)) were used in the crop yield/climate change scenario modeling to study the relative magnitudes of the direct physiological and the climatic effects of increased CO_2. Ratios were calculated between measured daily photosynthesis and evapotranspiration rates for a canopy exposed to a range of high CO_2 values, based on published experimental results (Allen et al. 1987; Cure and Acock 1986, and Kimball 1983). Instantaneous midday values were then modified to give daily integrated increases, allowing for lower light intensities in morning and evening. In the crop models, the photosynthesis ratios (Table 3) were applied to the maximum amount of daily carbohydrate production which is based on incoming solar radiation.

To account for the effect of elevated carbon dioxide on stomatal closure and increased leaf area index, and hence on potential transpiration, the evapotranspiration formulation of the IBSNAT models was changed to include a ratio of transpiration under elevated CO_2 conditions to that under ambient conditions. To derive the ratio, Peart et al. (1989) applied the Penman-Monteith equation (as written in France and Thornley 1984) to the same canopy and environment, except for differing CO_2 concentrations. The leaf resistances were calculated as a function of the differing CO_2 concentrations using equations developed by Rogers et al. (1983) based on experimental data for maize and soybean (used for all C3 crops) (Table 3). The ratio procedure results in a lower transpiration rate for higher CO_2 levels on a daily per unit leaf area basis. Seasonal evapotranspiration, however, may not change proportionately, and may even increase, because of the greater leaf area grown under elevated CO_2 conditions.

The simulation of direct CO_2 effects for soybeans, wheat, and maize under current climate conditions have been compared to experimental results (Peart et al. 1989; Jones and Allen, pers. comm.; Rosenzweig 1990). The wheat and soybean results compare well with experimental results, but maize simulations tended to overestimate yield increases due to high CO_2 at sites with low annual precipitation.

Rates of future emissions of trace gases, as well as when the full magnitude of their effects will be realized, are unknown. For this study, CO_2 concentrations are estimated to be 555 ppm in 2060 (based on Hansen et al. 1988). Because other greenhouse gases besides CO_2 (e.g., methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs)) are also increasing, an "effective CO_2 doubling" has been defined as the combined radiative forcing of all greenhouse gases having the same forcing as doubled CO_2 (usually defined as 600 ppm). The effective CO_2 doubling will occur around the year 2030, if current emission trends continue.

The climate change caused by an effective doubling of CO_2 may be delayed by 30 to 40 years or longer, hence the projections for 2060 in this study.

Limitations

The IBSNAT models contain many simple, empirically-derived relationships that do not completely mimic actual plant processes. These relationships may or may not hold under differing climatic conditions, particularly the higher temperatures predicted for global warming. For example, 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 35 or even 40°C during the growing period. Other simplifications of the crop models are that weeds, diseases, and insect pests are controlled; there are no problem soil conditions such as high salinity or acidity; and there are no catastrophic weather events such as heavy storms. The crop models simulate the current range of agricultural technologies available around the world; they do not include potential improvements in such technology, but may be used to test the effects of some potential improvements, such as improved varieties and irrigation schedules.

CALIBRATION AND VALIDATION

Individual investigators calibrated and validated the IBSNAT crop models using local experimental data, where possible. Where such procedures were not possible, previous calibrations of cultivars based on the IBSNAT minimum dataset methods were relied on, as well as previous validations. The IBSNAT crop models have been created with the express purpose of broad applicability across a wide range of environments.

The validation procedures and experimental data used for the 18 country studies are described in the following chapters. In general, genetic coefficients for different crop genotypes were estimated from data gathered in local agricultural experimental stations. Each parameter was calibrated directly from observed results (phase duration, biometric ratio, and growth rates) in order to obtain rough parameter values. These values were then used in model runs and adjusted in order to attain a pseudo-best fit of observed data. Overall, validation showed acceptable results in the experiments conducted.

CROP MODELING PROCEDURES

The participating agricultural scientists carried out a set of crop modeling simulation experiments for baseline climate, GCM doubled CO_2 and transient climate change scenarios with and without the physiological effects of CO_2 and sensitivity tests. This involved the following tasks:

1. Define the geographical boundaries of the major production regions of the country, and estimate the current production of major crops in those regions.

2. Provide observed climate data for representative sites within these regions, for the baseline period (1951-1980), or for as many years of daily data as are available, and specify the soil, crop, and management inputs necessary to run the crop models at the selected sites.

3. Validate the crop models with experimental data from field trials.

4. Run the crop models with baseline data and climate change scenarios, with and without the direct effects of CO_2 on crop growth, with irrigated production, sensitivity tests, and adaptation responses – for example, shifts in planting date and crop varieties. Report modeled yield changes and other

results, e.g., changes in crop growing season arising from climate change.

5. Identify and evaluate alterations in agricultural practices that would lessen any adverse consequences of climate change.

The chapters that comprise the following sections of this volume describe the agricultural system that was modeled, the methods and results of the crop modeling work, including adaptation responses, and the implications of the projected climate changes, yield and water use changes, and adaptation strategies for agriculture in the 18 individual countries.

ESTIMATION OF NATIONAL YIELD CHANGES

In order for the crop modeling results at individual sites to be used in the world food trade study, the initial task was to scale up from site results to changes in national crop yields. This was done first for the crops and countries in the crop modeling study. Then these results were extended to other crops based on agronomic characteristics, and to other countries and regions based on similarities in agro-ecological zones, previous climate change impact studies, and on comparison of GCM climate change scenarios for a full complement of global estimates of potential impacts of climate change on crop yields.

Crop model results from over 100 sites in the 18 countries were aggregated by weighting current regional production to produce national yield change estimates. This is an essential intermediate step that permits the extrapolation of results from crop modeling experiments at individual sites to national yield changes for the food trade model. The agricultural scientists in each country selected sites representative of major agricultural regions, described the agricultural practices of the regions, and provided regional and national production data for estimation of regional contributions to the national yield changes. All the crop modeling aggregation results used to develop the BLS estimates were either calculated by the agricultural scientists themselves or developed jointly with them.

A region is defined as an "area within a country where there are homogeneous agricultural practices, soils, and climate." In the most complete national studies, enough sites were modeled to represent all the major agroecological regions. In other cases, modelers were asked to analyze the sites modeled and the regions in their country in order to extend the results as appropriately as possible. The regional yield estimates represent the current mix of rainfed and irrigated acreage, the current crop varieties, nitrogen management and soils, as provided by the country participants. In most cases only one crop variety and one soil were modeled at each site.

A database was created for the current regional and national production for the 18 countries with crop model results, primarily provided by the participants. Another source of production data was the FAO (1988). For the USA, the data source was the USDA (Crop Production Statistical Division); for the former Soviet Union the data source was the USDA International Service.

Results were aggregated similarly for the 11 countries where wheat was modeled (Table 4). There are large differences among national results; for example, Brazil, Egypt, Pakistan, and Uruguay show significant decreases in wheat yields even with the direct effects of CO_2, while simulated wheat yields in Canada, and the USSR primarily increase under the climate change scenarios with the direct effects of CO_2. The other crops were aggregated using the same methodology.

The crop yield estimates incorporate some major improvements: 1) consistent crop simulation methodology and climate change scenarios; 2) weighting of model site results by contribution to regional and national, and rainfed and irrigated production; and 3) quantitative foundation for estimation of physiological CO_2 effects on crop yields. Another set of estimates incorporating the effects of farmer adaptation to climate change was also produced. All results forwarded to the world food trade model were in terms of percent change from current yields, rather than absolute values. Analysis of relative changes in yields are more appropriate given the many uncertainties involved in analysis of climate change impacts. It is important to note, however, that percent change in yield depends on absolute value of base yields which are different for the three crops, e.g., soybean base yields are low, so that a high percentage change does not represent a large absolute decrease in yield.

DESIGN OF THE ADAPTATION STUDY

Farmers will react dynamically to changing environmental conditions. Country participants tested the efficacy of several types of adaptations in crop simulation experiments. The adaptation strategies tested involved changes in current management practices, e.g., planting date, fertilizer, and irrigation; and changes in crop variety either to existing varieties or hypothetical new varieties. Several participants considered the expansion of crops (e.g., winter wheat in the former Soviet Union and Canada and rice in China) to areas that are temperature limited under the current conditions. The primary adaptation strategies tested are described below.

Planting Date

The most likely response of farmers to warmer temperature would be to plant earlier to utilize the cooler early season and to avoid high temperatures during the grain-filling period. All the crop model study participants suggested earlier planting as a strategy for adapting to global warming. A relatively small change in planting date, perhaps up to four weeks, should be easily supportable, but longer shifts in sowing date may alter the soil moisture (it may be either too wet or too dry) and change the solar radiation (it may be lower) at planting. In some country studies (Argentina, Philippines, and China) the sensitivity tests on planting date suggested large changes in seasonal agricultural production, implying major changes in the agricultural systems. In Argentina, planting date shifts of up to 4 months earlier or one month later were suggested by adaptation simulations.

Irrigation

The crop model simulations demonstrated that climate change may bring significant increases in the need for irrigation. In Petrolina, PE, Brazil, where soybeans are currently produced under rainfed conditions, soybean response to the UKMO climate change was negative even with direct CO_2 effects, but positive with full irrigation. Climate change may increase demand for irrigation water for crops already under irrigation and may encourage installation of new irrigation systems, if economic resources are available. Currently only about 15% of the world's agriculture is under irrigation. The potential problems associated with increased irrigation as an adaptive strategy are the questionable availability of water resources, the associated costs, and the environmental problems of soil salinization and water pollution.

Fertilizer

An increase in the amount of fertilizer applied can compensate in some cases for yield losses caused by climate change. Studies in Uruguay and Mexico used the nitrogen module in the IBSNAT crop models to test adaptation to climate change via fertilizer applications. In Uruguay, the barley response to nitrogen fertilizer under baseline and UKMO conditions was compared. For the baseline runs the currently available cultivar was used at the normal planting date. The same cultivar was used for the UKMO runs, but sown at an earlier date with the physiological effects of increased CO_2. The planting date was changed for the UKMO runs, because the warmer temperatures of the scenario resulted in a shorter growing season. Four nitrogen fertilizer rates were used, and the response curve was adjusted with linear regression analysis. Consequently, the baseline maximum yield was more than 1 t ha^{-1} higher than the corresponding yield under UKMO conditions. Also, the amount of N fertilizer needed to attain the maximum grain yield under UKMO was 2.6 times larger than the amount required to attain the same yield under current climatic conditions. These results may have significant implications for future fertilizer use under climate change conditions at the high end of the range of predicted warming and indicate an important area for future research.

Crop Variety

Since most regions are predicted to experience substantial increases in growing season temperature, country participants tested substitution of existing varieties with higher thermal requirements for currently grown varieties. In Mexico, use of existing cultivars produces slightly higher yields with the GISS climate change scenario (with the direct effects of CO_2), but does not overcome the negative climate change effects. Some researchers also tested hypothetical new varieties in the crop model simulations, a technique useful for establishing new breeding objectives. The crop models also allow testing of differing crop types, such as winter and spring wheats. In the former USSR, a comparison of winter and spring wheat simulations indicates that winter wheat will respond more favorably under the GCM climate change scenarios tested.

Cropping Area

With further analysis of crop-climate classification, estimation of changes in cropping systems may be made. In China, climate change as projected by the three GCM scenarios would bring significant shifts in the rice cropping pattern, based on the extension of the growing period and increased thermal regime during the rice growing season (Gao et al. 1987). The regions where triple, double, and single-rice crops per year could be grown would move northward and there would be increased sowing of "indica" rice now grown in southern China, replacing the current "japonica" types.

SOURCES OF UNCERTAINTY

The primary uncertainties in the crop yield modeling depend on the assumptions embedded in the IBSNAT crop models, as discussed earlier; the methods by which the IBSNAT models were used in the climate change impact study; and the difficulty of estimating future technological improvements in agriculture.

Regarding the use of the IBSNAT models for the climate change study, there are several key points. Climate data were taken from differing numbers of years and of differing quality in the various country studies, and artificially generated daily solar radiation were used in the absence of observed data. Changes in climate variability were not simulated.

Furthermore, the generalized soil characteristics do not encompass all the wide variety of global agricultural soils. The resetting of the initial profile of soil water content, in most cases to full, at the beginning of each cropping season leads to underestimation of the impacts of changes in the hydrological cycle on crop production. Varying levels of nitrogen fertilization were not considered in most of the country studies, exceptions being Argentina, Uruguay and Mexico. Consistent high levels of fertilization are especially unrealistic in developing countries. Limited (often only one) cultivars were simulated at each site, although in common practice several to many cultivars are planted in most cropping regions, which might respond differently to climate change.

Finally, the crop models simulate the current range of available agricultural technologies. They do not include potential improvements in such technology, although they may be used (as shown in this study) to test the effects of some potential improvements, such as improved varieties and irrigation schedules.

RESULTS

Sensitivity Tests

While the arbitrary sensitivity tests are dissociated from the processes that influence climate, they simulate a controlled experiment and provide better understanding of the factors affecting crop model responses. They can also help to identify climatic thresholds of critical impacts. Climate sensitivity tests were carried out in 13 countries for combinations of 0, 2, and 4°C temperature increases coupled with precipitation changes of 0%, +20%, and -20%. Changes were considered relative to the baseline yield at 330 ppm CO_2.

Without the direct effects of CO_2, crops averaged over all sites showed an increasingly negative response to increased temperatures, with percent decreases in yields approximately doubling from the +2 to +4°C cases. When direct CO_2 effects are included, wheat, soybean, and rice yields increase about 15% with a 2°C temperature rise, but turn negative at +4°C, indicating a possible threshold of compensation of direct CO_2 effects for temperature increases between 2 and 4°C as simulated in the IBSNAT crop models (Figure 3).

GCM Scenarios

Climate change scenarios without the direct physiological effects of CO_2 caused decreases in simulated crop yields in many cases, while the direct effects of CO_2 mitigated the negative effects primarily in mid and high latitudes (Table 4). Potential changes in national yields (averaged over all commodities in the BLS) varied for the GISS, GFDL, and UKMO climate change scenarios with the physiological effects of CO_2 (Figure 4). However, latitudinal differences were apparent in all the scenarios; high latitude changes were less negative or even positive in some cases, while lower latitude suffered more detrimental effects of climate change on agricultural production.

The GISS and GFDL climate change scenarios produced a range of yield changes from +30 to -30%, although there were regional differences. The GISS scenario is, in general, more detrimental to crop yields in Asia and S. America, and GFDL is more harmful in North America (USA and Canada) and the former USSR. The UKMO climate change scenario which has the greatest warming (5.2°C global surface air temperature increase) generally causes the largest yield declines (up to -50%).

The magnitudes of the estimated yield changes vary by crop. Maize production is most negatively affected, probably due to its lower response to the physiological effects of CO_2 on crop growth, while soybean is least affected because it responds significantly to increased CO_2, at least in the climate change scenarios with lower estimated mean global surface air temperature warming. Simulated yield losses are caused by a combination of factors, depending on location and nature of the climate change scenario. Primary causes of detrimental impacts on yield are:

1. Shortening of the growing period (especially grain filling stage) of the crop. This occurred at some sites in all countries.

2. Decrease of water availability caused by increased evapotranspiration and loss of soil moisture and in some cases a decrease in precipitation in the climate change scenarios. This occurred in Argentina, Brazil, Canada, France, Japan, Mexico, and USA.

3. Poor vernalization. Many temperate crops require a period of low temperature in winter to initiate

or accelerate the flowering process. Low vernalization results in low flower bud initiation and ultimately reduced yields. This caused decreases in winter wheat yields in Canada and the former USSR.

Simulated yield increases in the mid- and high-latitudes were caused primarily by:

1. The positive physiological effects of CO_2. At sites with cooler initial temperature regimes, increased photosynthesis more than compensated for the shortening of the growing period caused by warming.

2. The lengthened growing season and the amelioration of cold temperature effects on growth. At some sites near the high latitude boundaries of current agricultural production, increased temperatures extended the frost-free growing season and provided regimes more conductive to greater crop productivity.

Transient Scenarios

When the crop models were run with transient climate changes projected for the 2010s, 2030s, and 2050s from the GISS transient run A, yield responses were non-linear over time (Figure 5). Aggregated national wheat yields exhibited the widest range of effects and were the most non-linear of the three crops, displayed differing trajectories of change in different regions of the world. Soybean yield changes in the U.S. and Brazil were the most positive of the three crops, while maize yield changes tended to be the most negative.

Adaptation Studies

The adaptation studies conducted by the project participants suggest that ease of adaptation to climate change is likely to vary with latitude (Figure 6). With the existing pool of cultivars and current resources of water and fertilizer, agricultural adaptation to climate change seems likely in high and mid-latitude countries, but seems out of reach for nations in the low latitudes. In tropical and semi-tropical regions, especially semi-arid zones, the temperature changes suggested by the GCM scenarios tested are problematic. While soil moisture deficits can easily be made up with simulated automatic irrigation, the economic and environmental costs of establishing irrigation systems can be high.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

Climate change induced by increasing greenhouse gases is likely to affect crop yields differently from region to region across the globe. Under the climate change scenarios adopted in this study, the effects on crop yields in mid- and high-latitude regions appeared to be less adverse than those in low-latitude regions. However, the more favorable effects on yield in temperate regions depended to a large extent on full realization of the potentially beneficial direct effects of CO_2 on crop growth. Decreases in potential crop yields are likely to be caused by shortening of the crop growing period, decrease in water availability due to higher rates of evapotranspiration, and poor vernalization of temperate cereal crops. When adaptations at the farm level were tested (e.g., change in planting date, switch of crop variety, changes in fertilizer application and irrigation), compensation for the detrimental effects of climate change was found to be more successful in developed countries.

Future research needs include determining how countries, particularly developing countries, can and will respond to reduced yields. More detailed adaptation studies in many different locations will help to address this need. In order to minimize possible adverse consequences to climate change worldwide, the agricultural sector should be encouraged to continue to develop crop breeding and management programs for heat and drought conditions (these will be immediately useful in improving productivity in marginal environments today). Another important activity is to enlarge, maintain, and screen crop genetic resources at established seedbanks. Resilience of the agricultural production sector also depends on improved use of systems for monitoring weather, soil moisture, nutrient requirements, and pest infestations. Finally, strong communication links among the agricultural research, production, and policy sectors are essential.

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Table 1. GCM climate change scenarios.

GCM	Year*	Resolution**	Change in Average Global Temperature	Change in Average Global Precipitation
GISS[1]	1982	7.83° x 10°	4.2°C	11%
GFDL[2]	1988	4.4° x 7.5°	4.0°C	8%
UKMO[3]	1986	5.0° x 7.5°	5.2°C	15%

*When calculated.
**Latitude x longitude.
[1]Hansen, J. et al. 1983.
[2]Manabe, S. and R.T. Wetherald. 1987.
[3]Wilson, C.A. and J.F.B. Mitchell. 1987.

Table 2. Current world crop yield, area, production, and percent world production aggregated for countries participating in study.

Crop	Yield	Area	Production	Study Countries
	t ha^{-1}	ha x 1000	t x 1000	%
Wheat	2.1	230,839	481,811	73
Rice	3.0	143,603	431,585	48
Maize	3.5	127,393	449,364	71
Soybeans	1.8	51,357	91,887	76

Source: FAO, 1988.

Table 3. Photosynthetic ratios and stomatal resistances used to simulate direct physiological CO_2 effects in the IBSNAT models (555 ppm CO_2/330 ppm CO_2).

	Photosynthesis* Ratio	Stomatal Res.** $s\ m^{-1}$
Soybean	1.21	49.7/34.4
Wheat	1.17	49.7/34.4
Rice	1.17	49.7/34.4
Maize	1.06	87.4/55.8

*Based on experimental work reviewed by Cure (1985).
**Based on experimental work by Rogers et al. (1983).

Table 4. Current production and changes in simulated wheat yields under GCM 2 x CO_2 climate change scenarios, with and without the direct effects of CO_2[1].

Country	CURRENT PRODUCTION				CHANGE IN SIMULATED YIELDS					
	Yield t ha^{-1}	Area hax1000	Prod. tx1000	% Total	GISS[2] %	GFDL[2] %	UKMO[2] %	GISS[3] %	GFDL[3] %	UKMO[3] %
Australia	1.38	11,546	15,574	3.2	-18	-16	-14	8	11	9
Brazil	1.31	2,788	3,625	0.8	-51	-38	-53	-33	-17	-34
Canada	1.88	11,365	21,412	4.4	-12	-10	-38	27	27	-7
China	2.53	29,092	73,527	15.3	-5	-12	-17	16	8	0
Egypt	3.79	572	2,166	0.4	-36	-28	-54	-31	-26	-51
France	5.93	4,636	27,485	5.7	-12	-28	-23	4	-15	-9
India	1.74	22,876	39,703	8.2	-32	-38	-56	3	-9	-33
Japan	3.25	237	772	0.2	-18	-21	-40	-1	-5	-27
Pakistan	1.73	7,478	12,918	2.7	-57	-29	-73	-19	31	-55
Uruguay	2.15	91	195	0.0	-41	-48	-50	-23	-31	-35
Former USSR										
winter	2.46	18,988	46,959	9.7	-3	-17	-22	29	9	0
spring	1.14	36,647	41,959	8.7	-12	-25	-48	21	3	-25
USA	2.72	26,595	64,390	13.4	-21	-23	-33	-2	-2	-14
WORLD[4]	2.09	231	482	72.7	-16	-22	-33	11	4	-13

[1]Results for each country represent the site results weighted according to regional production. The world estimates represent the country results weighted by national production.
[2]GCM 2xCO_2 climate change scenario alone.
[3]GCM 2xCO_2 climate change scenario with direct CO_2 effects.
[4]World area and production x 1,000,000.

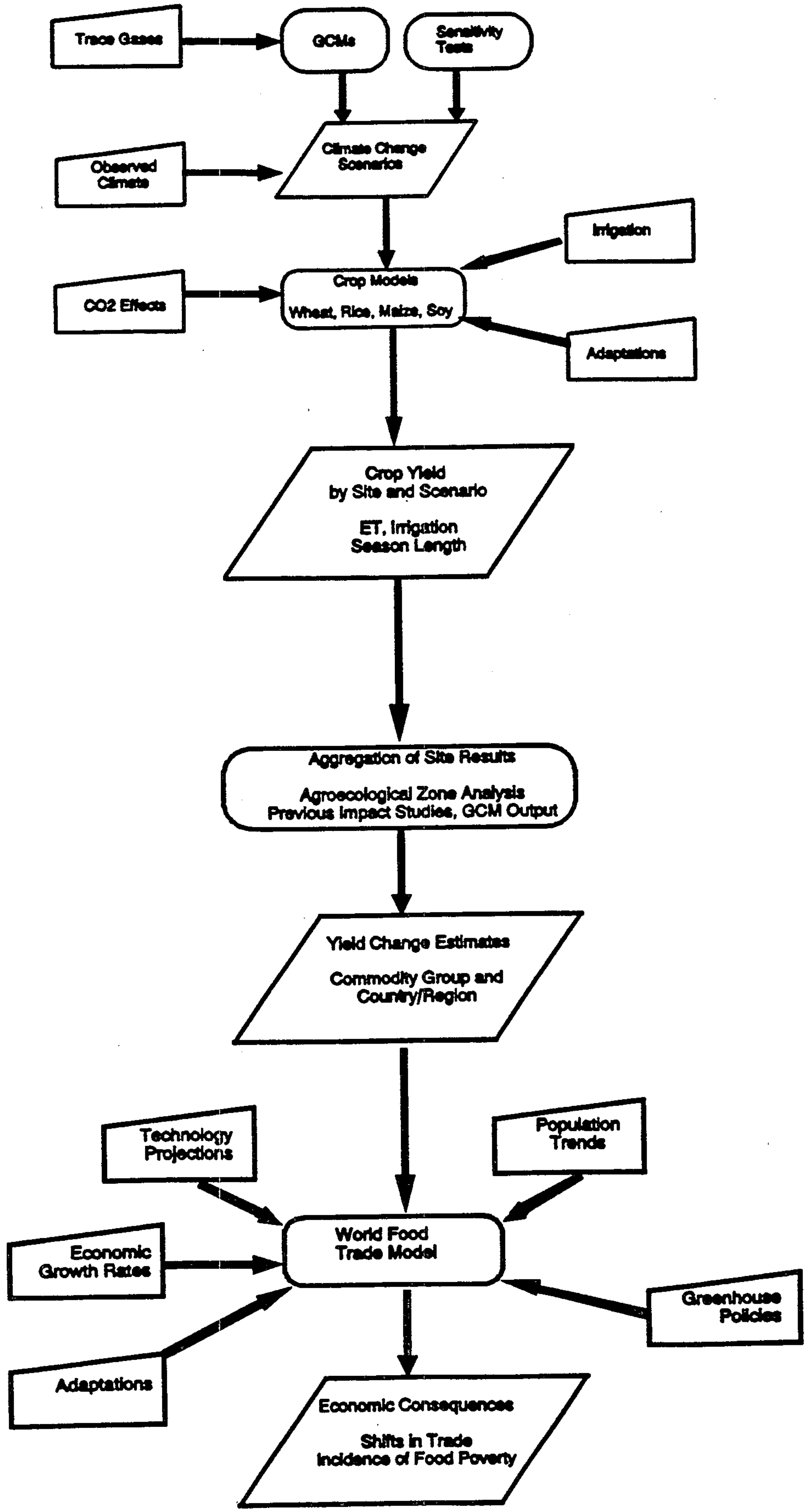

Figure 1. Key elements of crop yield and world food trade study.

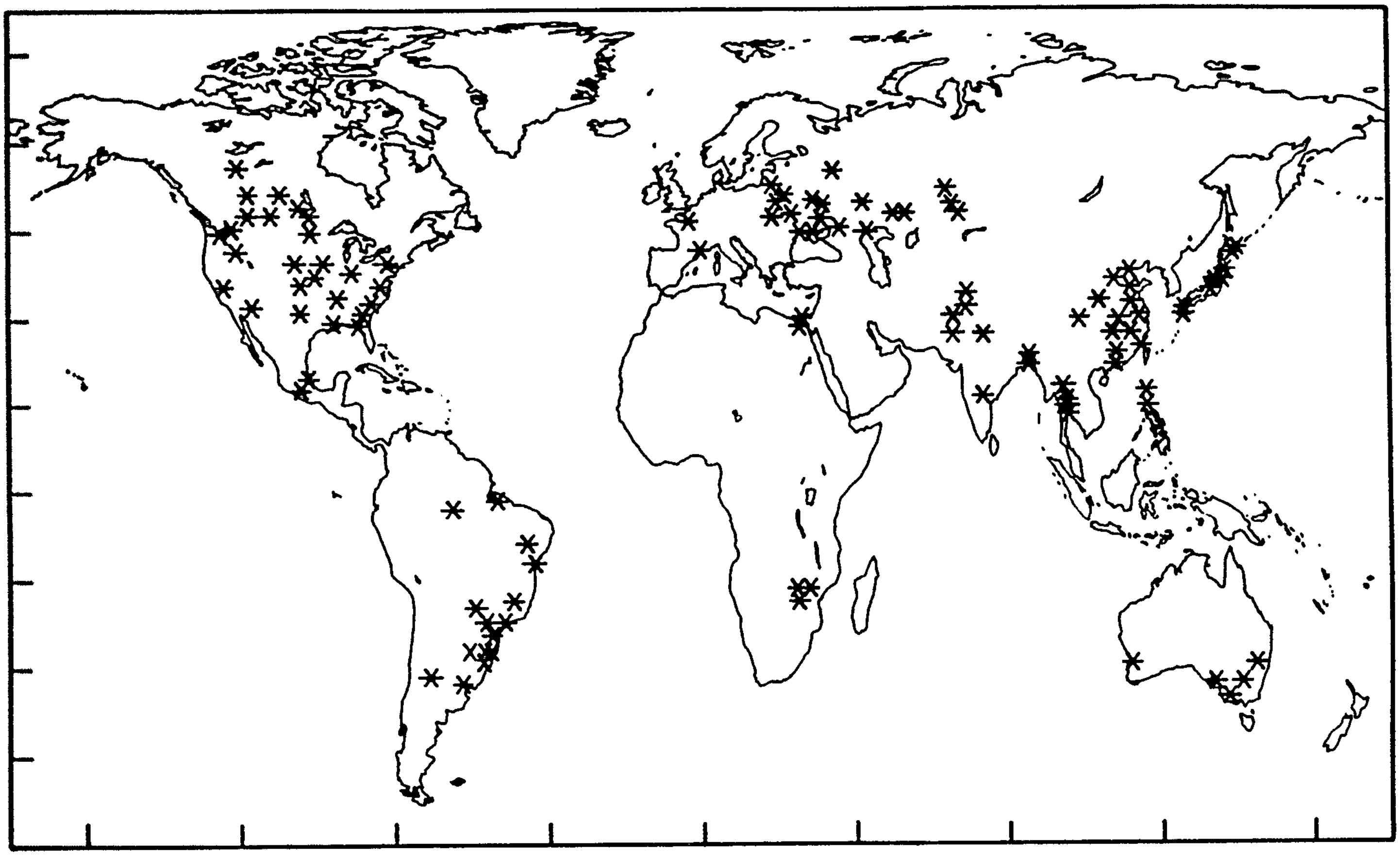

Figure 2. Crop model sites.

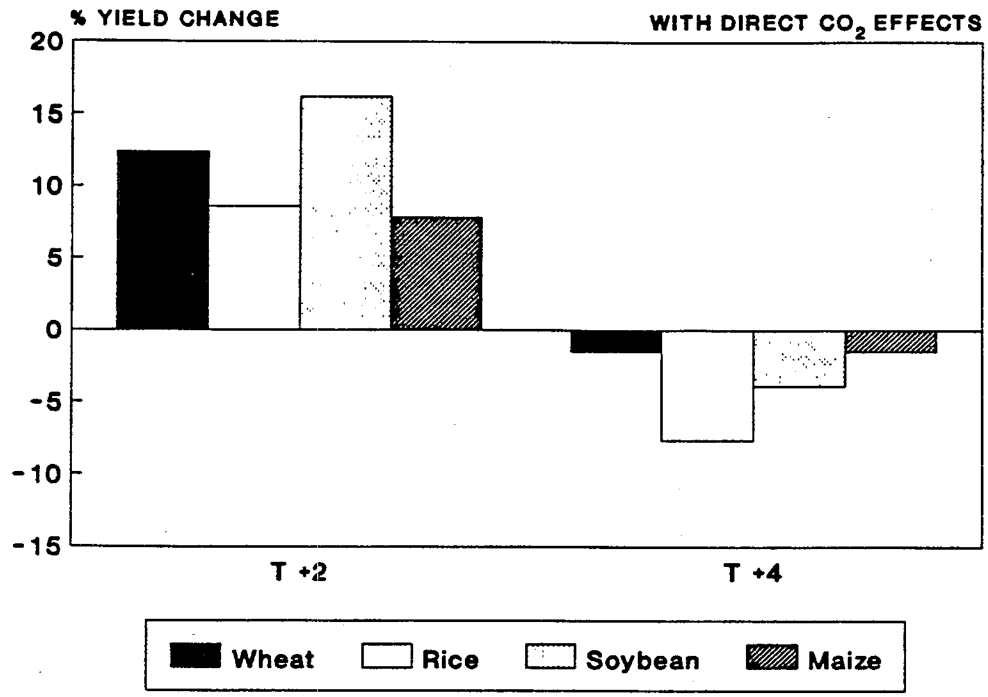

Figure 3. Aggregated IBSNAT crop model yield changes for +2°C and +4°C temperature increase. Country results are weighted by contribution of national production to world production. Direct effects of CO_2 on crop growth and water use are taken into account.

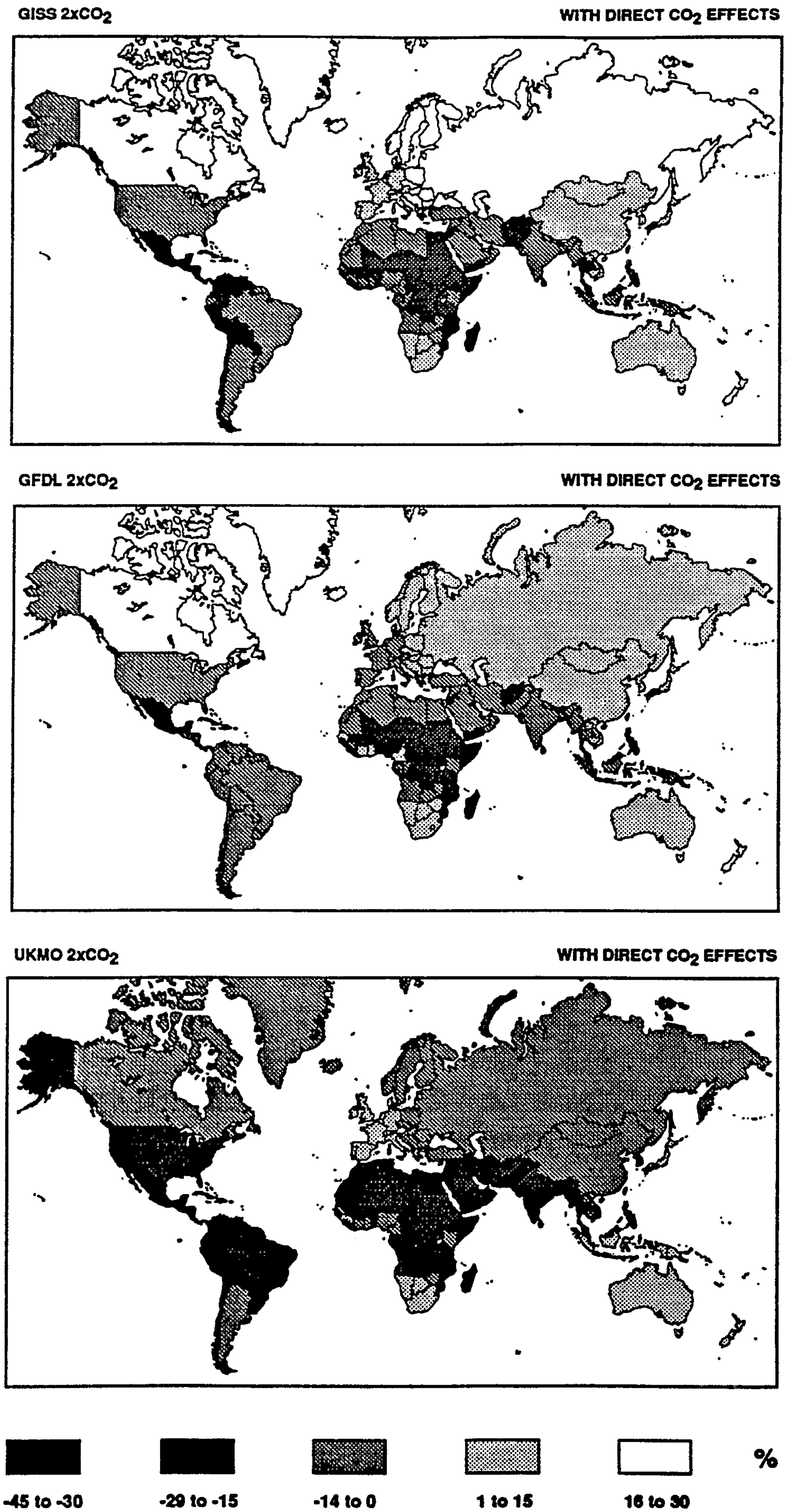

Figure 4. Estimated change in average grain yield (wheat, rice, coarse grains, and protein feed) for the GISS, GFDL, and UKMO climate change scenarios with direct CO_2 effects.

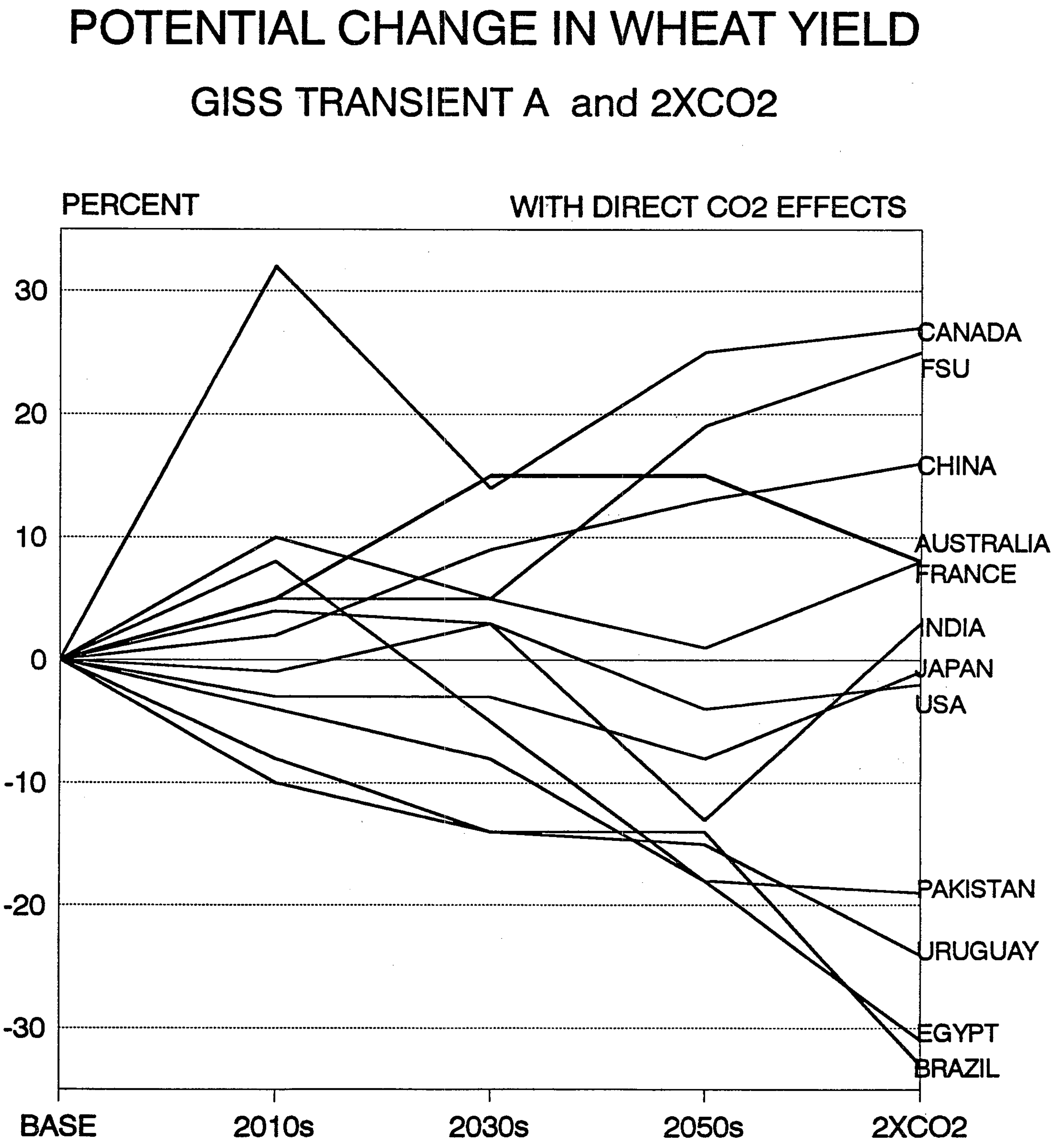

Figure 5a. Estimated change in average national yields of wheat for the GISS transient run A and doubled CO_2 climate change scenarios. Direct effects of CO_2 on crop growth and water use are taken into account.

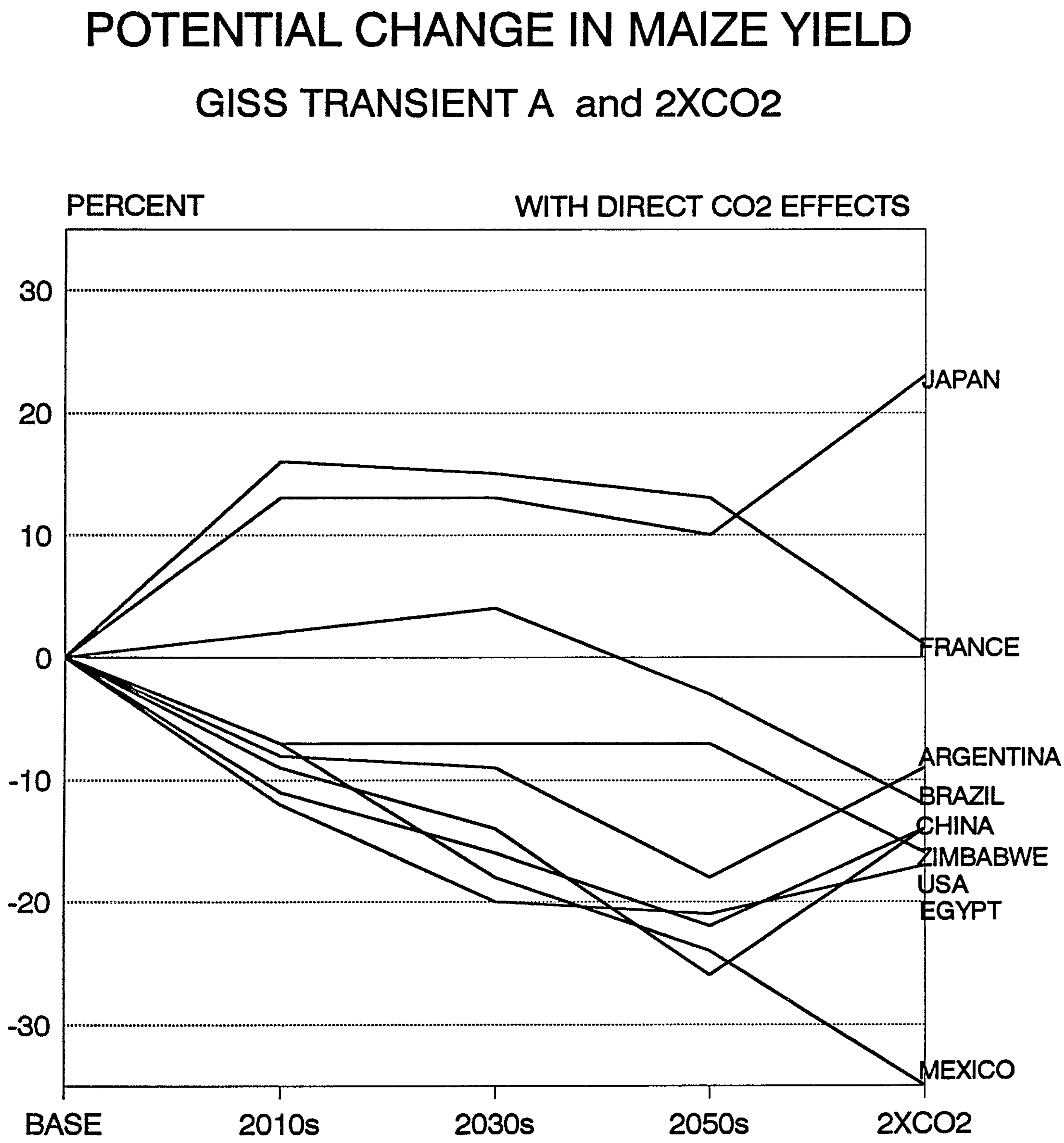

Figure 5b. Estimated change in average national yields of maize for the GISS transient run A and doubled CO_2 climate change scenarios. Direct effects of CO_2 on crop growth and water use are taken into account.

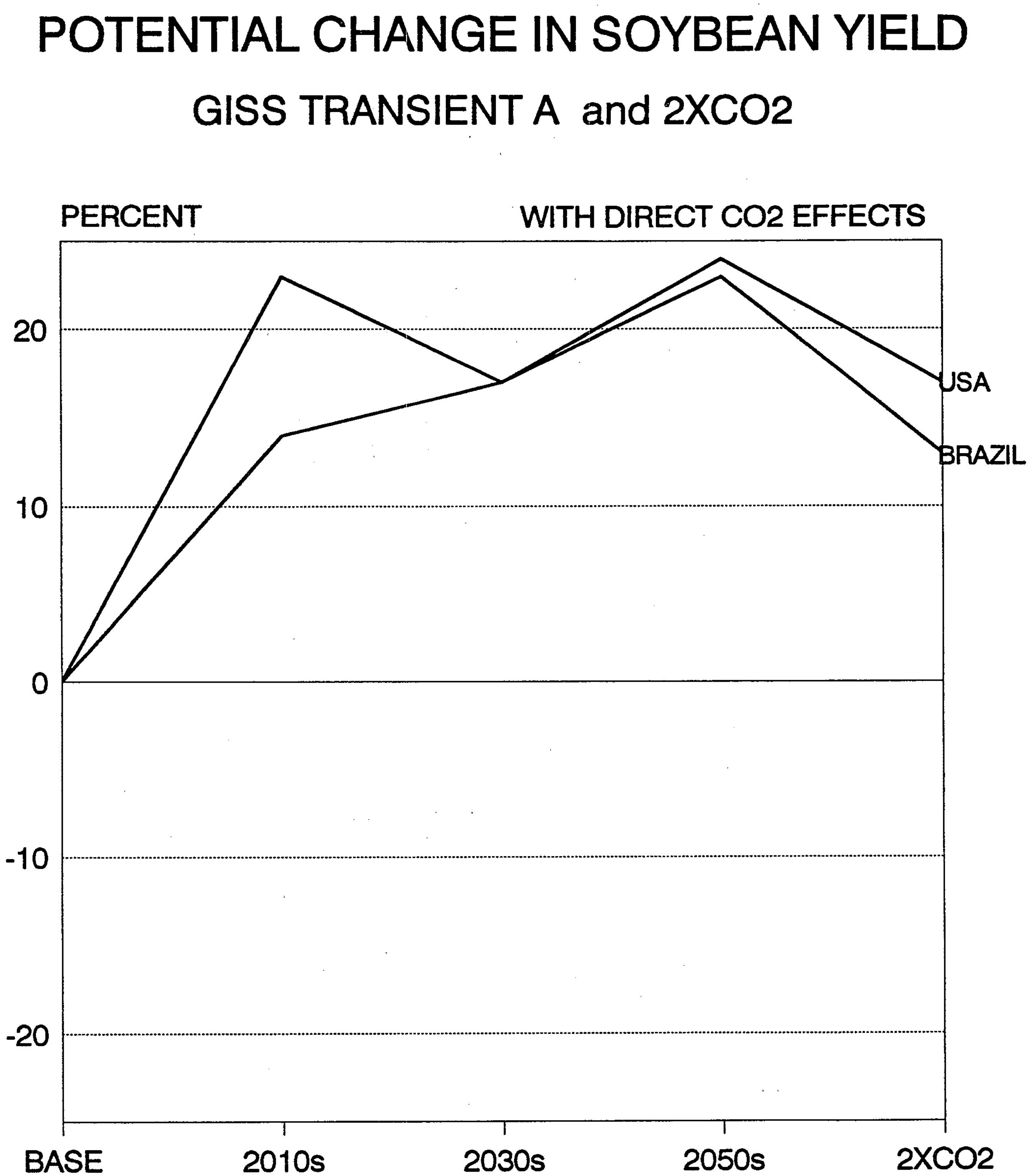

Figure 5c. Estimated change in average national yields of soybean for the GISS transient run A and doubled CO_2 climate change scenarios. Direct effects of CO_2 of crop growth and water use are taken into account.

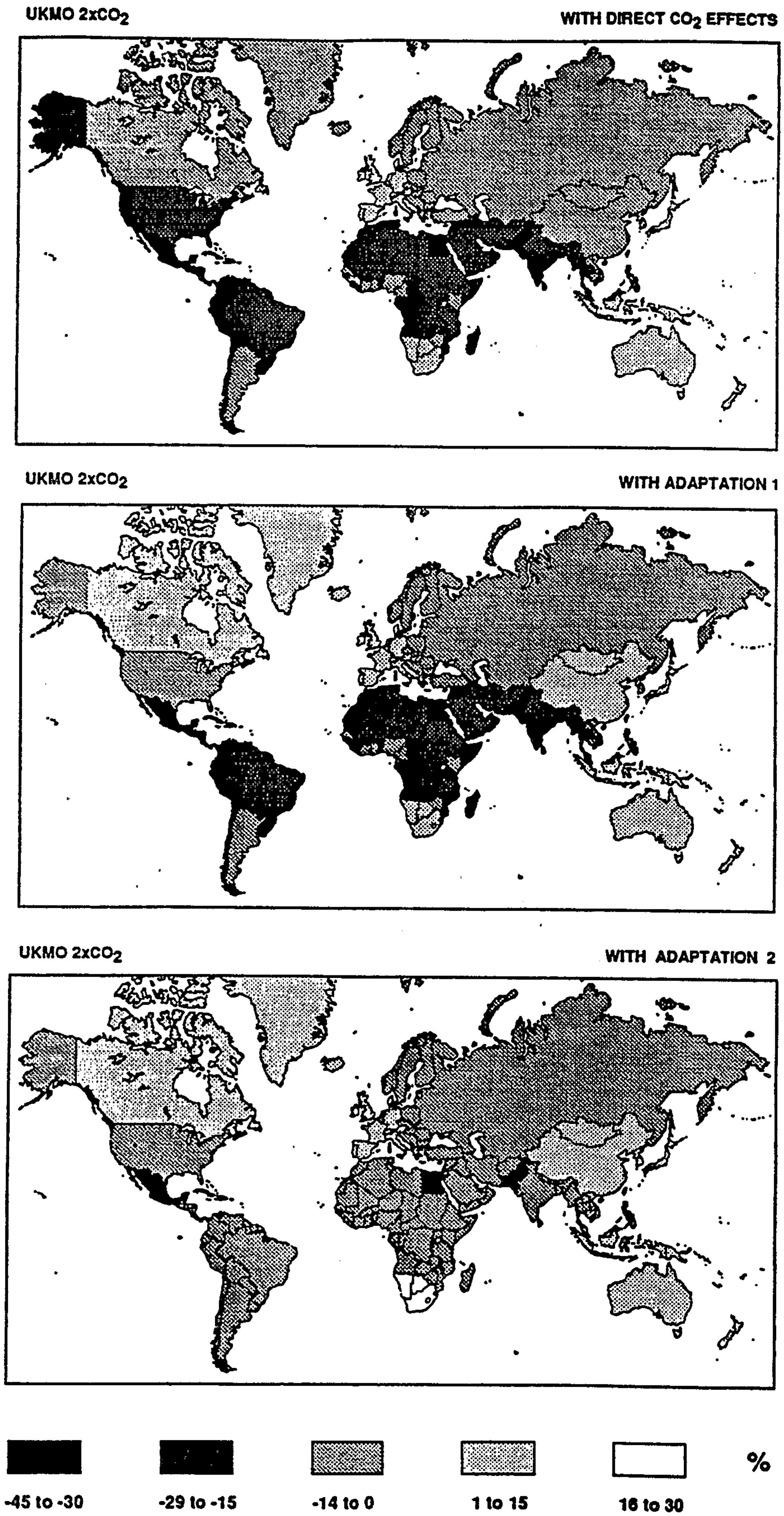

Figure 6. Estimated change in average grain yield (wheat, rice, coarse grains, and protein feed) under two levels of adaptation for the UKMO climate change with direct CO_2 effects.

SECTION 2: NORTH AMERICA

EFFECTS OF GLOBAL CLIMATE CHANGE ON WHEAT YIELDS IN THE CANADIAN PRAIRIE

M. Brklacich

Department of Geography, Carleton University
Ontario, Canada

R. Stewart

Bureau for Environmental Sustainability
Agriculture Canada, Ontario, Canada

V. Kirkwood

Centre for Land & Biological Resources Research (CLBRR)
Agriculture Canada, Ontario, Canada

R. Muma

Horticulture & Special Crops Division
Agriculture Canada, Ontario, Canada

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SUMMARY

Climate change, as projected by three General Circulation Models (GCMs), caused simulated spring wheat yields to decrease at all sites selected for the study in the Canadian prairie. Yield decreases were caused primarily by significant increases in temperature, which shortened the growing season and resulted in less time for biomass accumulation. When the direct effects of CO_2 were considered, the results varied with the scenario. Under the GISS scenario, wheat yields increased at most sites, while under the more severe UKMO scenario (hotter and drier), wheat yields declined at most sites.

Adaptation strategies designed to offset the negative effects of climate change were successful in some areas. Higher temperatures allowed regions in southern Canada to plant winter wheat instead of spring wheat, taking advantage of more favorable climatic conditions to produce higher yields, but northern regions were still too cold to grow winter wheat. Irrigation was found to be an effective method of adaptation at the driest sites.

INTRODUCTION

Background

Agriculture in Canada is highly diversified, an important influence on the national economy, and a major contributor to international export markets. In the Atlantic provinces, livestock, dairy, poultry, and potatoes are the major commodities. Central Canada benefits from many advantages, including superior soils and climatic conditions, proximity to urban markets, and highly developed processing and transportation sectors. The agriculture in this region is diversified and is a major contributor to Canadian livestock, field crop, and vegetable production. In British Columbia, agriculture is a relatively small industry, focusing on dairy, poultry, vegetable, and fruit production. In the Canadian prairie provinces (Manitoba, Saskatchewan, and Alberta), the agri-food industry is a major component of the economy (51% of the total Canadian cash farm receipts). In Saskatchewan, agriculture accounts for about 16% of the provincial gross domestic product (the highest percentage of any Canadian province). In the prairie provinces, spring wheat is the main commodity (96% of the national production), and most of the crop is destined for export markets. Canada is the third largest wheat exporter in the world.

Extensive dryland agriculture is the dominant characteristic of farming systems in the prairie region. Annual production for the 1981-85 period averaged more than 21 million t, and more than 11 million ha are used for spring wheat production each year. Spring wheat is important in all three prairie provinces, but approximately 55% of total production is from Saskatchewan.

The potential impacts of a greenhouse-induced global climate warming on agroclimatic resources, crop yield, and regional production potential have been previously reported in regional studies (Arthur 1988; Bootsma *et al.* 1984; Brklacich and Smit 1991; Singh and Stewart 1991; Smit *et al.* 1989; Stewart 1990; Williams *et al.* 1988; Bootsma and de Jong 1988b). Current agroclimatic conditions for many regions of Canada are characterized by relatively short periods without frost, and therefore a majority of the Canadian research on the agricultural impacts of global warming has focused on possible alterations in the growing season properties for annual crops with concomitant adjustments to productivity levels. As knowledge of climatic processes, climatic change, and climate-agriculture relationships improve, these assessments need to be refined. In addition, a study that goes beyond regional impact studies, considers the agri-food sector in the broader context of national and international economies, and analyzes the extent to which climatic change might alter comparative advantages among various regions in Canada and its agricultural trading partners is essential.

Objectives

This study is the Canadian contribution to a project designed to assess the potential implications of global warming on major world agricultural commodities and their international trade. It was coordinated by the U.S. Environmental Protection Agency and the U.S. Agency for International Development. Contributing countries were requested to appraise the impacts of a range of scenarios for global warming on production opportunities for a major export or import crop. This study focussed on spring wheat production in the Canadian prairie provinces. The primary analytical tool used in this study was the CERES-Wheat model (Godwin *et al.* 1989). Spring wheat was selected because it has regional and national significance to the Canadian economy and because Canada is one of the top three wheat exporters in the world. Consequently, changes in climatic (or other) conditions which would alter Canada's potential for wheat production or the country's comparative advantage, could have repercussions on national and international levels.

Wheat production occurs over a vast area in the prairie region which transverses several soil and climatic zones. The projected global climatic change scenarios suggest that long-term climatic alterations may not be distributed uniformly across the prairie region. In order to capture some of the spatial variability in the region's biophysical properties, seven indicator sites, which include all major biophysical zones in the prairie provinces, are considered in this study (Figure 1 and Table 1). The extent to which these indicator sites represent the region as a whole is not known, and therefore this report does not attempt to generalize the findings across the region.

DATA, PROCEDURES, AND ASSUMPTIONS

Baseline Climate Data

Daily maximum and minimum temperatures and daily total precipitation data (from 1951-80) for the seven sites were obtained from the Canadian national weather archive maintained by the Atmospheric Environment Service (AES), Environment Canada. Daily solar radiation data were not available for the full baseline period at all sites and therefore were estimated using the procedure described in Doorenbos and Pruitt (1977). The method uses daily observations of bright sunshine hours (obtained from the national archive), estimates of solar radiation at the top of the atmosphere, and daylength (according to Russelo *et al.* 1974). The observed and estimated solar radiation values obtained by this method are comparable.

Climate Scenarios Derived from GCMs

Climate change scenarios for each site were generated from three equilibrium General Circulation Models: the Goddard Institute for Space Studies Model (GISS), (Hansen *et al.* 1983), the Geophysical Fluid Dynamics Laboratory Model (GFDL), (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office Model (UKMO), (Wilson and Mitchell 1987). The method for creating scenarios for each site involved the following procedures: (a) the GCM grid point located closest to each indicator site was identified; (b) for each of the identified grid points, the changes in mean monthly temperature were calculated as the difference between the $2XCO_2$ and the control ($1XCO_2$) GCM runs, and for mean monthly precipitation and solar radiation, the change was calculated as the ratio of the $2XCO_2$ run to the control run; (c) changes in the monthly mean values derived under step (b) were then applied to the observed daily baseline record.

Table 2 shows the temperature and precipitation changes used in this study. Temperature increases considerably under the three GCMs at all sites, with the largest increases occurring in the winter. The GISS and GFDL scenarios present similar temperature changes. In the southern Canadian prairies, temperature increases are 3°C-6.5°C, and the largest increases correspond to the northern site in Alberta (Fort Vermillion). Summer temperature increases are 2°C-3°C lower than winter increases. The UKMO scenario is characterized by the largest temperature increases (5°C-10°C). Winter increases are 3°C-5°C higher than summer increases and are largest in the Alberta and Manitoba sites.

The three GCMs estimate precipitation increases for most seasons, but the magnitude of the increases varies considerably among GCMs and sites. For the critical growing period of spring wheat (May to August), the GISS model predicts precipitation increases up to 25% above the current average; winter precipitation also increases. The direction of the precipitation changes predicted by the UKMO model are similar to those projected by the GISS model, but the increases in the winter are larger than those in the summer. The GFDL model predicts smaller precipitation increases than the other two GCMs, and no trend was discernable for the Canadian prairie sites. Late winter, spring, and summer precipitation changes for the sites in Manitoba tracked 50%-70% above current averages. For the sites in Saskatchewan, winter and spring precipitation increases up to 50%, but there are no significant changes in summer precipitation.

Solar radiation changes under the $2XCO_2$ scenarios (not shown) are not very large in comparison to the current levels.

Transient Scenarios

This study also considered a set of transient climate scenarios (as opposed to the atmospheric equilibrium scenarios), derived from the GISS transient climatic simulations (Hansen et al. 1988) for the 2010s, 2030s, and 2050s, and assuming CO_2 concentrations of 405, 460, and 530 ppm, respectively. Transient scenarios for each site were developed by using the same procedure as that used for the equilibrium scenarios.

In general, each step in the transient scenario implies a further temperature increase, with winter increases higher than the summer increases. Except for Fort Vermillion, the largest estimated increase in temperature occurs between the 2030s and the 2050s. For the sites in Saskatchewan and Alberta, precipitation changes mostly during the 2010s. Solar radiation changes little under the transient scenarios, with only slight decreases during the winter.

Sensitivity Analysis

An alternative approach for incorporating changes to the current climate is to specify incremental adjustments to selected climatic variables and to apply these changes uniformly to the daily observed weather record. While this approach is removed from the processes that influence climate, it has the advantages of simulating a controlled experiment and thereby providing a better understanding of the factors affecting responses. In addition, the approach can also identify climatic thresholds that could ultimately imply substantial impacts for agriculture. Combinations of temperature increases of 0°C, +2°C, and +4°C and precipitation changes of 0%, -20%, and +20% were considered in this study.

Crop Model, Cultivars, Management Variables, and Soils

The crop model used in this simulation study is the CERES-Wheat model (Godwin *et al.* 1989). The model simulates crop responses to the major factors driving plant growth and development. Simulated processes include soil moisture balance, phenological development, yield and biomass production.

Cultivars. The area sown with different spring wheat varieties has changed over the past fifty years. In 1988, the most important varieties were Katepwa (49% of the total area of spring wheat in the prairie), Neepawa (21%), and Columbus (18%) (Prairie Pools, Inc. 1988). In the first half of the 1980s, Neepawa and Benito were the most popular varieties. The differences among varieties are usually related to resistance to pests and diseases, resistance to shattering, and susceptibility to root rot. For example, the major difference between Katepwa and Neepawa is that the Katepwa "has better stem and leaf rust resistance and is easier to thresh" (Saskatchewan Agriculture and Food 1990).

These important factors, which ultimately affect crop yield, are not considered by the CERES-Wheat model. Therefore, given that a few varieties account for the majority of the area sown with spring wheat and that many of the differences among varieties are beyond the scope of the CERES-Wheat model, a single variety can adequately represent a substantial proportion of the varieties currently used in the Canadian prairie. We selected the Manitou variety for the simulation study, with the genetic coefficients derived by Godwin et al. (1989). Manitou was an important variety used in the 1960s and 1970s, and many of the varieties used in the 1980s are derived from it. The major differences between Manitou and other varieties used in the 1980s are confined to characteristics not considered in the CERES-Wheat model, and therefore, the genetic coefficients associated with the Manitou are still applicable (Morrison, personal communication).

The genetic coefficients for winter wheat used in the adaptation section of this study were the representative winter wheat genetic coefficients for varieties grown in the northern plains of the United States (Godwin *et al.* 1989).

Management variables. The seeding dates for spring wheat were derived from Bootsma and de Jong (1988a) (Table 3). These seeding dates were estimated using the observed weather record (1951-80) and represent the average dates for this period. Yearly variability in the weather conditions result in a considerable range of seeding dates. For example, the earliest and the latest seeding dates estimated for Lethbridge between 1951 and 1980 were April 24 and May 23, respectively. At Winnipeg the estimated seeding dates ranged from April 24 to June 9. The importance of an early or late spring on seeding date, crop growth, and grain yield is beyond the scope of this study.

For winter wheat (considered in the Adaptation section of this study), seeding dates were derived from provincial field crop production guides (Manitoba Agriculture 1988; McLelland 1985a; Saskatchewan 1981).

Field crop production guides and agronomists determined the planting densities for the spring and winter wheats (Manitoba Agriculture 1988; McLelland 1985a, 1985b; Saskatchewan Agricultural Services Coordinating Committee 1981). The midpoint in the seeding rate was selected, and seeding rates in kg ha^{-1} were converted to plants m^{-2} using an average seed weight of 30 mg (Fei and Ripley 1985).

The adaptation study considers the effects of irrigation on wheat yields. In this study, irrigation was triggered when the soil moisture estimated for the 1.2-meter rooting zone dropped below 50% of the moisture-holding capacity. It was assumed that the amount of water required to return the rooting zone to field capacity was applied at that time, with an irrigation efficiency of 100%.

Soils. A representative soil for each site was identified in consultation with a prairie-soil expert (Shields, personal communication). For all sites except for Fort Vermillion, data on horizon depths, texture, bulk density, organic carbon, coarse fractions, pH, and soil classification were extracted from the Canada Soil Information System (CanSIS) (Canada-Alberta 1989; Canada-Manitoba 1989; Canada-Saskatchewan 1989). Permeability, drainage, slope, quantity of roots, and soil color were estimated by Shields (personal communication). Soil surveys for the Fort Vermillion area are incomplete, and data on soils for this area are not available from CanSIS. The Donnelly series has been characterized for the neighboring Grinshaw and Notikewin areas (Scheelar and Odynsky 1968), and these data were used in this study.

The CERES-Wheat model estimates the soil moisture storage capacity from the input soil profile. This estimate represents the maximum amount of soil moisture that could be available to the crop at seeding. The version of the CERES-Wheat model used in this study does not estimate soil moisture recharge between harvest and seeding, but it does allow users to specify soil moisture conditions at seeding as a percentage of the estimated storage capacity. Since soil moisture reserves of prairie soils at seeding are typically well below the moisture-holding capacity, the initial soil water conditions were adjusted. The estimates of soil-moisture conditions at seeding presented in Table 3 were derived from de Jong and Bootsma (1987). These estimates are long-term, average values for the entire soil profile and were calculated using the observed weather record for 1951-80, assuming a continuous wheat-farming system.

Simulation of the Physiological Effects of CO_2

Higher levels of atmospheric CO_2 have been shown to increase photosynthesis and water-use efficiency, resulting in yield increases in experimental settings (Acock and Allen, 1985). Because the climate change scenarios are associated with levels of CO_2 that are higher than the current climate GCM simulations (330 ppm), the physiological effects of alternative CO_2 levels on crops were included in the crop model simulations.

Other gases such as CH_4, N_2O, and CFCs are expected to contribute to the greenhouse effect, and therefore, the equivalent of a $2xCO_2$ atmosphere would be reached before the actual doubling of CO_2. To account for this effect, an atmospheric CO_2 concentration of 555 ppm was used to represent the equivalent of a $2xCO_2$ atmosphere.

Performance of the CERES-Wheat Model in the Canadian Prairie

Previous studies. The CERES-Wheat model has been used previously to estimate wheat yields in the Canadian prairies. Fei and Ripley (1985) used the model to estimate wheat yields from 1964-84 for the Saskatoon crop-reporting district (more than 2 million ha of cropland). After accounting for technological advances, their main conclusions were: (a) for the entire period, the CERES model overestimated observed yields by 24%; and (b) the model tended to overestimate yields in the good years and underestimate yields in the poor years.

Fei and Ripley suggested that the following factors could have contributed to the observed and simulated yield discrepancies: (a) the weather and soil data used as input for the CERES-Wheat model did not accurately represent the range of weather and soil conditions occurring in the area; (b) the model does not account for yield losses due to pest and disease damage; and (c) the model underestimates root growth, and therefore, moisture-deficit stress was exaggerated in dry years, as there was insufficient root growth to exploit water reserves from the deeper layers. In wet years, the model would produce excessive above-ground growth, greater leaf area development, and higher yields. In addition, there are the usual concerns regarding the reliability of the reported yields. The estimates are based on samples of farmers' estimates of yields, and the extent to which these estimates are influenced by unreported crop failures and/or portions of fields not used for crop production is not known.

Current study. For this study, observed and simulated yields and season lengths were compared (Table 4). These parameters were closely related at all sites, although the modeled season lengths tended to be longer, with the greatest discrepancies occurring at Prince Albert and Letherbridge. The simulated grain yields at Winnipeg, Dauphin, Swift Current, and Prince Albert were comparable to previous estimates (Fei and Ripley 1985). On average, the model tended to overestimate yield by about 25%. The model was considerably less reliable for the three Alberta sites, especially for the central and northern Alberta sites (Ellerslie and Fort Vermillion), suggesting that the version of the model used in this study has not adequately captured the influence of longer days and lower light intensities associated with these northern latitudes.

For all the sites, the CERES-Wheat model simulated season length reasonably well. For Winnipeg, Dauphin, Swift Current, Prince Albert, and Letherbridge, the model provides reasonable estimates of long-term grain yields. However, for Ellerslie and Fort Vermillion, the yield-predicting capability of the CERES-Wheat model needs to be refined.

These performance characteristics suggest that results from the Canadian analysis should be applied in similar fashion to the results obtained from GCMs, i.e., as percent differences between baseline and scenario runs. Relative changes from baseline simulations rather than absolute values from crop model runs should be used. Impacts on yield in a particular region thus can be estimated and compared to results from other scenarios and regions. The value of the CERES-Wheat model is that it provides estimates of the direction and magnitude of yield change among different sets of conditions. It is not intended to provide an exact measure of yield nor absolute predictions of climate change impacts.

IMPLICATIONS OF GLOBAL WARMING AND CO_2 INCREASES FOR SPRING WHEAT

Global Warming in Isolation

The $2xCO_2$ scenarios for climate change provide a basis for comparative static assessments of the implications of an altered climate on crop yields. This section evaluates the effect of three GCM global climate change scenarios on agro-climatic conditions and wheat yields at seven sites throughout the prairies.

Maturation Time. The large temperature increases associated with the GISS, GFDL, and UKMO scenarios imply a decrease in the time required for spring wheat to mature (Figure 2). For the indicator sites in the southern portion of the Canadian prairies, the GISS and GFDL scenarios simulated a growing period that is 11 to 14 days shorter than the current growing period. The impacts were more pronounced for the northern sites, with the GISS and GFDL scenarios shortening the growing period by approximately 3 and 4 weeks, respectively. The UKMO scenario showed the largest decreases in the growing period due to its higher temperature predictions. A three-week reduction in the amount of time required for spring wheat to mature was typical in the southern prairies under this scenario, with a 4-5-week reduction estimated for the northern parts of the Canadian prairie.

Crop Moisture Stress. Each of the climate change scenarios had a different impact on crop moisture stress (Table 5). (Crop moisture stress is the difference between precipitation and simulated evapotranspiration during the crop growing period.) Under the current conditions, deficits in crop moisture characterize wheat production throughout the Canadian prairies. The GISS scenario had little impact on the magnitude of the moisture deficit accumulated over the maturation period of the crop. However, these accumulated deficits, coupled with considerable declines in the time required for wheat to mature, resulted in an increase in average deficits per day. Under the GFDL and UKMO scenarios, precipitation increased in the eastern sites and decreased in the western sites. These altered precipitation patterns eliminated moisture deficits for the sites in the eastern prairie, while the deficits became somewhat more severe in the western sites. Under the UKMO scenario, precipitation increases provided some relief to moisture stress, but the shortened maturation period of the crop offset this potential benefit, and an increase in the average daily crop moisture deficit was estimated.

Yields. The overwhelming trend of the impacts of all three climate change scenarios on wheat yields was negative, but the magnitude of the impacts varied with scenario and site (Figure 3). The simulated shortening of the season length caused a decrease in the time available for the grain filling, and thereby contributed to a decline in crop yields. The GISS and UKMO scenarios had considerably smaller impacts on the driest part of the prairie (Swift Current and Lethbridge), with larger declines in crop yields elsewhere. The yield impacts under the GISS scenario in the dry areas were negligible, but in the rest of the regions yield decreased about 20%-30%. Under the UKMO scenario yield decreases showed similar trends, but the substantially shorter simulated season length had a larger effect on yields. Yields decreased about 20% in the dry areas and 45%-60% elsewhere.

In the eastern sites of Winnipeg and Swift Current, there were modest yield increases under the GFDL scenario, probably due to the scenario precipitation increases. In the western sites, however, precipitation decreases, coupled with higher temperatures, created a less favorable regime for wheat and led to substantial yield declines.

CO_2 Increases and Global Warming

This section evaluates the combined effects of global climate change with the beneficial effects of increased CO_2 on crop yield—improved water-use efficiency and increased net photosynthesis (Figure 3).

Under the GISS scenario, the direct effects of CO_2 compensated for the yield decreases under the scenario of climate change alone at all sites. The most noticeable changes were at the driest sites (Swift Current and Lethbridge), where the benefits of increased water-use efficiency were larger, and the direct effects of CO_2 caused simulated yields to increase by about 40%-50% above the current level. Yield increases were about 15% at the other sites.

The GFDL scenario projected precipitation increases for the eastern sites. The combination of a more favorable moisture regime and additional CO_2 caused simulated wheat yields to increase above the current level. The increase was more pronounced in areas that are currently very dry. However, at the sites where the GFDL scenario projects precipitation decreases (the western sites), simulated wheat yields decreased, even with the direct effects of CO_2.

Under the UKMO scenario, yields increased at the driest sites and decreased elsewhere. Once again, the benefits of increased CO_2 on enhanced water-use efficiency were more noticeable in the driest areas. At the rest of the sites, the benefits of elevated CO_2 levels only partially offset the negative impacts of the UKMO scenario conditions on simulated yields, and yields decreased 25%-40%.

Sensitivity Analysis

Maturation Time. A 2°C temperature increase caused the simulated maturation period of the crop to decrease 7-12 days in the southern sites, and 2-3 weeks in the northern sites (Figure 4). A 4°C increase reduced season length by 2-3 weeks in the southern sites and by more than 30 days in the northern sites.

Crop Moisture Stress. Increased evapotranspiration rates caused by the 2°C and 4°C temperature increases added to crop moisture stress at all sites (Table 5). These higher temperatures, coupled with a 20% reduction in precipitation, increased the severity of moisture deficits accumulated over the crop-growing period by up to 41%. On the other hand, a 20% precipitation increase more than offset the negative impacts of a 2°C temperature increase, but seasonal moisture deficits persisted. Increases in evapotranspiration due to a 4°C temperature increase tended to offset a 20% increase in precipitation.

Yields. A temperature increase alone caused decreases in simulated yields at all sites (Table 6). At Swift Current and Lethbridge, relatively severe moisture deficits currently cause wheat yields to be low. As a result, the impacts of a shorter time for crop growth and drier conditions were not as pronounced at these sites. Of course, the opposite trend is anticipated if the moisture regime becomes more favorable for wheat production. The yield benefits from a 20% precipitation increase were greater at the driest sites.

For all sites except those in the driest areas, a 2°C temperature increase offset the benefits of a 20% precipitation increase, and therefore, simulated yields decreased. A 2°C temperature increase tempered the yield benefits of additional moisture in the driest areas, and simulated yields increased about 20% under these conditions.

A 20% precipitation decrease caused substantial declines in wheat yields at all sites. Prairie agriculture currently suffers from a deficit of moisture and the simulated yield losses due to the additional stress associated with a 20% reduction in precipitation ranged from 22%-39%. Higher temperatures exacerbated the consequences of reductions in precipitation (-40% and -60% if precipitation declines are coupled with a +2°C and a +4°C, respectively).

The direct beneficial CO_2 effects offset the yield decreases in some of the scenarios considered in this sensitivity analysis (Table 6). In the least favorable of the scenarios considered (a +4°C increase combined with a 20% precipitation decrease), yield decreases were estimated at all sites, even with the direct effects of CO_2. In contrast, under the +2°C and +20% precipitation scenario, wheat yields increased substantially at all sites.

The GISS Transient Scenarios

Simulated wheat yields under the transient scenarios (Figure 5) were nonlinear. For all sites except Fort Vermillion, there was an initial increase in yields through the 2010s, followed by a decrease from the 2010s to the 2030s, and then a recovery of the yields from the 2030s to the 2050s. This suggests that under the GISS transient scenarios, the temperature increase until the 2010s would have a relatively small impact on yield, and the beneficial effects of CO_2 (405 ppm) would stimulate grain productivity compared to base levels. However, the influence of temperature increases with concomitant reductions in the maturation period of the crop dominated the impact by the 2030s, and in some cases outweighed the benefits of the CO_2 increase to 460 ppm.

Temperature increases between the 2030s and the 2050s were small, and therefore, the yield increases associated with this period were a consequence of the increased beneficial effects of rising CO_2 levels (530 ppm in the 2050s).

ADAPTIVE STRATEGIES: RESPONDING TO GLOBAL CLIMATE CHANGE

The analysis in the previous section has isolated the impacts of climate change on wheat yields, but it is reasonable to assume that many other biophysical and socioeconomic conditions will also change during this time period, and that these adjustments will act in concert with the climate change. In this section three possible responses to climate change are considered: irrigation, changes in the planting date, and a shift from spring to winter wheat production. These adjustments represent different levels of economic adaptation, with irrigation being the most expensive. The results presented in this section include the beneficial CO_2 effects on simulated wheat yields. An appraisal of economic and technical feasibility of each option is beyond the scope of this study, as are the changes in other conditions, including the technological advances or adaptive measures taken by farmers or public institutions.

Irrigation

Under all three climate change scenarios and at all sites, irrigation was an effective adaptive strategy to improve wheat yields under the climate change scenarios. The sites that benefited the most from irrigation are the driest sites: Swift Current and Lethbridge.

Earlier Seeding

Sowing spring wheat earlier in the season would take advantage of cooler temperatures during the earlier part of the frost-free period and therefore lessen the negative impacts of climate change on yield. This option was most effective at the driest sites. Under the UKMO scenario, which predicts the largest yield decreases, earlier seeding compensated for the yield decreases only in the driest areas. Under the GISS and GFDL scenarios, earlier seeding compensated for yield losses at all sites except Fort Vermillion and Ellerslie. Overall, the earlier seeding option is the easiest to implement, but it was the least effective of the three options considered, and in some cases it did not fully offset the negative impacts of climate change on wheat yields.

Winter Wheat Conversion

Winter survival is the main factor that currently deters winter wheat production in the Canadian prairies. Global warming (especially if there is a substantial increase in winter temperature and sufficient snow cover to ensure winter survival) would allow cereal grains to take better advantage of spring moisture reserves and thereby contribute to a more favorable set of conditions for winter cereals. A shift from spring to winter wheat increased yields under GCM climate change scenarios at the southern sites. Winter wheat would allow a better use of spring moisture supplies and would diminish the impacts of relatively high summer temperatures. For the northern locations (Fort Vermillion, Ellerslie, and Prince Albert), the temperature increases under the GCM scenarios during the winter were not enough to eliminate cold damage due to winter kill and therefore limited the effectiveness of a conversion to winter wheat at these sites.

CONCLUSIONS

This study considered the extent to which global climate change, increases in atmospheric CO_2 concentrations to 555 ppm, and selected adaptive strategies would alter simulated wheat yields at seven sites in the Canadian prairie. The climate scenarios were derived from three General Circulation Models (GCMs); additional climate scenarios were created by altering the observed temperature and precipitation records by fixed amounts. An assessment of the crop model used (CERES-Wheat) under the Canadian prairie conditions indicated that the model can provide an estimate of the direction and magnitude of yield shifts stemming from a potential climatic change. However, the model is not intended to predict reliable yield estimates for a particular year.

The conclusions of the simulation study were:

1. Each of the three GCM scenarios used (GISS, GFDL, and UKMO) imply a different set of agro-climatic conditions for the region.

2. There is no uniform response to climate change throughout the Canadian prairie. Each climate change scenario results in different wheat yield response at each site.

3. Without the beneficial effects of increased CO_2, wheat yields decreased under the climate change scenarios in comparison with current yields. The shortening of the time required for wheat to mature under the climate change scenarios was the main factor responsible for the yield decreases.

4. When the direct effects of CO_2 are included in the simulation, wheat yields increased compared to current yields at all sites under the GISS scenario; yields increased only in the northern sites under the GFDL scenario; and yields decreased at all sites except two under the UKMO scenario.

5. The beneficial effects of increased CO_2 have the greatest effect on the driest sites in the prairie under the climate change scenarios.

6. Although the overall impact of global climate change on Canadian wheat yields may not be negative, it appears that a considerable redistribution in yield patterns is possible.

7. The effectiveness of possible adaptation strategies varies from region to region, and therefore it is reasonable to expect that no single response strategy will adequately mitigate the possible negative impacts of climate change on all of the Canadian prairie provinces.

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Table 1. Recent production and land use data (1981-85) for Canadian spring wheat in the areas represented by the indicator sites in the Canadian prairie provinces.

Province/Site	Lat. Long.	Wheat Production T x 1000	Estimated contribution to National Production (%)	Average Yield (T/Ha)	Soil
MANITOBA		3,882			
Winnipeg	+49.5 N		15	2.24	Black Soils
	-97.1 W				
Dauphin	+51.1 N		4	2.1	Other Soils
	-100.3 W				
SASKATCHEWAN		11,869			
Swift Current	+50.2 N		32	1.65	Brown Soils
	-107.4 W				
Prince Albert	+53.1 N		23	1.95	Black Soils
	-105.4 W				
ALBERTA		5,661			
Lethbridge	+49.4 N		16	1.93	Brown Soils
	-112.5 W				
Ellerslie	+53.3 N		7	2.06	Black Soils
	-113.3 W				
Fort Vermillion	+58.2 N		3	1.9	Northern Soils
	-116.0 W				

Table 2. Temperature differences (°C) and precipitation changes (%) between GCM $1xCO_2$ and $2xCO_2$ climate change scenarios, at selected sites in Canada.

	Temp. Diff. (°C)					Precip. Changes (%)				
Site/GCM	Spr.	Sum.	Fall	Win.	Ann.	Spr.	Sum.	Fall	Win.	Ann.
Winnipeg										
GISS	4.6	2.8	4.8	5.5	4.4	7	17	5	12	11
GFDL	5.0	2.9	5.4	5.0	4.6	70	46	27	-3	36
UKMO	9.3	7.4	8.5	10.2	8.8	33	-3	2	22	9
Dauphin										
GISS	4.6	2.8	4.8	5.5	4.4	7	17	5	12	11
GFDL	5.0	2.9	5.4	5.0	4.6	70	46	27	-3	36
UKMO	9.5	6.5	8.0	9.6	8.4	55	15	24	42	27
Swift Current										
GISS	3.9	3.2	5.9	6.2	4.8	19	9	5	30	15
GFDL	5.5	3.6	5.3	4.9	4.8	59	13	15	18	24
UKMO	7.1	5.9	7.6	7.5	7.0	30	9	17	25	17
Prince Albert										
GISS	3.9	3.2	5.9	6.2	4.8	19	9	5	30	15
GFDL	5.5	3.6	5.3	4.9	4.8	59	13	15	18	24
UKMO	7.1	5.9	7.6	7.5	7.0	30	9	17	25	17
Lethbridge										
GISS	3.9	3.2	5.9	6.2	4.8	19	9	5	30	15
GFDL	5.2	4.2	5.0	4.9	4.8	38	1	0	6	9
UKMO	5.5	5.7	7.3	6.7	6.3	27	18	19	24	21
Ellerslie										
GISS	3.9	3.2	5.9	6.2	4.8	19	9	5	30	15
GFDL	5.2	4.2	5.0	4.9	4.8	38	1	0	6	9
UKMO	9.0	5.4	7.2	5.9	6.9	58	20	34	28	31
Fort Vermillion										
GISS	2.9	2.7	5.1	6.9	4.4	28	13	26	56	26
GFDL	5.2	3.6	5.5	6.3	5.1	19	-9	13	22	12
UKMO	8.6	5.3	7.2	7.3	7.1	53	23	41	47	35

Table 3. Management variables for spring and winter wheat used in the simulation at different sites.

Site	Seeding	Plants/m^2	% Soil moisture at seeding[1]
Spring Wheat			
Winnipeg	May 13	333	63
Dauphin	May 11	333	71
Swft Current	May 8	190	49
Prince Albert	May 6	277	57
Lethbridge	May 7	172	42
Ellerslie	May 8	390	61
Ft. Vermillion	May 13	390	63
Winter Wheat			
Winnipeg	Sept 15	283	
Dauphin	Sept 6	283	
Swft Current	Sept 21	224	
Prince Albert	Sept 8	277	
Lethbridge	Sept 29	224	
Ellerslie	Sept 8	283	
Ft. Vermillion	Sept 8	283	

[1]% of water holding capacity

Table 4. Simulated and observed yield (kg ha^{-1}) and season length (days) at selected sites.

Site		Season Length		Yield	
		Days	% Diff.	kg ha^{-1}	% Diff.
Winnipeg	Observed	89		2,275	
	CERES	93	+6	2,682	+18
Dauphin	Observed	90		2,531	
	CERES	98	+9	3,210	+21
Swift Current	Observed	98		1,385	
	CERES	100	+2	1,612	+16
Prince Albert	Observed	96		2,223	
	CERES	106	+10	3,020	+36
Lethbridge	Observed	90		1,930	
	CERES	102	+13	1,550	-20
Ellerslie	Observed	106		2,060	
	CERES	111	+4	5,450	+164
Ft. Vermillion	Observed	119		1,900	
	CERES	119	0	3,850	+102

Table 5. Impacts of changes in climate on crop moisture stress* (mm).

Scenario	Crop Moisture Stress (mm)						
	WINN	DAUP	P.A.	S.C.	LETH	ELLE	F.V.
BASE	-49	-67	-53	-48	-35	-69	-55
GISS	-48	-60	-55	-47	-37	-66	-54
GFDL	15	2	-45	-36	-30	-77	-68
UKMO	-44	-55	-56	-40	-32	-39	-46
T+2, P0	-50	-66	-57	-50	-40	-64	-57
T+4, P0	-59	-69	-61	-51	-43	-71	-61
T 0, P+20	-13	-38	-27	-35	-14	-19	-30
T+2, P+20	-26	-48	-41	-43	-27	-34	-42
T+4, P+20	-40	-54	-50	-44	-32	-46	-49
T 0, P-20	-61	-77	-60	-53	-43	-83	-62
T+2, P-20	-64	-78	-64	-54	-47	-84	-66
T+4, P-20	-70	-79	-65	-55	-48	-86	-69

*Precipitation during the crop season length less evapotranspiration simulated by the CERES-Wheat model during the crop season length).

Table 6. Sensitivity analysis of CERES-Wheat to climate and CO_2 changes at selected sites.

VARIABLE CHANGE		SIMULATED YIELD CHANGES FROM CURRENT (%)						
Temp. change	Precip. change	WINN	DAUP	P.A.	S.C.	LETH	ELLE	F.V.
(°C)	(%)							
330 ppm CO_2								
+2	0	-22	-29	-21	-14	-12	-25	-25
+4	0	-44	-30	-43	-27	-26	-43	-47
0	+20	24	24	27	40	31	14	23
+2	+20	-4	-10	-2	19	14	-13	-9
+4	+20	-30	-36	-28	-4	-6	-34	-37
0	-20	-31	-27	-32	-39	-39	-23	-26
+2	-20	-45	-48	-45	-43	-43	-43	-43
+4	-20	-59	-63	-58	-48	-48	-57	-59
555 ppm CO_2								
+2	0	11	4	13	35	31	2	5
+4	0	-16	-24	-17	10	7	-21	-26
0	+20	71	69	74	112	95	46	66
+2	+20	33	26	33	79	62	13	25
+4	+20	0	-7	2	42	33	-13	-13
0	-20	3	9	5	-1	-2	11	7
+2	-20	-19	-23	-18	-12	-13	-16	-16
+4	-20	-39	-45	-40	-24	-25	-37	-42

Table 7. Impact on simulated wheat yield of adaptation strategies to GCM climate change.

	Changes in simulated yield (% from current)						
Strategy	WINN	DAUP	P.A.	S.C.	LETH	ELLE	F.V.
GISS							
no change	10	2	14	50	40	-2	6
IRRIG	68	56	82	219	234	18	76
-2WK	14	3	11	66	72	-6	3
-4WK	22	5	12	75	92	-10	6
-6WK	24	9	16	84	110	-12	13
WIN WH	39	21	23	132	200	-1	22
GFDL							
no change	40	31	13	66	-7	-26	-35
IRRIG	60	48	63	183	218	11	57
-2WK	51	39	20	103	46	-23	-33
-4WK	56	41	27	117	90	-20	-31
-6WK	58	45	31	131	116	-21	-25
WIN WH	62	49	35	167	145	-23	-25
UKMO							
no change	-40	-32	-26	19	17	-25	-31
IRRIG	11	9	47	155	181	-7	39
-2WK	-28	-31	-25	25	55	-36	-37
-4WK	-15	-28	-25	24	68	-41	-42
-6WK	-2	-25	-24	25	84	-43	-46
WIN WH	13	2	-25	48	139	-39	-42

IRRIG = changes from dryland to irrigation
-2WK, -4WK and -6WK = changes in the planting date two, four and six weeks earlier
WIN WH = shift to winter wheat.

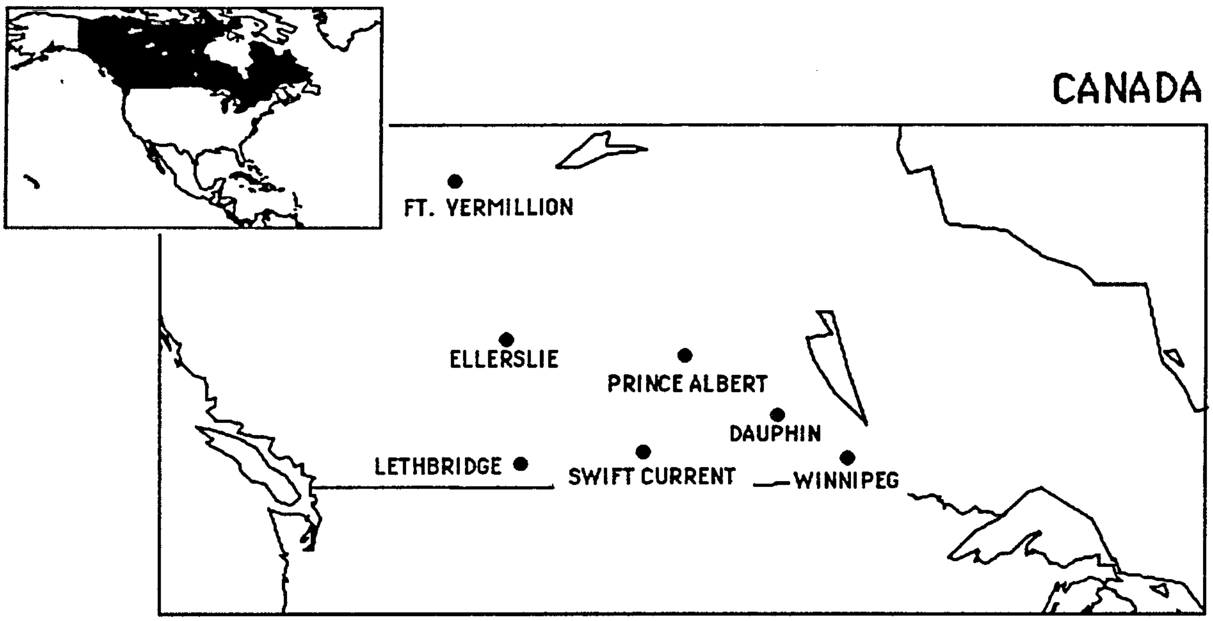

Figure 1. Location of the indicator sites in the Canadian prairie provinces: Manitoba (Winnipeg, Dauphin), Saskatchewan (Swift Current, Prince Albert) and Alberta (Lethbridge, Ellerslie, Fort Vermillion).

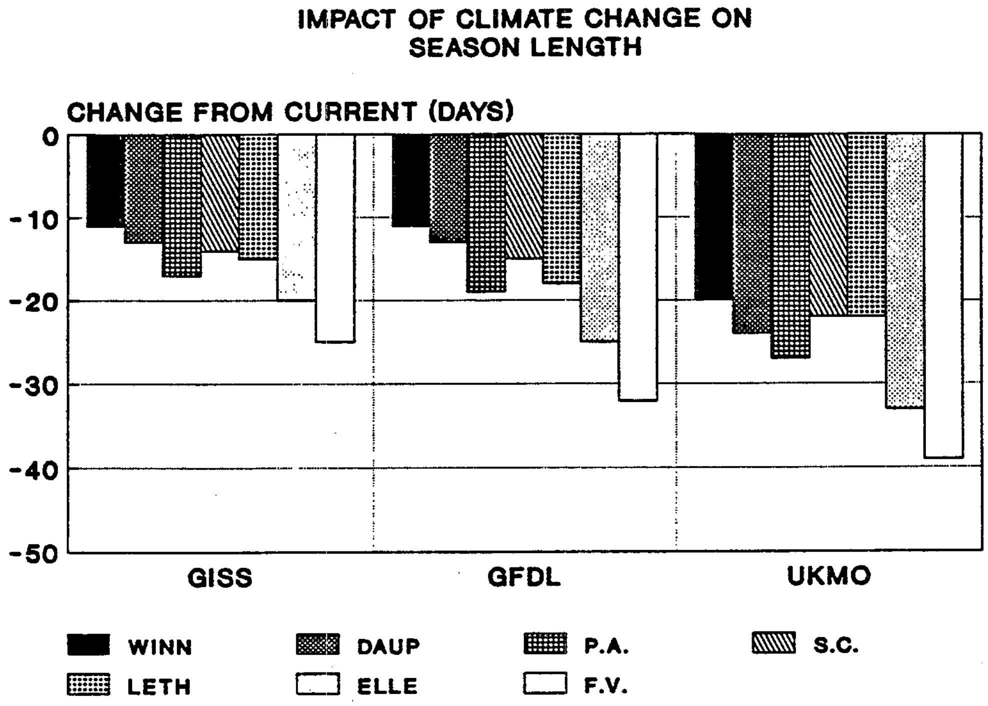

Figure 2. Impacts of GCM climate change on simulated wheat season length at selected sites in the Canadian prairie provinces.

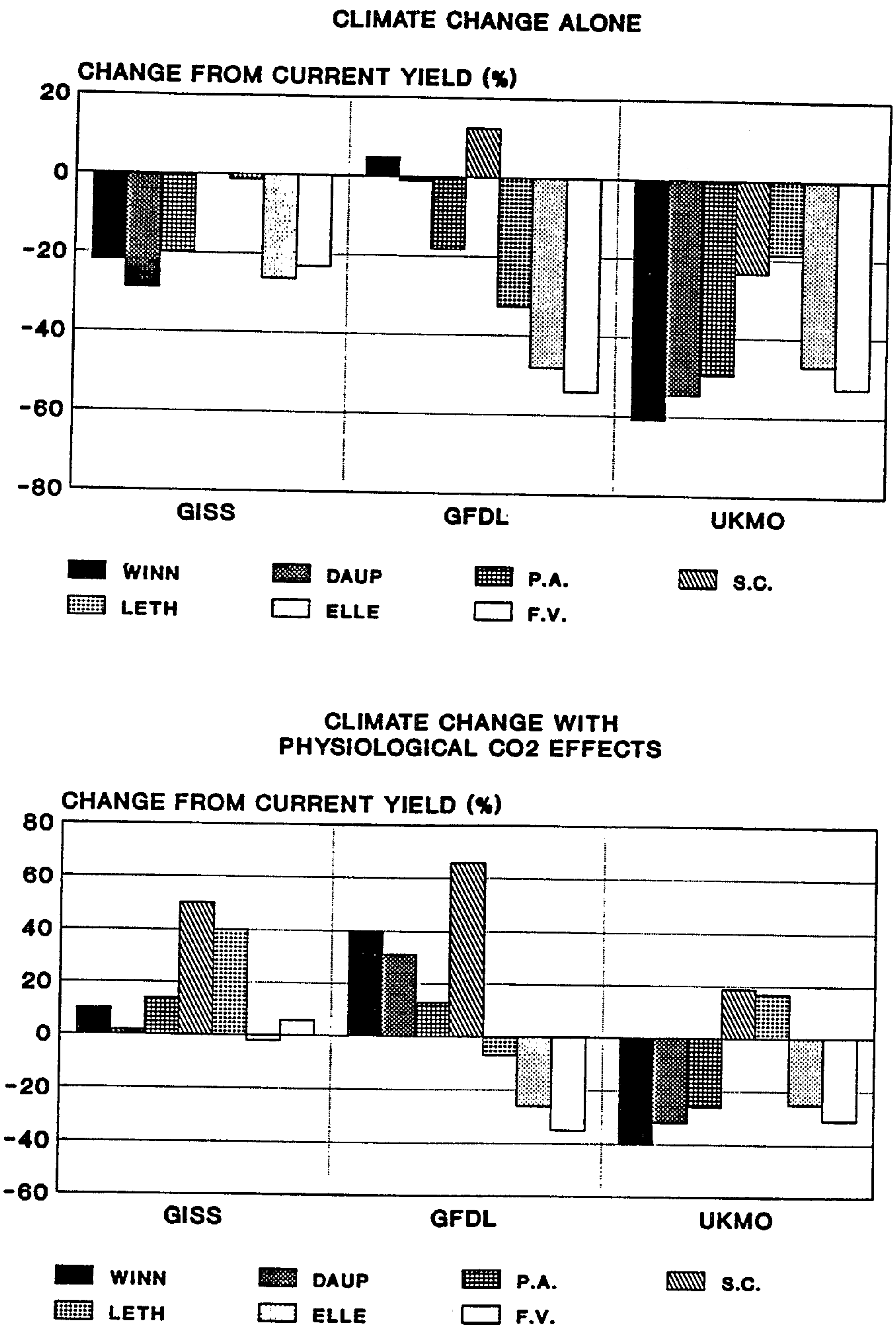

Figure 3. Impacts of GCM climate change on simulated spring wheat yields (% change from current) at selected sites in the Canadian prairie provinces.

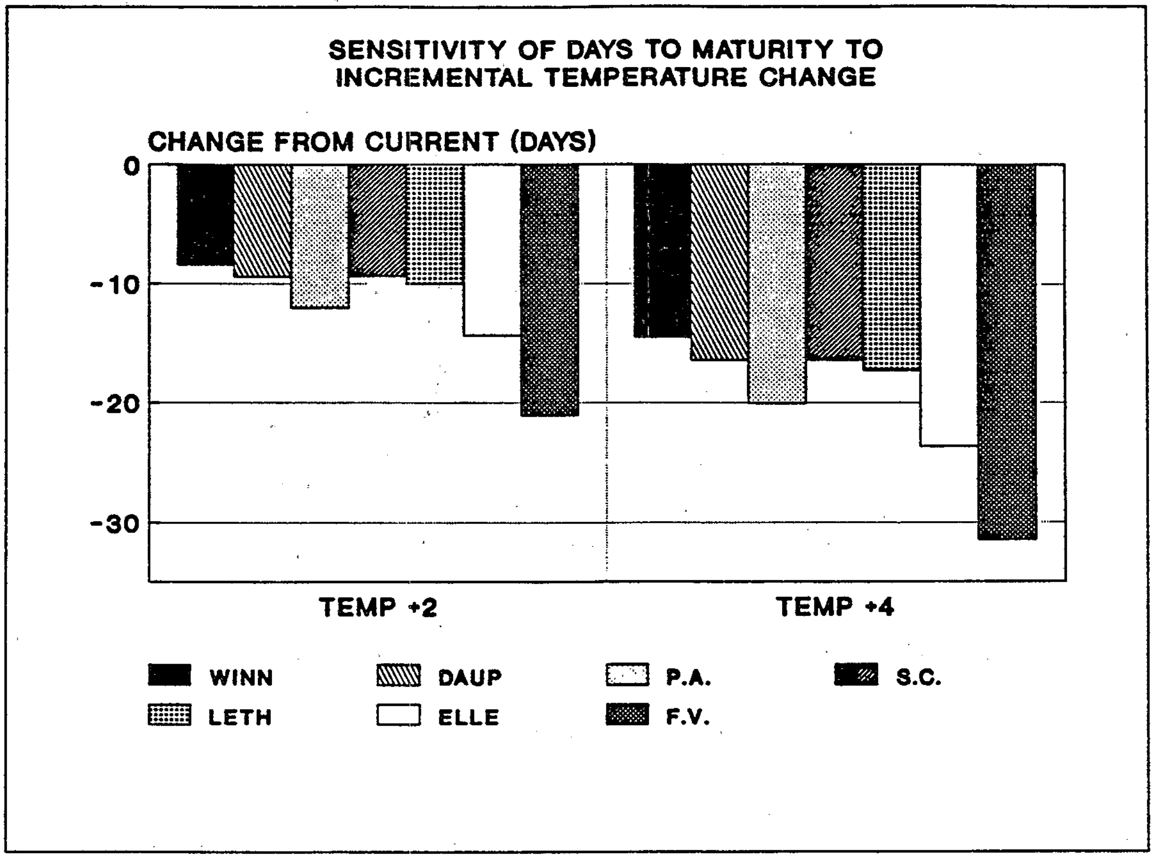

Figure 4. Sensitivity of simulated wheat season length (days to maturity) to incremental temperature changes at selected sites in the Canadian prairie provinces.

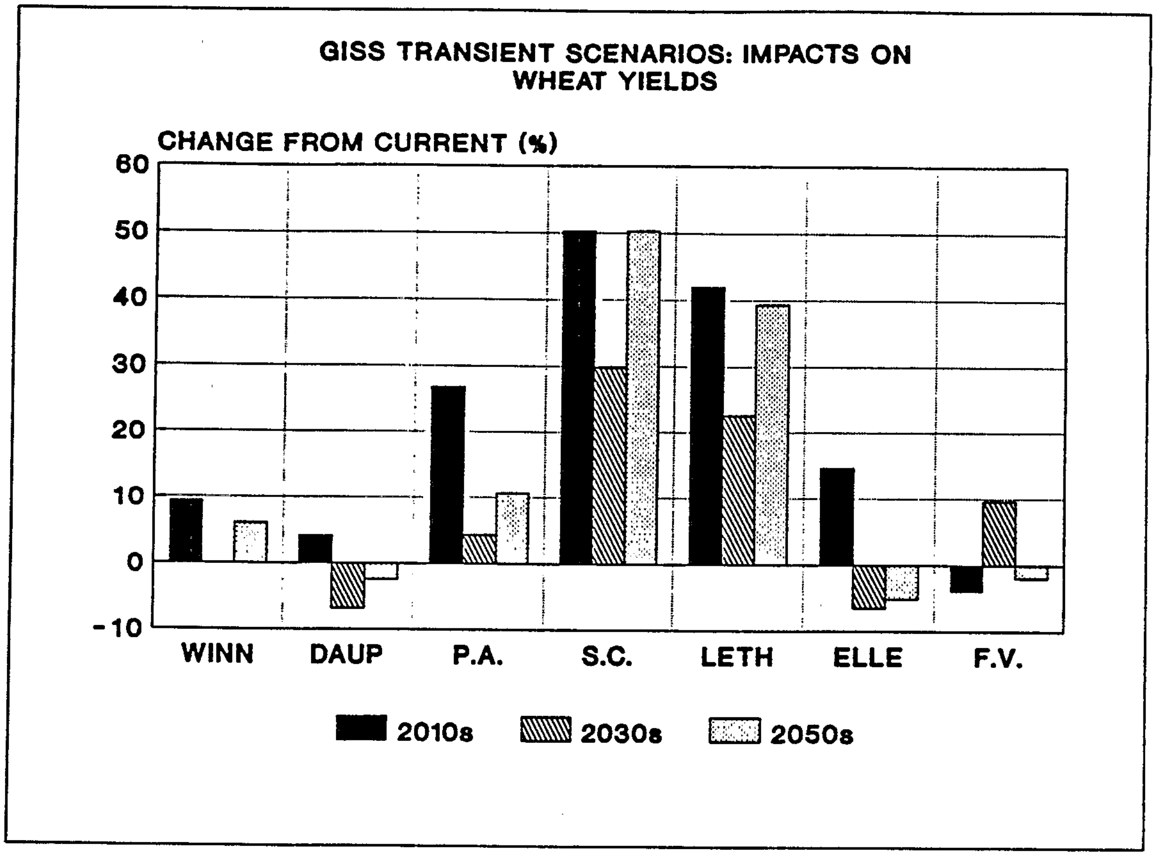

Figure 5. Impact of GISS transient scenarios on simulated wheat yield changes at selected sites in the Candian prairie provinces.

THE EFFECTS OF POTENTIAL CLIMATE CHANGE ON SIMULATED GRAIN CROPS IN THE UNITED STATES

C. Rosenzweig

Columbia University and Goddard Institute for Space Studies
New York, USA

B. Curry

University of Florida, Gainesville, USA

J.T. Ritchie

Michigan State University, USA

J.W. Jones

University of Florida, Gainesville, USA

T.-Y. Chou

Taiwan National University, Taiwan

R. Goldberg

Columbia University and Goddard Institute for Space Studies
New York, USA

and

A. Iglesias

Int. Nacional de Investigaciones Agrarias (INIA), Spain

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SUMMARY

The study considered the potential effects of global climate change on wheat, maize, and soybean production in the United States. Climate scenarios derived from three General Circulation Models (GCMs) were used in combination with crop growth models to characterize yield and irrigation water demand changes of the three main crops in major agricultural regions. Under the present management system, projected climate change caused simulated wheat, maize, and soybean yields to decrease at most sites even when the direct effects of CO_2 were included. These decreases were caused primarily by temperature increases which shortened the duration of the crop life cycles, particularly the grain-filling periods. At some northern sites, yields increased, probably because crop growth is temperature-limited at these high latitudes. Yield decreases varied among GCM scenarios. Adaptation strategies were identified that compensated for the negative effects of climate change at some but not all sites. These strategies included changing planting date and shifting to cultivars more adapted to the projected future climate. Patterns of agriculture in the U.S. are likely to shift as a result of changes in regional crop yields and in crop irrigation requirements.

INTRODUCTION

Background

The enhanced greenhouse effect of increased atmospheric concentration of CO_2 and other trace gases could lead to higher global surface temperatures and changed hydrological cycles (IPCC 1990a). Most previous climate impact assessments suggest significant consequences for agriculture, including shifts in agricultural zones, changes in irrigation demand, and loss of fertile lands in deltas due to sea-level rise (Parry et al. 1988; IPCC 1990b). The heavy dependence on North America for world grain reserves (almost 80% of the 1975-77 global marketable surplus) has increased the sensitivity of the world food supply to the climate of that region. Crop impact studies in the U.S. suggest a range of outcomes depending on scenario and region (Smith and Tirpak 1989.

Aims and Scope of the Study

The purpose of this study was to investigate the potential effects of climate change on crop yield and irrigation demand of the three major U.S. crops, based on 19 crop modeling sites that characterize the main agricultural regions. The results generated from this study have been used in an economic world trade model to determine the possible impact of climate change on world cereal production and prices (Rosenzweig and Parry, 1994). The approach taken here is to compare output of crop simulations under three equilibrium GCM, transient, and sensitivity climate scenarios to simulations of present climate and growing conditions.

The study incorporated simulation results of the three major crops using consistent methodology so that comparisons can be made between crops and regions. Since agricultural production and systems are not regionally isolated processes, projecting differential regional effects is important. While some crops are not significant in a particular region at present, this study tests whether climate change may alter their zonation in the future. The simulations also test the differential effects of climate change on winter (wheat) and spring (maize and soybean) crop production.

Because the driving force for a greenhouse-gas-induced climate change is the observed increase in CO_2 and other gases, the crop models have been modified to simulate the physiological effects of higher atmospheric CO_2 on crop growth and water use, based on experimental literature. Thus the simulated changes in crop parameters under the climate change scenarios are driven by two interacting effects, changes in climate and CO_2 enrichment. It is interesting to compare the responsiveness of each crop to higher levels of atmospheric CO_2. Finally, this study evaluates changes in crop management that may represent ways in which farmers adapt to changed climate.

Agricultural Regions and Crops

The three most important U.S. crops both in domestic and export markets are wheat, maize, and soybean. The U.S. ranks first in world maize and soybean production and third in wheat production. The U.S. raises about half of the world total of both maize and soybean. We selected 19 sites in major agricultural regions to represent different agroclimatic and production conditions (Figure 1 and Table 1).

Although wheat is produced in most states, the most productive regions is the Great Plains (Figure 2). About 80% of U.S. wheat production comes from winter wheat; therefore we only simulated winter wheat in the study. Two different practices were simulated: rainfed and irrigated. The only major irrigated zone for wheat is the southern area of the Pacific Northwest; irrigated wheat areas in California and Arizona are not significant contributors to the national production (Table 2).

U.S. maize production is centered in the Midwest (Figure 2 and Table 2). Soybean production is mainly located in the eastern two-thirds of the country, with the heaviest concentration in the Corn Belt (Figure 2). Most soybean production occurs in a rotation plan with maize on the best soils in a given area; the highest yields are in Iowa. We estimate that in the soybean and maize growing areas only about 10% of the land area is irrigated (Table 2). Although only a small area of grain production in the U.S. is irrigated, some regions (especially the southeastern part of the Pacific Northwest and California) rely heavily on irrigation (Table 2).

STUDY DESIGN

The approach taken was to compare output from the crop models under climate change scenarios (either arbitrary changes in climate variables or derived from global climate models) to model output from simulations of current climate. The scenarios derived from GCM results included both equilibrium doubled CO_2 and transient projections of climate change. Results for both yield and irrigation water use are analyzed as percent change from baseline simulations in order to provide indications of possible direction and magnitude of responses to changed climate conditions. Additionally the study evaluated possible adaptation strategies to climate change.

Climate

Baseline climate. Observed daily climate data (1951-80) were obtained for the 19 sites, consisting of daily maximum and minimum temperatures and precipitation. Daily solar radiation was simulated using a weather-generating program, WGEN (Richardson and Wright, 1984). Figure 3 shows the baseline (observed) monthly precipitation and temperature regimes at six of the 19 sites.

Sensitivity scenarios. In order to test the crop models' sensitivity to climate change, fixed combinations of temperature (0°C, +2°C, +4°C) and precipitation changes (-20%, 0%, +20%) were tested.

GCM equilibrium scenarios. Climate change scenarios were created from GCMs because they produce climate variables which are internally consistent and because they allow for comparisons among regions. Output from the GCMs is not accurate enough for direct use in crop models on a daily basis. Therefore, mean monthly changes in climate variables from doubled CO_2 simulations of three GCMs: Goddard Institute for Space Studies (GISS); Geophysical Fluid Dynamics Laboratory (GFDL); and United Kingdom Meteorological Office (UKMO), were applied to observed daily climate records to create climate change scenarios for each site. The GCMs compute mean climatic variables for large (~100,000 km^2) gridboxes and they do not explicitly account for variation of these quantities within the gridbox. Therefore no interpolation was made of the GCM output.

The projected monthly GCM precipitation and temperatures changes for the U.S. are shown in Figure 3. All three models predict significant warming: the GISS and GFDL scenarios produce comparable temperature increases (3°C to 5°C), while the UKMO scenario produces more drastic rises (6^{oC} to 9°C). Annual precipitation generally increases at most sites. (GCMs predict increases in global precipitation associated with warming since warmer air can hold more water vapor.) However, the projected precipitation shows considerable seasonal and geographical variation and is very uncertain.

Transient scenarios. Most of our knowledge concerning the climate response to greenhouse-gas forcing has been obtained from equilibrium response GCM experiments. These are experiments which consider the steady-state response of the model's climate to step-function changes in atmospheric CO_2. Recent evidence from a few GCM experiments incorporating time-dependent greenhouse-gas forcing suggest that there may be important differences between the equilibrium and transient responses (Hansen et al. 1988, Bryan et al. 1988; IPCC 1992).

Crop Models and Inputs

Potential changes in crop yields at the selected sites in the U.S. were estimated with the CERES-Wheat, CERES-Maize, and SOYGRO crop models (Ritchie and Otter 1985; Jones and Kiniry 1986; Jones et al. 1988). The models simulate physiological crop responses (water balance, phenology, and growth throughout the season) on a daily basis to the major factors of climate (daily solar radiation, maximum and minimum temperature, and precipitation), soils, (albedo and a variety of measures relating to water in the profile) and management (cultivar, planting date, plant population, row spacing and sowing depth).

The CERES and SOYGRO models have been validated with experimental data from many locations encompassing a wide range of environments (Otter-Nacke et al. 1986; Jones and Kiniry 1986; Egli 1992; Jones and Ritchie 1991).

All simulations were made using DSSAT, v2.5 (Jones et al. 1990). Changes were computed in the mean and standard deviation of yield, evapotranspiration (ET), water applied for irrigation, and crop maturity date.

Soils. Representative agricultural soils for each site were chosen with reference to the Major Land Resource Area descriptions, State Soil Conservation Stations, and information provided by County Agricultural Extension Agents. Soil characteristics for the representative soils were specified by 12 generic soil types (Table 1). The generic soil most representative of each site was used. Soil characteristics included in the model are: albedo, water drainage, soil evaporation, runoff, and characteristics describing each layer such as depth, lower and upper limit of plant extractable water, saturated water content, organic carbon, ammonium, nitrate, and pH values. Since the present model did not simulate a soil water balance during the entire year, we assumed that the soil moisture level was full at the beginning of each growing season. While this assumption represents crop planting conditions at most sites in most years in the U.S., it overestimates soil moisture at planting for dry years.

Crop varieties and management. In the CERES and SOYGRO models, crop varieties are defined by a set of coefficients that represent characteristics such as photoperiodism, vernalization, and crop maturity type. The varieties used in the simulations are representative of common varieties grown in each region (Table 3). The management variables for the CERES and SOYGRO models were determined for each location according to information on current practices provided by the County Agricultural Extension Agents as well as state publications (Table 3).

For the irrigation simulation, the water demand was calculated assuming 100% efficiency of the automatic irrigation system; a 1-meter irrigation management depth; and automatic irrigation when the available soil water is 50% or less of capacity.

Physiological Effects of CO_2

Higher levels of atmospheric CO_2 have been found to increase photosynthesis and stomatal resistance, resulting in yield increases in experimental settings (Acock and Allen 1985). Because the climate change scenarios are associated with concomitant higher levels of CO_2 and other trace gases, we have included the physiological effects of 555 ppm CO_2 in the crop model simulations (Peart et al. 1989).

Limitations of the Study

Climate change scenarios. While GCMs are useful for climate change studies, current climate models oversimplify many aspects of the climate system, especially ocean dynamics, cloud physics, and land-surface hydrology. GCMs do not simulate current climate well at regional scales and they were not designed for predictive regional studies. Therefore, the climate change scenarios created from GCM output must not be considered as predictions, but only as examples of possible future climates for the regions under study.

As configured, the climate change scenarios do not alter the patterns of events in the base climate. Therefore they do not simulate changes in the underlying variability (e.g., extended periods of high temperature, droughts, etc.) that can be vital for crops. Dryland yields may be considerably different depending on whether a change in precipitation results from a change in mean, frequency or intensity. However, the scenarios created for this study do result in an increased frequency of temperatures above certain thresholds.

Crop models. In the crop model simulations, technology is held constant; nutrients are not limiting; weeds, diseases and insect pests are controlled; and there are no problem soil conditions or catastrophic weather events. All these assumptions tend to overestimate simulated yields. In this study an important assumption is that climatic tolerances of cultivars do not change. It is also important to note that the physiological effects of CO_2 in the crop model may be overestimated because experimental results from controlled environments, used to calibrate the model, may not be accurate under windy, and pest-infected field conditions.

EFFECTS ON CROP YIELD AND SEASON LENGTH

Sensitivity Analysis

The results of the sensitivity analysis for wheat, maize and soybean for three sites without the direct effects of CO_2 are presented in Figure 4. The main conclusions of the sensitivity study are:

- Increased temperatures cause simulated yield decreases. The greatest percentage yield decreases caused by high temperature are found in soybean.

- The three crops are slightly more sensitive to a decrease in precipitation than to an increase.

- In general, a 20% increase in precipitation mitigates yield decreases caused by a 2°C temperature increase, resulting in yield changes that are close to zero. With the same 20% precipitation increase and a 4°C temperature rise, yield decreases are still significant.

- The greatest percent yield decreases are caused by a 4°C temperature increase and a 20% precipitation decrease.

GCM Climate Change Scenarios

Tables 4, 5, and 6 show the simulated changes in crop yields under the GCM climate change scenarios, both with and without the direct effects of CO_2. Since the driving force for a greenhouse temperature change is the increase in CO_2 and other gases, the most important comparison from an agricultural system response point of view is between the base (current climate under 330 ppm CO_2) and the GCM scenarios with increased CO_2 (555 ppm CO_2).

Soybeans. Yield changes under the climate change scenario vary with location and scenario considered (Table 4), but in general soybean yields decrease under the three climate change scenarios. The largest decreases occurred under the UKMO scenario and the smallest decreases under the GISS scenario. In some cases the effect of increased CO_2 on photosynthesis was enough to compensate for the yield decreases under climate change alone. When the crop was simulated under irrigated conditions, many locations showed an increase in yield compared to the base (see section on Adaptation). The main cause of the yield decrease is the shortening of the growing season (by about two weeks) (Table 7).

Maize. Maize yield decreased significantly at almost every site with the climate change scenarios alone (Table 5). When the direct effects of CO_2 were included, significant yield decreases were still projected for the GFDL and UKMO scenarios, but negative yield effects of the GISS scenario were completely mitigated. The yield decreases were caused by the combined effects of high temperature shortening the grain-filling period and by increased moisture stress. Maturity dates advanced by an average of over two weeks under the three scenarios (Table 7). In the highest latitude site (Spokane) there was a large increase in maize yield as simulated with all three GCM scenarios; the maize crop appears to be temperature-limited in the current climate at this relatively high latitude.

In the case of climate change with the physiological effects of CO_2, simulated maize yields increased only slightly compared to climate change alone; this is consistent with the lower photosynthetic response of C4 crops to increased CO_2 levels (Acock and Allen 1985). At all sites except Spokane, irrigated maize yields decreased significantly even when the direct effects of CO_2 were considered.

Wheat. Wheat was simulated under dryland and irrigated conditions at all locations except Fresno (California), where dryland wheat produces negligible yields under current climate. Overall, there were large changes in simulated wheat yields under the climate change scenarios compared to the baseline yield (Table 6). Under the GISS scenario, modeled wheat yields decreased in every location except in the northernmost sites, with the largest decreases at the lower latitude sites. Some of the major areas of wheat production, (e.g., Dodge City, Abilene) showed very negative yield changes under each of the climate change scenarios.

The yield decreases were driven primarily by increased temperatures, which caused the duration of crop growth stages (particularly the grain-filling period) to be shortened (Table 7). Shortening of the grain-filling period reduces the amount of carbohydrates available for grain formation and harvestable yield. Maturity dates of wheat occurred, on average, about two weeks earlier under the scenarios. In the sites of the Pacific Northwest region (Spokane, Yakima and Boise), the unusually large simulated dryland wheat yield increases were probably due to the large increase in winter precipitation projected by the GISS climate change scenario. Under the GFDL and UKMO scenarios, yields decreased at all but a few sites. The yield increases in the northern sites may be due to the positive effects of higher temperatures on growth in colder, high-latitude sites. In contrast, in the Southern Great Plains, the temperatures are already high to begin with, and the additional stress of higher temperatures can lead to drastic yield decreases.

The addition of the physiological CO_2 effects to the simulations caused a significant increase in wheat yield at all sites. This was due to the beneficial increases in simulated dry matter conversion and stomatal resistance. Nevertheless, in the lower latitude sites substantial yield decreases were simulated even when the direct effects of CO_2 were taken into account.

Aggregated Results

The simulated changes in crop yield at different sites suggest that regional and national production may be significantly affected by climate change. In order to estimate these possible changes, we developed an aggregation scheme based on actual regional production from 1979-1989 as reported by the USDA Crop Reporting Service. A relative "production weighting factor", based on the amount of production of a particular crop, was assigned to each site. We also produced a "dryland/irrigation weighting factor" for each site, which is an estimation of the percent of harvested area associated with each site which is dryland production (Table 2).

Aggregated U.S. crop yield results are shown in Figure 5. The magnitudes of the estimated yield changes varied by crop and scenario. When the direct CO_2 effects were included, maize (a C4 crop) production was most negatively affected, probably due to its lower growth response to higher levels of atmospheric CO_2; soybean and wheat (C3 crops) production responded significantly to increased CO_2. The aggregated production results also imply:

- Without physiological CO_2 effects, production of all three crops decreased. The warmest scenario (UKMO) produced the largest decreases, with soybean the most severely effected.

- Under the GISS and GFDL scenarios with direct CO_2 effects included, soybean production increased, wheat production remained unchanged, while maize production was reduced. Under the UKMO scenario all three crops showed decreases in yields.

- Simulated U.S. maize production was negatively affected in all scenarios, both with and without the physiological CO_2 effects.

Transient Scenarios

When the crop models were run with transient climate changes projected for the 2010s, 2030s, and 2050s from the GISS transient run A, yield responses were non-linear over time (Figure 6). Aggregated wheat yield was the most non-linear of the three crops, showing a positive response to climate change in the 2010s and 2030s, and a negative response in the 2050s. Soybean yield changes were positive throughout the time trajectory, and maize yield changes were slightly negative.

EFFECTS ON EVAPOTRANSPIRATION AND IRRIGATION WATER DEMAND

The temperature increases under the GCM climate change scenarios are likely to lead to increased daily potential evapotranspiration and therefore changes in crop water use and irrigation demand. The following simulation results considered both the effect of climate change and the effect of increases in CO_2 level on crop growth, water use, and irrigation demand. Because the calculation of the irrigation water in the CERES and SOYGRO models assumes nonlimiting situations, only relative changes in crop water use requirements are analyzed (Tables 8 and 9).

Soybeans. Water use efficiency (WUE), defined as yield/total crop evapotranspiration (kg/ha mm^{-1}), declined at most locations under the GFDL and UKMO scenarios, because yield reductions are relatively greater than ET reductions (Table 8). Table 9 shows that irrigation demand increased substantially under the climate change scenarios, with the warmer scenarios producing the largest increases.

Maize. The maize WUE increased almost everywhere under the GISS scenario, in about half of the sites under the GFDL scenario, but decreased under the UKMO scenario except in the northernmost sites (Table 8). Under the GISS scenario, irrigation demand decreased at most of the study sites, while under the more severe GFDL and UKMO scenarios, irrigation demand increased at some sites, while decreasing at other sites. The decreases in irrigation water requirements (Table 9) have to be carefully interpreted, since they primarily reflect the decreases in total crop evapotranspiration due to the significant shortening of the crop growing season and are often accompanied by significant yield reductions.

*Wheat.*The wheat WUE values decreased at most sites under the GISS scenario, but increased under the GFDL and UKMO scenarios. Irrigation water demand for wheat shows very mixed results (Table 9).

EFFECTS UNDER DIFFERENT MANAGEMENT STRATEGIES: ADAPTATION

Farmers and agricultural systems will, in reality, try to adjust to changing environmental conditions. This study evaluated changes in planting dates, cultivars, and irrigation as possible changes in crop management under climate change conditions. Estimates of yield changes were based on crop model simulations. Changes in economics or domestic agricultural policies were beyond the scope of the adaptation estimates. Neither the costs of adaptation nor changes in water availability under the climate change scenarios were considered.

Soybeans. Rainfed soybean yields decreased by more than 50% under climate change scenarios (Table 4), but adding irrigation tripled yields. Even though irrigation was found to increase yield, it may not be possible to use it as a widespread amelioration tool, since the demand would probably exceed the water resources available. Only about 10% of U.S. cropping regions is currently irrigated. Establishing irrigation as an adaptation to climate change could be costly.

The soybean adaptation results using different cultivars and planting dates showed that adaptation to temperature changes can be met with existing cultivars in the U.S. Midwest. In the southern part of the U.S. where temperatures are higher, potential temperature changes suggested by some GCMs may exceed crop physiological tolerance and increase water stress.

Maize. Changes in planting date (10, 20, and 30 days earlier), changes in variety, or combined strategies of both were examined for Des Moines. With an earlier planting date, the yield, with the direct CO_2 effect included, could not be restored to current levels. The selection of alternative varieties helped ameliorate some of the yield losses, but not completely (Figure 7). The combination of earlier planting dates and a different variety resulted in yield increases for the GISS scenario, and for the irrigated GFDL scenario. However, under the UKMO scenarios, yields still decreased.

Wheat. When the automatic irrigation is applied, wheat yields improve over the baseline in all locations, except in the southernmost latitudes, with combined climatic and direct effects of CO_2 in both GISS and GFDL scenarios.

DISCUSSION

Simulated yield decreases occurred in the Southern Great Plains and the Southeast in response to the climate change scenarios tested in this study, even when the direct effects of CO_2 were included. In those regions, high temperatures shortened the duration of crop stages, especially the grain-filling period, and increased water stress, resulting in moderate to severe yield decreases. The hotter UKMO model produced the most severe yield reductions, while the GISS model was the most benign of the three GCM scenarios. Increased temperatures had a beneficial effect (due to a longer frost-free period) on simulated yields at the northern sites.

Farmer and agricultural system adaptations (change in planting date, crop variety, and irrigation) helped mitigate yield losses. However, successful adaptation to climate change often implied significant changes to current agricultural systems, and so some adaptations to climate change may be costly. A potential need for increased irrigation is suggested, particularly at lower latitudes. Currently only a small percentage of the area of wheat, maize and soybean is irrigated. Whether this would actually change depends on many factors such as the availability and cost of water, which are beyond the scope of this study.

Adjusting to a need for increased irrigation water may be difficult. The country's hydrological system has a complicated legal framework that limits flexibility; in addition the existing irrigation systems may be subjected to climatic conditions for which they were not designed. Even without climate change, U.S. water-allocation institutions need to evolve toward programs that encourage a more efficient use of water. Currently there is little incentive to irrigate without wasting water. The environmental problems (salinity, erosion and water pollution) derived from increased irrigation also need to be further addressed.

This study has not addressed the issue of changes in climate variability. Possible changes in climatic variability under GCM climate change scenarios (such as the magnitude and frequency of droughts, storms, and heat waves) are important factors in determining production amounts. Since crop yields exhibit nonlinear responses to heat and cold stress, changes in the probability of extreme temperature events beyond critical thresholds can be significant. Differential effects on minimum and maximum temperatures also need to be studied. A farmer can adapt to gradual changes in mean weather variables, but he or she is highly vulnerable economically to increased variability, e.g., crop failure in one or several years in a row with only adequate yield in others. Government policies regarding crop insurance also need to be examined.

Overall, while national production does not appear to be at risk, shifts in regional patterns of agricultural are implied by this study. The northern states could become much more productive for annual crops such as corn and soybeans because of the lengthening of the frost-free period, while the southern states could become less productive, due to heat and moisture stress.

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Table 1. Sites selected for the study and representative soils for each site.

Site	Long.	Lat.	Soil
Spokane	+47.63	-117.53	DSL
Yakima	+46.57	-120.53	DSL
Boise	+43.57	-116.21	DSL
Fresno	+36.77	-119.72	DSL
Phoenix	+33.43	-112.02	DSnL
Fargo	+46.90	-96.97	DSC
North Platte	+41.08	-100.41	DSn
Topeka	+39.00	-96.00	DSL
Dodge City	+37.46	-99.58	DSL
Abilene	+32.43	-99.68	DSnL
Des Moines	+41.53	-93.65	DSL
Indianapolis	+39.73	-86.28	MSL
Memphis	+35.05	-89.98	MSL
Baton Rouge	+30.53	-91.15	MSC
Columbia	+33.95	-81.12	MSnL
Macon	+32.42	-83.39	MSnL
Tallahassee	+30.38	-84.37	OrSnL
Lynchburg	+37.33	-79.20	MSL
Williamsport	+41.25	-79.92	MSC

DSL: deep silty loam; DSnL: deep sandy loam; DSC: deep silty clay; DSn: deep sand; MSL: medium silty loam; MSC: medium silty clay; OrSnL: Orangesburgh sandy loam.

Table 2. Regional wheat, maize and soybean production (% of total national production) and area irrigated (% of total grain area irrigated at site or in the region).

		WHEAT		MAIZE		SOYBEANS	
Region	Site	% P	% I	% P	% I	% P	% I
Pacific NW	Spokane	12.0	0	0.4	100		
	Yakima		100		100		
	Boise		100		100		
South West	Fresno	3.0	100	0.6	100		
	Phoenix		100		100		
N Mnt Plains	Fargo	27.0	0	0.4	20	7.0	20
N Great Plains	N.Platte	20.0	0	1.5	50		
	Topeka				50	7.0	25
	Dod. C.				50		
S Great Plains	Abilene	13.0	0	2.0	10	1.0	25
Corn Belt	Des Mo.	11.0	0	71.0	10	37.0	25
	Indiana.		0	16.0	10	28.0	5
Delta	Memph.	3.0	0	0.5	0	8.0	15
	B.R.		0		0	5.0	15
Southeast	Colum.	2.0	0	1.5	0	2.0	10
	Macon		0		0	2.0	15
	Tallahas.		0		0	0.5	10
	Lynch.	2.0	0	4.1	0	2.0	5
Northeast	William.		0	2.5	0	2.0	0

Table 3. Management variables.

	WHEAT					MAIZE		SOYBEAN	
Site	Cultivar	P.Date	pl m^{-2}	Dpth (cm)	Row (m)	Cultivar	P.Date	Cultivar	P.Date
Spokane	Pacific	25Sep	195	5.08	0.18	C2	10Mar	G-00	20May
Yakima	Pacific					C2		G-1	
Boise	Stephens					C2		G-0	
Fresno	India	16Oct	180	7.62	0.28	C4	10Mar	Essex	1May
Phoenix	S.Plains	16Oct	180	7.62	0.28	C4	1May	Bragg	1May
Fargo	N.Plains	11Sep	270	3.2	0.17	C1	11May	G-00	25May
N. Platte	N.Plains	14Sep	180	4.0	0.18	C2	5May	G-0	20May
Topeka								Williams	15May
Dodge C.	S.Plains	28Sep	125	4.4	0.28	C2	11Apr	G-4	15May
Abilene	S.Plains	16Oct	180	7.6	0.28	C3	25Feb	Forrest	15May
Des Moines	N.Plains	20Sep	180	4.0	0.18	C2	5May	G-2	25May
Indianapolis	East	16Sep	360	3.8	0.15	C2	1May	Williams	15May
Memphis	East	16Nov	270	1.3	0.15	C3	25Mar	Forrest	15May
B. Rouge	East	16Nov	225	8.9	0.15	C4	25Feb	Tracy	20May
Columbia	East	16Nov	180	2.5	0.15	C3	15Mar	Bragg	15May
Macon								Bragg	15May
Tallahassee	East	1Dec	270	3.2	0.15	C4	28Feb	Cobb	20May
Lynchburg	East	16Nov	180	2.5	0.15	C3	21Apr	Essex	15May
Williamsport	East	16Sep	360	3.8	0.15	C2	1May	G-2	15May

The simulation of all crops started 10 days before the planting date. Soil water initial content= drained upper limit. Maize was planted in 61 cm rows; 5 plants m^{-2} for dryland and 7 plants m^{-2} for irrigation.

Table 4. Effects of GCM climate change on dryland and irrigated soybean yields.

Site	BASE ($t\ ha^{-1}$)	GCM Scenario alone			GCM Scenario + D.E. CO_2		
		GISS	GFDL	UKMO	GISS	GFDL	UKMO
DRYLAND							
Spokane	0.79	-11	-32	-51	52	13	-20
Yakima	0.34	-26	-35	-65	12	-9	-47
Boise	0.38	-16	-47	-29	26	-32	-5
Fresno	0.45	-53	-49	-98	-33	-24	-96
Phoenix	0.30	-57	-93	-77	-40	-93	-57
Fargo	1.35	-10	71	-46	58	150	-4
North Platte	0.74	-12	-18	-31	50	42	16
Topeka	2.49	-31	-36	-40	-6	-11	-18
Dodge City	1.42	-49	-57	-58	-26	-40	-42
Abilene	0.92	-62	-63	-84	-32	-41	-73
Des Moines	2.72	-7	-26	-76	26	8	-64
Indianapolis	2.43	-12	-37	-43	16	-14	-23
Memphis	2.06	-40	-63	-80	-21	-46	-72
Baton Rouge	2.49	-43	-43	-82	-17	-17	-72
Columbia	2.41	-19	-35	-22	4	-14	7
Macon	1.75	-24	-61	-86	1	-45	-74
Tallahassee	3.44	-23	-21	-69	-3	0	-50
Lynchburg	2.42	2	-65	-71	34	-48	-58
Williamsport	2.11	-5	-55	-37	34	-29	-9

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 4.
(Cont.)

Site	BASE (t ha^{-1})	GCM Scenario alone GISS	GFDL	UKMO	GCM Scenario + D.E. CO_2 GISS	GFDL	UKMO
IRRIGATION							
Spokane	2.66	16	13	-2	58	58	39
Yakima	3.24	-7	-3	-40	20	28	-19
Boise	2.99	-12	-28	-31	28	14	-13
Fresno	3.32	-37	-36	-68	-18	-14	-56
Phoenix	3.93	-38	-37	-37	-20	-3	-7
Fargo	2.48	15	22	2	65	66	50
North Platte	2.55	-4	-10	22	47	44	30
Topeka	2.90	-14	-13	-20	8	10	0
Dodge City	3.03	-65	-25	-36	-26	-5	-19
Abilene	4.15	-36	-40	-63	-18	-19	-46
Des Moines	3.42	-1	-5	-46	25	21	-30
Indianapolis	3.47	-2	-1	-15	21	22	5
Memphis	4.03	-27	-18	-48	-10	1	-36
Baton Rouge	3.60	-15	-15	-41	5	5	-26
Columbia	3.90	-12	-6	-12	6	14	7
Macon	3.90	-14	-9	-25	4	10	-6
Tallahassee	3.69	-13	-10	-30	5	9	-2
Lynchburg	3.61	0	-2	-16	24	22	6
Williamsport	2.86	8	7	-5	38	39	23

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 5. Effects of GCM climate change on dryland and irrigated maize yields.

Site	BASE ($t\ ha^{-1}$)	GCM Scenario alone GISS	GCM Scenario alone GFDL	GCM Scenario alone UKMO	GCM Scenario + D.E. CO_2 GISS	GCM Scenario + D.E. CO_2 GFDL	GCM Scenario + D.E. CO_2 UKMO
DRYLAND							
Fargo	10.25	-10	-6	-47	2	3	-28
North Platte	6.25	-22	-17	-57	11	16	-33
Dodge City	8.36	-8	-14	-18	7	1	-10
Abilene	5.89	15	-9	-17	22	8	-6
Des Moines	11.58	-21	-27	-42	-18	-21	-34
Indianapolis	9.74	-7	-59	-20	1	-32	-12
Memphis	7.82	-6	-27	-44	5	-13	-34
Baton Rouge	6.58	10	-45	-14	26	-23	-4
Columbia	7.00	-28	-90	-28	-3	-75	-14
Tallahassee	9.31	-5	-41	-34	0	-22	-21
Lynchburg	8.30	-58	-61	-21	-20	-35	-3
Williamsport	8.55	-21	-51	-23	7	-29	-2

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 5. (Cont.)

Site	BASE (t ha^{-1})	GCM Scenario alone GISS	GCM Scenario alone GFDL	GCM Scenario alone UKMO	GCM Scenario + D.E. CO_2 GISS	GCM Scenario + D.E. CO_2 GFDL	GCM Scenario + D.E. CO_2 UKMO
IRRIGATION							
Spokane	9.88	40	59	32	48	62	39
Yakima	12.92	-5	7	-28	0	13	-24
Boise	14.58	-22	-20	-24	-17	-16	-20
Fresno	12.19	-4	1	-3	-3	1	-2
Phoenix	7.78	-35	-28	-57	-31	-24	-55
Fargo	13.37	-8	-12	-24	-3	-7	-21
North Platte	12.94	-22	-22	-38	-17	-17	-34
Dodge City	12.66	-9	-15	-21	-5	-10	-21
Abilene	10.49	-2	-1	-36	1	0	-32
Des Moines	13.68	-25	-28	-38	-21	-24	-34
Indianapolis	13.04	-20	-6	-25	-15	-3	-21
Memphis	11.53	-19	-14	-42	-14	-10	-39
Baton Rouge	11.47	-9	4	-39	-4	5	-36
Columbia	10.75	-16	9	-23	-11	12	-19
Tallahassee	11.65	-10	-13	-9	-5	-9	-6
Lynchburg	12.67	-24	-3	-11	-19	0	-7
Williamsport	12.86	-21	-8	-14	-17	-14	-10

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 6. Effects of GCM climate change on dryland and irrigated wheat yields.

Site	BASE ($t\ ha^{-1}$)	GCM Scenario alone			GCM Scenario + D.E. CO_2		
		GISS	GFDL	UKMO	GISS	GFDL	UKMO
DRYLAND							
Spokane	2.62	76	-6	29	126	33	71
Yakima	1.48	103	-37	-7	180	-84	31
Boise	1.38	97	-20	43	172	14	102
Phoenix	0.89	-99	-93	-99	-99	-91	-99
Fargo	4.13	-18	-14	-38	8	10	-13
North Platte	2.79	-18	-36	-33	11	-15	-10
Dodge City	3.56	-48	-44	-32	-29	-26	-10
Abilene	2.60	-58	-33	-67	-43	-10	-57
Des Moines	4.76	-4	-12	-15	16	7	1
Indianapolis	4.95	-3	-6	-16	14	10	-1
Memphis	4.41	-25	-10	-37	-12	4	-26
Baton Rouge	3.86	-57	-58	-98	-48	-50	-97
Columbia	4.38	-22	-19	-35	-8	-5	-22
Tallahassee	3.58	-56	-80	-100	-46	-76	-100
Lynchburg	4.72	-6	-2	-25	13	17	-10
Williamsport	4.88	-2	0	-6	17	19	12

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 6.
(Cont.)

Site	BASE (t ha^{-1})	GCM Scenario alone			GCM Scenario + D.E. CO_2		
		GISS	GFDL	UKMO	GISS	GFDL	UKMO
IRRIGATION							
Spokane	5.41	6	-6	10	25	10	29
Yakima	5.34	-3	-4	-3	14	12	14
Boise	5.67	2	8	13	24	27	32
Fresno	7.29	-37	-39	-63	-16	-15	-45
Phoenix	4.85	-92	-67	-96	-91	-62	-96
Fargo	5.12	-8	-15	-8	8	0	9
North Platte	4.91	8	12	1	28	31	19
Dodge City	5.59	-7	-8	-12	9	8	3
Abilene	5.24	-30	-24	-48	-18	-11	-40
Des Moines	4.90	0	4	-11	17	13	4
Indianapolis	5.26	-8	-12	-20	7	3	-6
Memphis	4.42	-24	-12	-36	-11	4	-25
Columbia	4.53	-22	-20	-34	-9	-6	-22
Tallahassee	3.93	-45	-80	-100	-35	-76	-100
Lynchburg	5.15	-12	-9	-27	4	7	-15
Williamsport	5.35	-8	-6	-9	8	11	7

D.E. = Direct physiological effects of 555 ppm CO_2.

Table 7. Season length (days) of dryland soybeans, maize and wheat simulated with GCM climate change scenarios.

	SOYBEAN				MAIZE				WHEAT			
SITE	BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO
Spokane	133	102	99	92	113	118	86	95	284	263	265	250
Yakima	140	111	112	103	96	88	85	80	266	241	248	238
Boise	121	104	102	97	90	89	79	79	236	218	223	212
Fresno	137	133	132	107	102	95	93	84	167	128	132	111
Phoenix	159	148	84	104	85	94	89	110	194	233	217	247
Fargo	111	91	93	85	115	91	92	84	301	285	285	267
N. Platte	100	88	87	84	115	97	96	93	278	256	261	254
Topeka	113	108	108	107								
Dodge C.	128	125	124	124	108	100	97	94	253	234	234	228
Abilene	122	125	126	129	115	106	105	103	202	194	188	199
Des Moines	109	103	102	107	107	91	89	85	274	256	256	245
Indianapolis	116	109	109	109	109	96	85	88	274	254	256	245
Memphis	125	126	125	130	103	95	95	94	179	170	164	172
B.Rouge	125	126	127	133	111	103	95	100	171	180	180	201
Columbia	151	147	147	148	107	96	82	96	178	169	170	169
Macon	147	145	146	150								
Tallahassee	150	149	149	156	119	107	103	104	165	167	175	---
Lynchburg	131	124	124	123	110	93	86	90	190	178	175	171
Williamsport	115	104	104	101	117	104	87	91	282	259	261	236

Table 8. Water use efficiency (dryland yield (kg ha^{-1})/total dryland crop evapotranspiration (mm)), with direct CO_2 effects.

	SOYBEAN				MAIZE				WHEAT			
Site	BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO	GISS	GISS	GFDL	UKMO
Spokane	2.6	3.9	3.1	2.2	9.9	26.6	6.3	16.3	5.6	12.3	6.6	9.0
Yakima	1.4	1.5	1.3	0.8	0.6	5.3	2.9	2.4	3.9	10.7	3.2	4.9
Boise	1.5	1.8	1.1	1.4	2.2	6.6	1.5	3.6	3.6	9.5	3.8	7.0
Fresno	1.7	1.1	1.3	0.1	0.3	2.2	1.8	1.7	22.7	32.1	32.8	27.1
Phoenix	0.9	0.7	0.1	0.6	1.6	1.0	2.2	0.9	2.7	0.0	0.2	0.0
Fargo	3.5	5.8	8.6	3.5	22.1	26.5	27.4	17.7	7.8	8.6	8.5	6.8
N. Platte	2.7	4.1	3.9	3.0	16.5	19.4	20.5	13.1	6.4	7.8	5.9	5.9
Topeka	5.5	4.8	4.4	3.9								
Dodge City	2.7	1.9	1.6	1.4	16.9	19.6	19.7	14.3	6.8	5.7	5.5	6.5
Abilene	2.0	1.3	1.2	0.6	13.4	17.9	14.6	11.6	5.9	3.6	5.6	2.5
Des Moines	5.6	6.8	5.7	1.8	23.1	23.5	21.9	17.2	8.1	10.1	8.4	8.2
Indianapolis	5.1	5.9	4.5	3.7	20.6	24.6	15.8	19.2	8.4	10.2	9.7	8.3
Memphis	4.0	2.8	2.2	1.0	16.6	20.7	15.2	9.8	8.8	8.3	11.0	5.8
B. Rouge	4.6	3.6	3.4	1.2	14.5	20.2	10.8	13.8	7.6	3.5	3.4	0.2
Columbia	4.2	4.0	3.4	4.0	15.6	18.2	4.7	11.9	8.8	8.2	8.8	6.5
Macon	3.2	2.9	1.7	0.9								
Tallahassee	5.8	5.2	5.1	2.6	19.2	23.2	17.3	14.4	6.7	3.4	1.4	
Lynchburg	5.0	6.3	2.7	2.0	18.5	19.2	13.3	19.0	9.2	11.4	11.8	8.7
Williamsport	5.0	6.6	3.7	4.2	19.0	24.2	16.7	20.0	8.4	10.4	9.7	9.5

Table 9. Change in irrigation water with GCM climate change scenarios compared to base (%). Direct CO_2 effects were included.

	SOYBEAN			MAIZE			WHEAT		
Site	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Spokane	-7	7	26	-14	26	-17	-31	-2	6
Yakima	0	9	33	-19	-7	11	-26	14	11
Boise	5	37	20	-18	12	4	-30	12	0
Fresno	28	29	68	-7	-10	3	-73	-77	-87
Phoenix	34	50	31	20	-12	69	134	97	193
Fargo	6	-48	57	-30	-44	32	0	-20	32
North Platte	12	16	35	-15	-18	29	14	45	42
Topeka	41	69	63	--	--	--	--	--	--
Dodge City	43	64	59	-36	-17	13	22	13	4
Abilene	37	56	84	-72	-17	-4	32	4	44
Des Moines	7	46	183	-56	-21	13	-12	16	16
Indianapolis	7	50	61	-66	36	-39	-41	-63	-30
Memphis	29	64	94	-69	21	28	22	-48	37
B. Rouge	61	67	162	-58	34	-20	126	88	328
Columbia	17	62	68	21	164	44	-9	-12	-12
Macon	17	71	217	--	--	--	--	--	--
Tallahassee	68	98	416	-81	47	57	48	5	-100
Lynchburg	-16	96	122	14	-26	-25	-32	-44	-10
Williamsport	20	151	100	-59	52	-19	-18	-16	-8

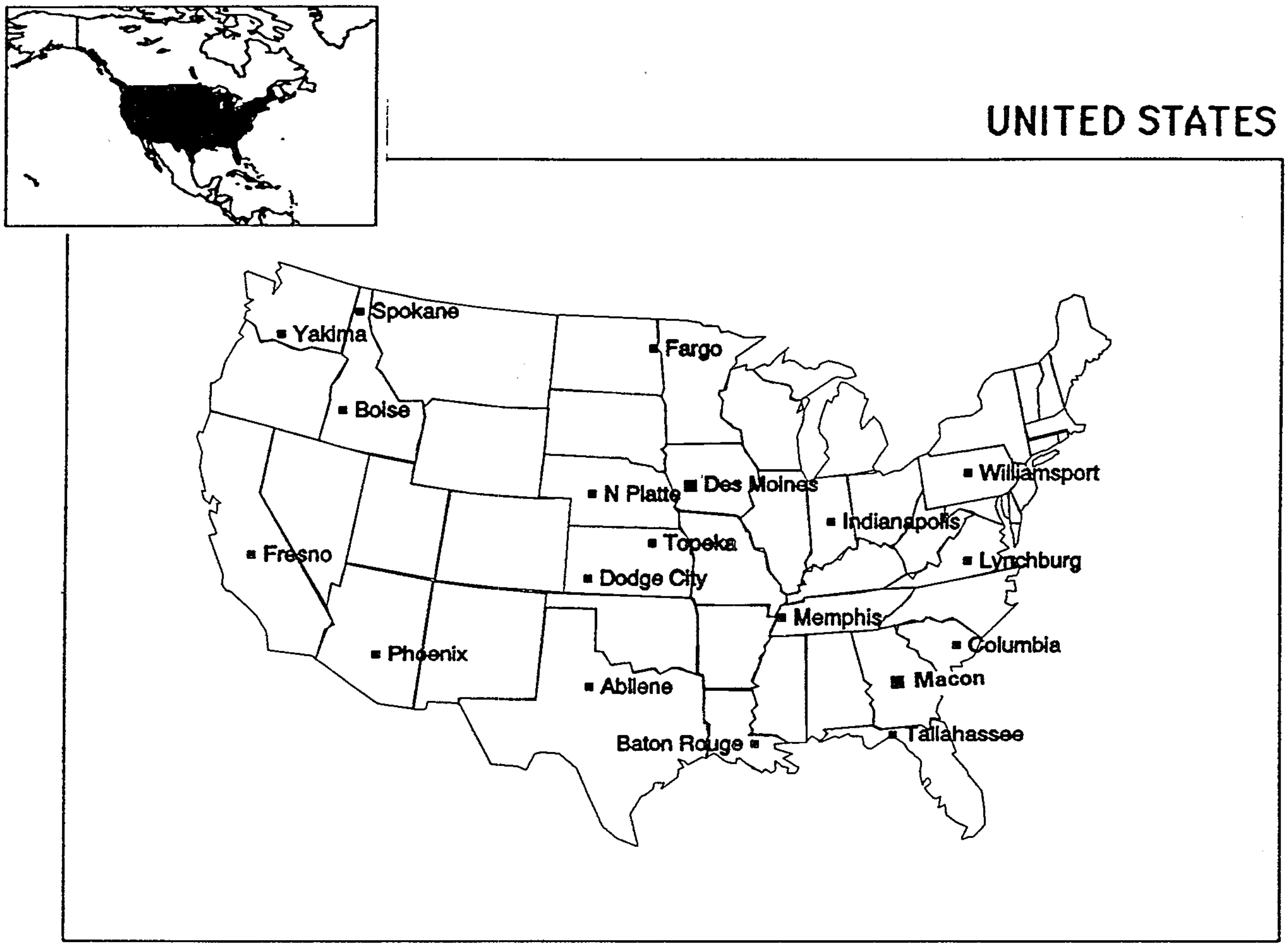

Figure 1. Map of the United States and location of the study sites.

US REGIONAL PRODUCTION

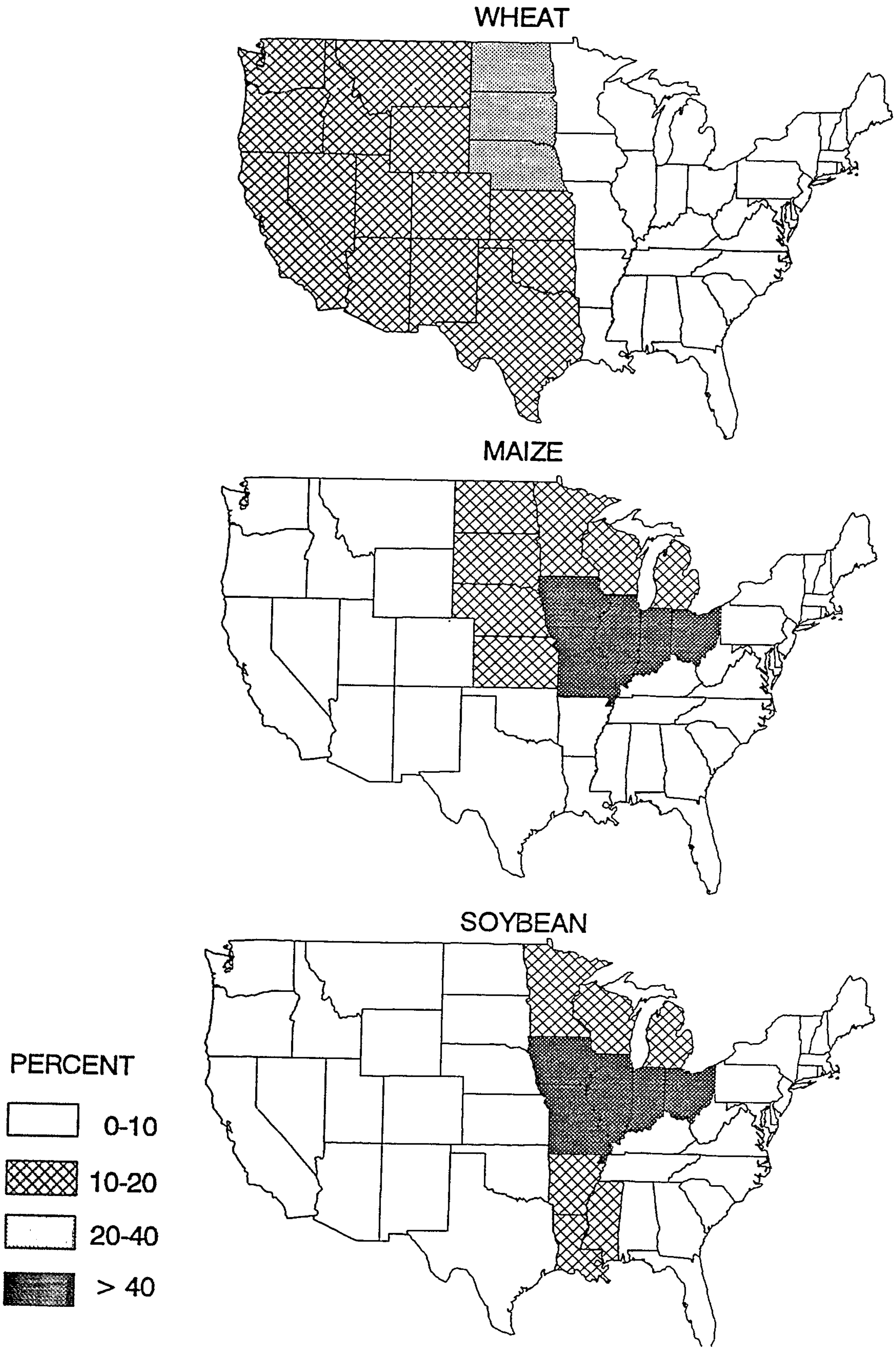

Figure 2. Regions of wheat, maize and soybean production.

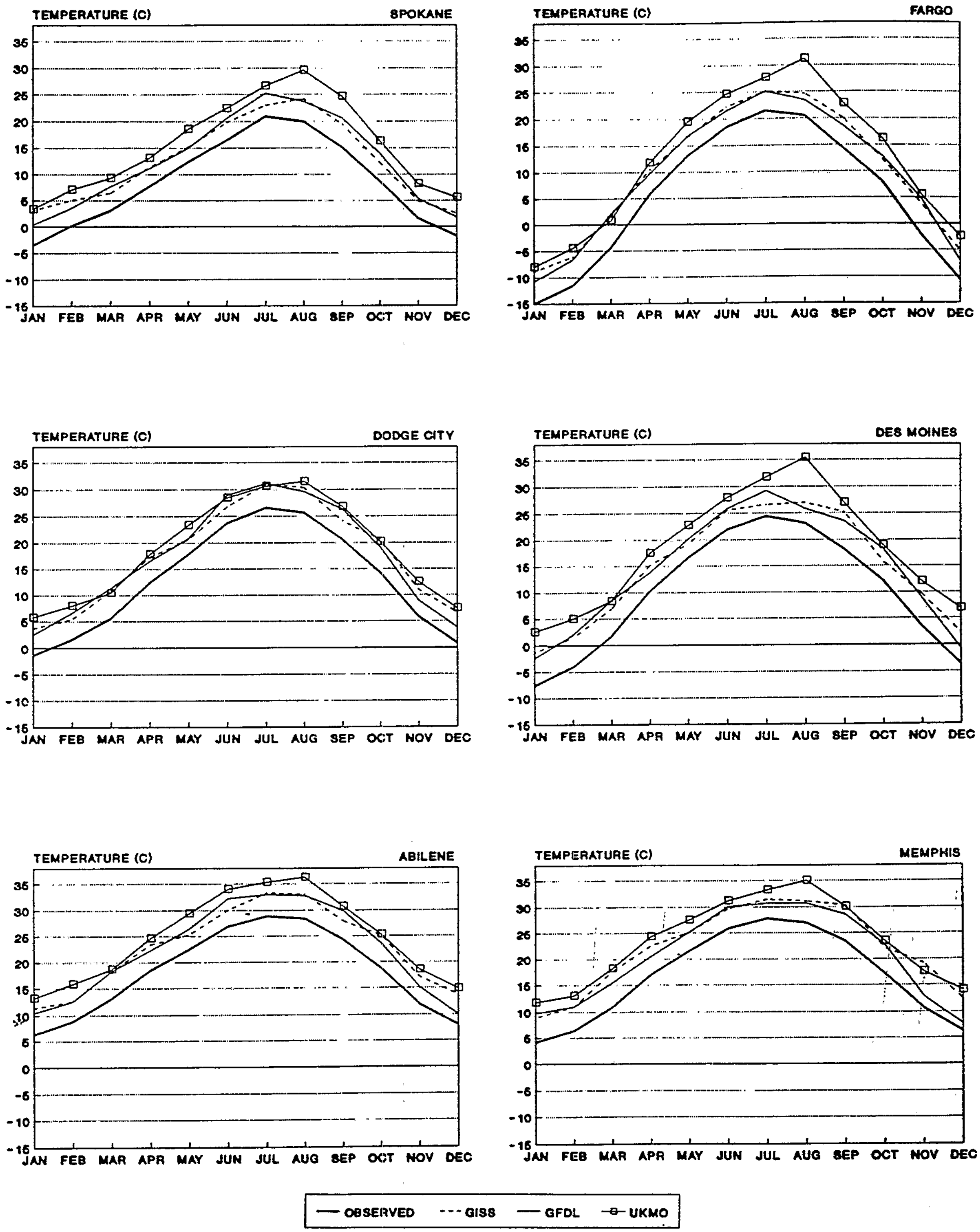

Figure 3a. Observed and 2 x CO_2 scenario temperature at selected sites in the U.S.

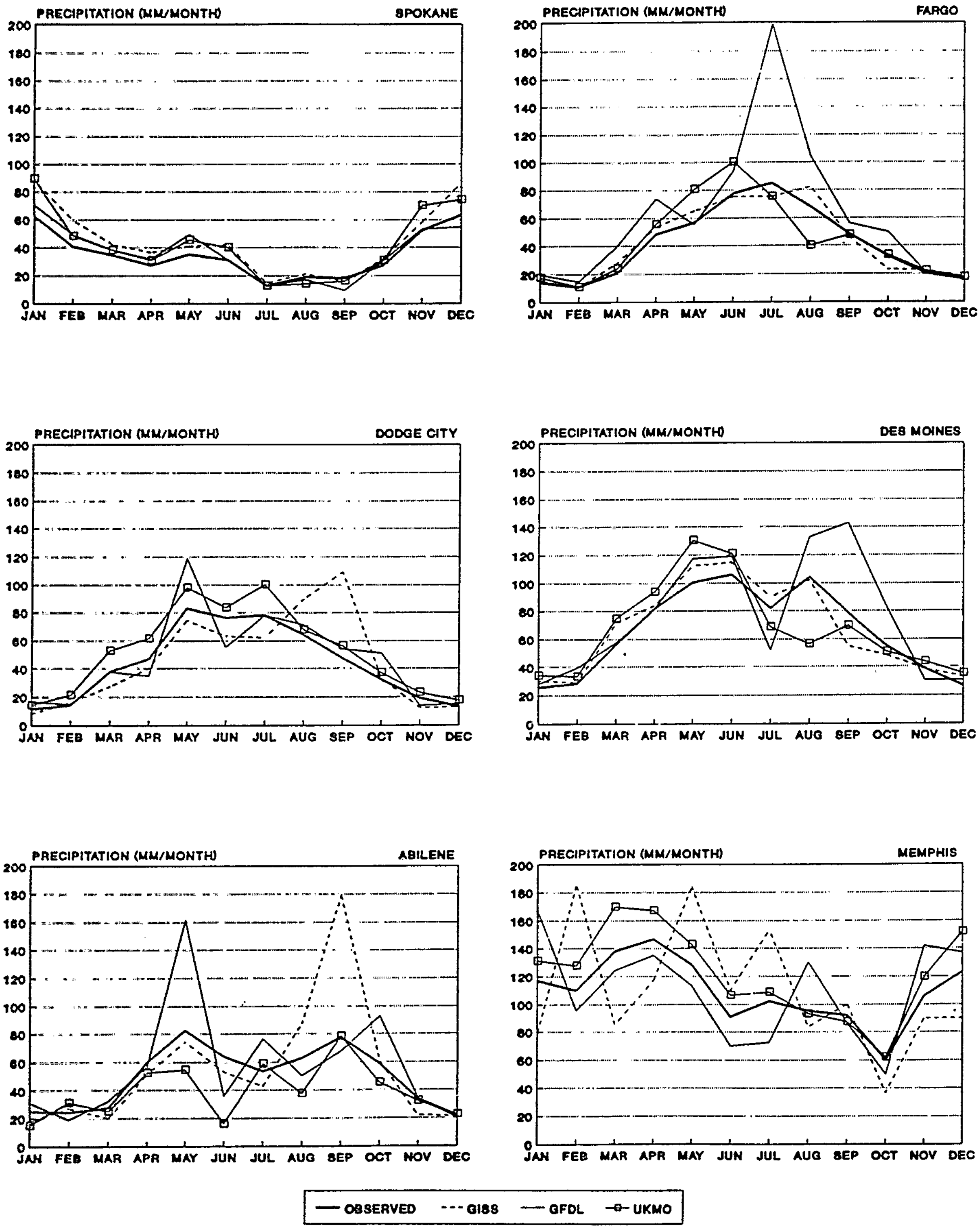

Figure 3b. Observed and 2 x CO_2 scenario precipitation at selected sites in the U.S.

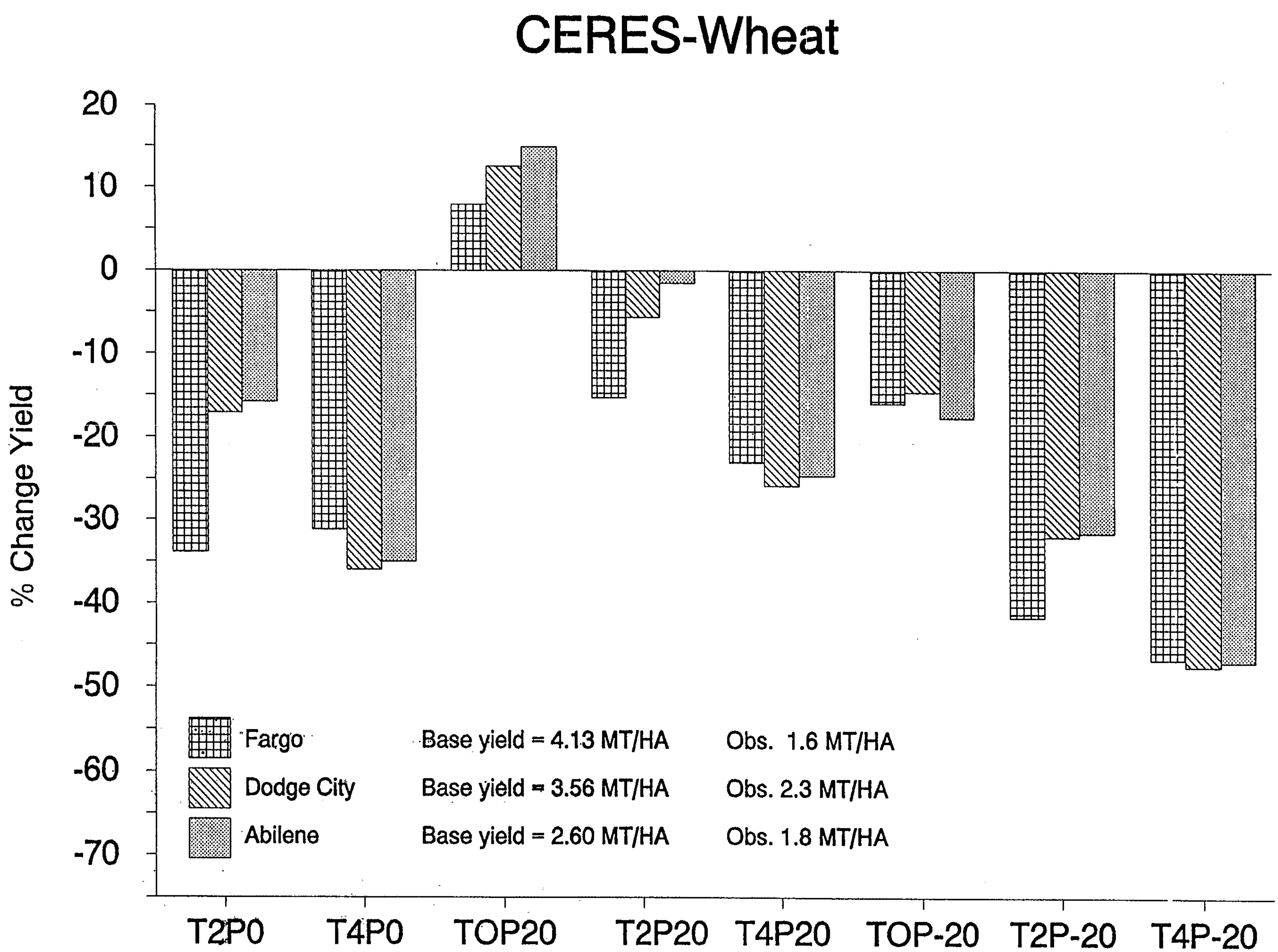

Figure 4a. Sensitivity analysis of CERES-Wheat in Fargo, North Dakota; Dodge City, Kansas; and Abilene, Texas.

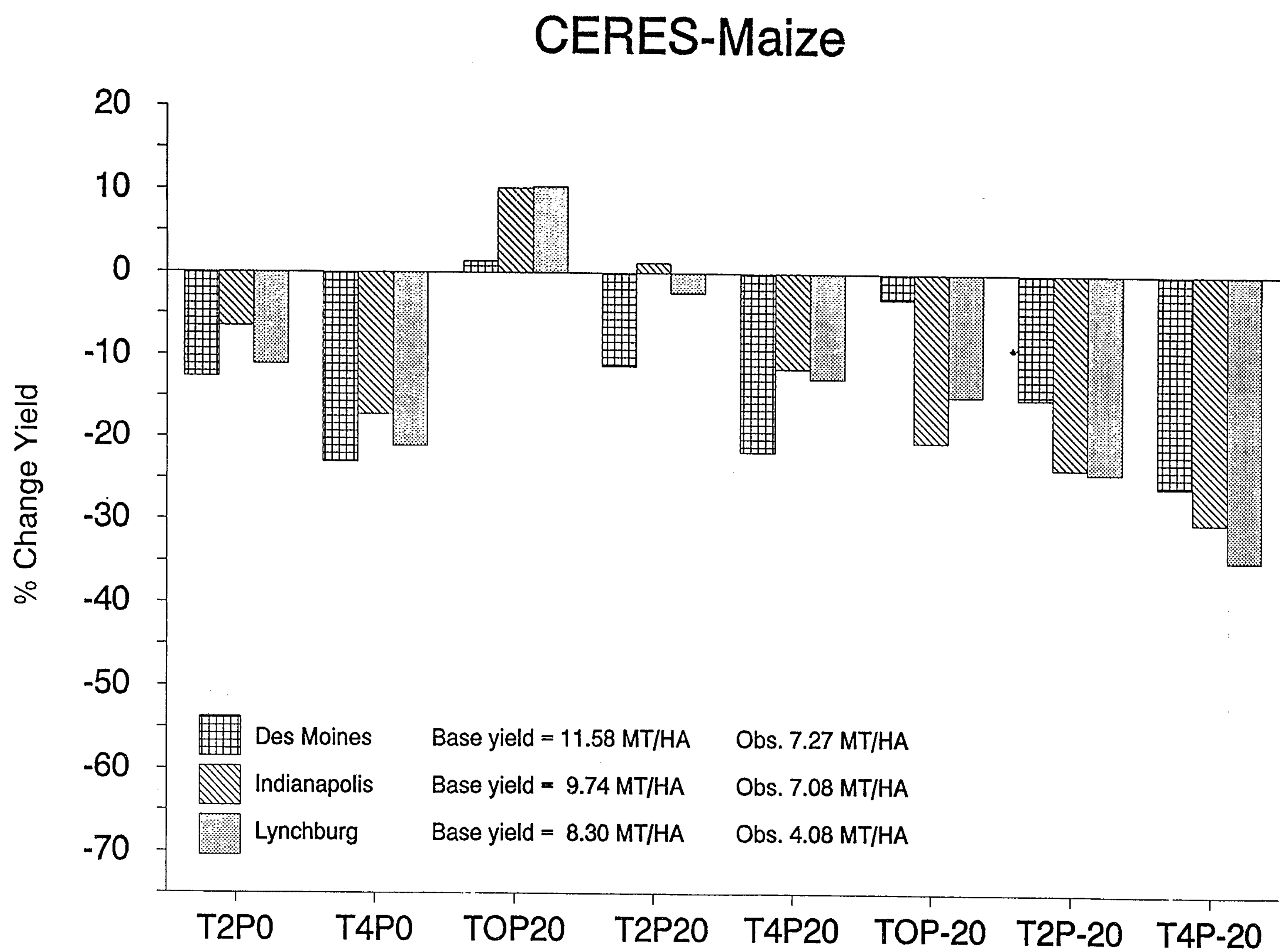

Figure 4b. Sensitivity analysis of CERES-Maize in Des Moines, Iowa; Indianapolis, Indiana; and Lynchburg, Virginia.

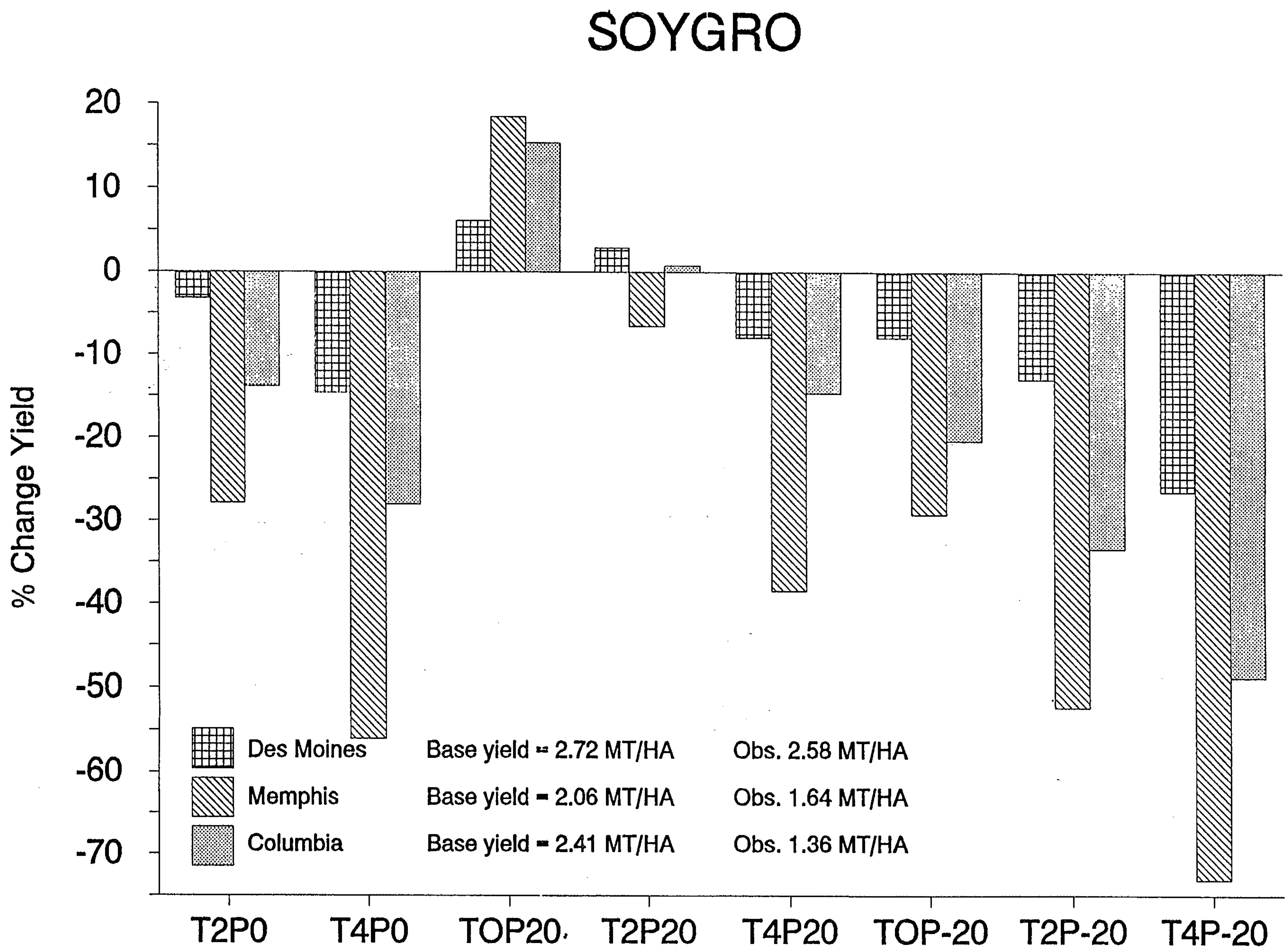

Figure 4c. Sensitivity analysis of SOYGRO in Des Moines, Iowa; Memphis, Tennessee; and Columbia, South Carolina.

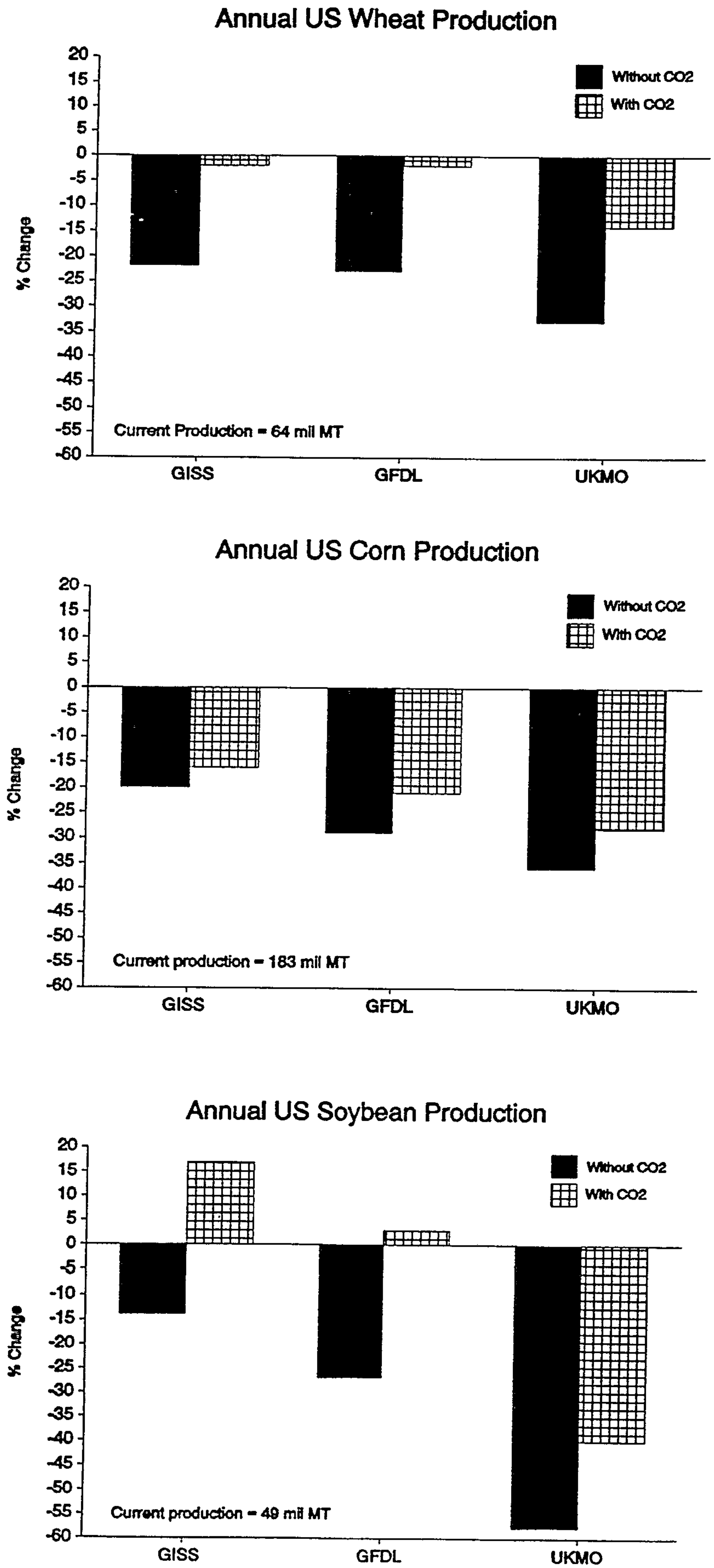

Figure 5. Change in annual national production of wheat, maize and soybean with the GCM climate change scenarios.

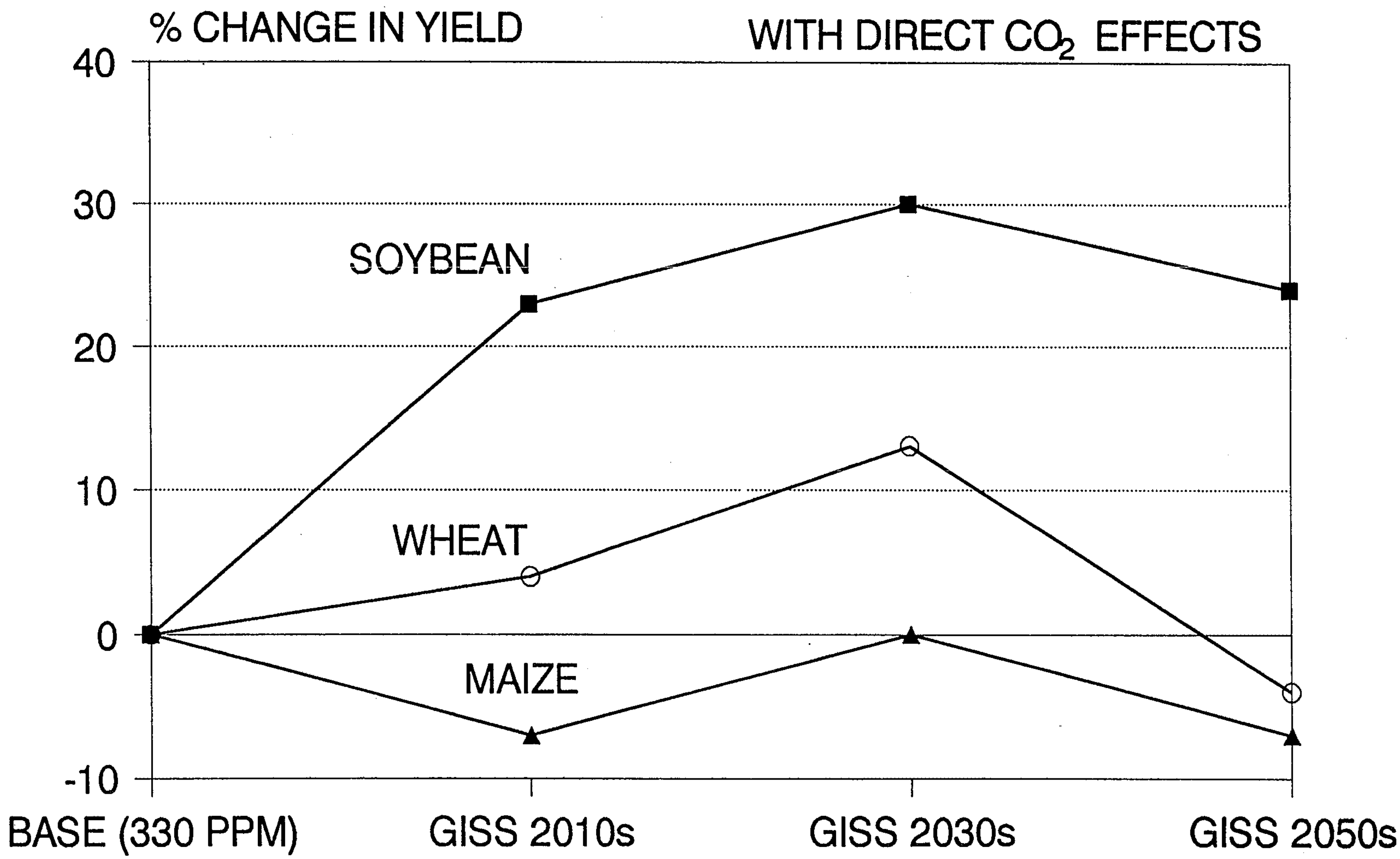

Figure 6. Change in national wheat, maize and soybean yield with the GISS transient run A scenario for the 2010s, 2030s, and 2050s.

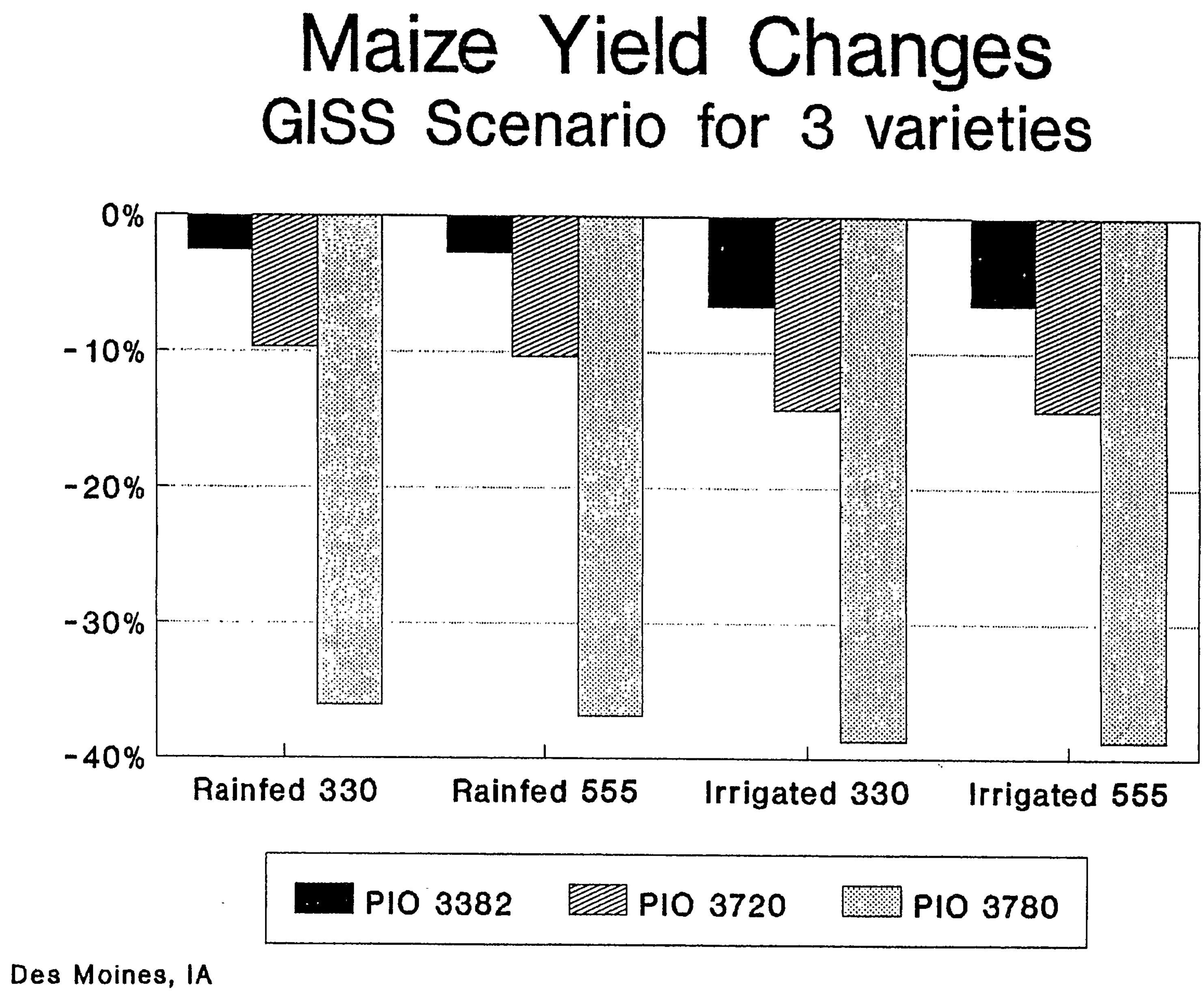

Figure 7. Effect of changes in maize variety on yield under the GISS climate change scenario in Des Moines, Iowa.

POSSIBLE IMPACTS OF CLIMATE CHANGE ON MAIZE YIELDS IN MEXICO

Diana Liverman, Max Dilley, and Karen O'Brien

Pennsylvania State University, Pennsylvania, USA

Leticia Menchaca

Centro de Ciencias de la Atmosfera, UNAM, Mexico

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SUMMARY

This study used global climate models and a crop growth model to estimate the potential impacts of climate change on maize yields in Mexico. Projected climate change caused simulated maize yields to decrease dramatically in two main Mexican regions, but the magnitude of the decrease varied with climatic scenario and with the initial set of management variables selected for the simulation. The decreases in yield were caused primarily by temperature increases, which shortened the duration of the crop's life cycle, particularly the grain-filling period. The duration of the crop's growth period became shorter, exerting a dramatic negative pressure on yields. These decreases were slightly counteracted by the beneficial physiological CO_2 effects, as simulated in this study. A sensitivity analysis indicated that decreases in crop yields would be severe under global warming unless irrigation expands, fertilizer use increases, or new varieties that are more tolerant of heat are developed.

INTRODUCTION

Background

With production of 25 million metric tons per year, Mexico is one of the world's top fifteen cereal producers. Although Mexico has exported cereals in the past, net cereal imports have exceeded 5 million metric tons in recent years. Mexico imported $284 million worth of maize in 1987, $394 million in 1988, and $441 million in 1989. The country is continually striving to support a growing population with an agricultural system that relies on relatively low and variable rainfall. For Mexico, an increase in temperature could aggravate the existing nutritional and economic problems. More than one-third of Mexico's rapidly growing population works in agriculture, a sector whose prosperity is critical to the nation's debt-burdened economy. Although only one-fifth of Mexico's crop land is irrigated, this area accounts for half of the value of the country's agricultural production, including many export crops. Many irrigation districts rely on small reservoirs or wells that deplete rapidly in dry years. The remaining rainfed crop land supports many subsistence farmers and provides much of the domestic food supply. Frequent droughts reduce harvest and increase hunger and poverty in many areas of Mexico.

Maize Production

Maize is the most important crop grown in Mexico. In 1988, production totalled 14.4 million tons (52% of the total production of major crops), grown on 11.5 million hectares of land (56% of the total crop land). Almost every region in Mexico produces maize, but the states of Veracruz, Tamaulipas, and Michoacan tend to be the largest producers. Yields are generally low, ranging from about 350 kg ha^{-1} in Quintana Roo in 1986 to 3,670 kg ha^{-1} in Sonora in 1986. Average yields are 1,250 kg ha^{-1}. Maize is produced in a wide variety of environments, from highlands to coasts, dry to humid climates, and poor to fertile soils.

Maize was probably domesticated in Mexico, and many of its wild ancestors can still be found. It was the staple crop of pre-Columbian populations and continued to be an important component of the diet under Spanish colonialism. In contemporary Mexico, maize is the basis of subsistence and the primary cash crop for the majority of poorer and smaller farms. It also provides the corn flour for the tortillas eaten with almost every meal in both urban and rural Mexico. Each Mexican consumes approximately 250 kilograms of maize per year. Most maize is rainfed. In recent years, 11% of the maize area has been irrigated, providing about 20% of the production. Thus, maize production is extremely vulnerable to climatic variation and drought. The rapid increase in the Mexican population has contributed to the growth in the demand for maize in recent years. Coupled with environmental and economic problems, the situation has led the Mexican government to import considerable amounts of maize in recent years.

In 1950, the expansion of the area planted to maize combined with the use of improved seeds and fertilizer led to a large increase in Mexican maize production. Mexico was one of the leading participants in the "Green Revolution" and considerable attention has been focused on breeding improved varieties of both rainfed and irrigated maize. The use of improved seeds and fertilizer varies widely in Mexico. In some regions, such as the Valley of Puebla, improved seeds, agricultural chemicals, and agricultural extension work has led to much higher yields in good years. However, in other regions, some farmers cannot afford additional chemical fertilizer or irrigated land, and yields remain low.

Analysis of Climate Change Scenarios

Liverman and O'Brien (1992) analyzed the possible impacts of global warming on climate and water availability in Mexico. Their study used five climate models to construct scenarios for temperature, precipitation, and evaporation at a range of stations in Mexico, and highlighted some of the problems that arise from using climate models to predict future climate. Their model versions are the same as those used in this study, and they used the same methodology that we have used to construct the climate scenarios. Climate models are unable to adequately represent current climate in many parts of Mexico, and climate change scenarios created with different models vary widely. The principal conclusion of the study is that Mexico is likely to be warmer and drier under global warming conditions. With all of the climate models analyzed, potential evaporation increased and moisture availability decreased, even in those cases where the model projected an increase in precipitation. A sensitivity analysis of our calculations of evaporation and moisture deficit indicates that water availability could increase only with higher rainfall and relative humidities, or significantly less solar radiation and windiness.

Study Design

In this study, we used a crop simulation model (CERES-Maize) (Jones and Kiniry 1986; IBSNAT 1989) and climate change scenarios generated from three General Circulation Models to analyze the possible impacts of global warming on Mexican maize yields. The CERES-Maize model uses daily weather data to estimate the effects of climate on yields of rainfed or irrigated maize. The model is physiologically based, simulating the influence of solar radiation, temperature, nutrients, and water availability on maize development through major phenological stages.

It has been suggested that crops will benefit from higher levels of atmospheric carbon dioxide, resulting in higher yields. The CERES-Maize model also includes an option to simulate the direct physiological effects of elevated CO_2 levels on crop growth and the efficiency of water use (Acock and Allen 1985). However, the model does not account for losses from, and changes in, pests and diseases. It may, therefore, overestimate yields.

Site Characteristics

Our choice of sites for this study was limited by the availability of long time-series of daily climate data, and by the need to find sites where experimental data were available for calibrating and validating the CERES model. With the cooperation of CYMMIT, we were able to obtain daily climate data and limited crop experimental data for Poza Rica, a site on the Gulf Coast of Mexico, (+20°32' N, 97°26' W; 60 m altitude) and Tlaltizapan, a site in the highlands south of Mexico City (+18°41' N, 99°08' W; 940 m altitude) (Figure 1). These sites are representative of important maize-growing regions in Mexico. The Tlaltizapan site is representative of maize in the central plateau and might be used to approximate conditions in the states of Mexico and Puebla. Poza Rica is more typical of the Gulf coast states such as Veracruz, Tabasco, and Tamaulipas.

METHODS

Base Climate and Climate Change Scenarios

We were able to obtain climate data from 1973 to 1989 for Tlaltizapan and Poza Rica, with missing data for 1986 at the first site. Because observed solar radiation data were only available for a small number of years, we used sunshine hours to generate the solar radiation for the two sites using WGEN (Richardson and Wright 1984).

The climate change scenarios for each site were generated from three GCMs: GISS (Goddard Institute for Space Studies, Hansen et al. 1983); GFDL (Geophysical Fluid Dynamics Laboratory Model, Manabe and Wetherald 1987); and UKMO (United Kingdom Meteorological Office Model, Wilson and Mitchell 1987). Changes in temperature, precipitation, and solar radiation projected by the GCMs were applied to the observed (base) climate variables to create the climate change scenarios for Tlaltizapan and Poza Rica. The base climate sets were also modified with the GISS transient model to create transient scenarios for the 2010s, 2030s, and 2050s (Hansen et al. 1989). Table 1 presents the seasonal and annual temperature and precipitation changes projected by the GCMs.

The mean annual observed temperature at Tlaltizapan is 24°C; and the average observed rainfall is about 96 mm from November to May, and 729 mm from June to October. The mean annual temperature at Poza Rica is 23°C, and the average rainfall is about 380 mm from November to May, and 834 mm from June to October.

Soils and Management Variables

The soils in Tlaltizapan are silt-clay soils 1.0 to 1.8 m deep ("isothermic udic pellusterts"). Because we were unable to obtain detailed soil information, we used an isothermic udic pellusert from Guatemala from a soil data base. Soils in Mexico tend to be poor in nutrients and extremely dry at the beginning of the growing season. Therefore, we modified the initial soil conditions to represent low soil nitrogen and water content. We also reduced the organic content of the soil by reducing the amount of crop residue in the initial conditions.

In Poza Rica, the site with a lower altitude, soils are typically sandy loam of moderate depth. Because of the lack of detailed soil information, we used a generic medium-depth sandy loam soil from the IBSNAT data base and modified the initial soil conditions to reflect low soil fertility and water content at the beginning of the growing season.

In rural Mexico, maize is typically grown by poorer farmers who cannot afford chemical fertilizers. Rather than use the high levels of fertilization and plant densities practiced at the experimental stations, we selected agronomic conditions more typical of average farmers in the region. We used 50 kg of nitrogen fertilizer at planting in the model runs and soils of relatively low fertility and moisture content to represent Mexican conditions. In addition, we have simulated maize yields in the absence of nitrogen limitations for purposes of comparison. We used a planting date of May 20 at Tlaltizapan and June 15 at Poza Rica. In the cases where we simulated irrigated maize, we assumed a 0.5 m irrigation depth at a rate of 50% efficiency.

Crop Model Calibration and Validation

The CERES–Maize crop model (Ritchie et al. 1989) was used for the simulation of maize yield, season length duration, and crop growing season evapotranspiration. To calibrate the model for the varieties and conditions of this study, we used several databases obtained from CYMMIT experimental plots between 1987 and 1989. Five genetic coefficients may be modified to calibrate the model phenology and yield with observed phenology and yield data (Table 2). We began by running the model using the genetic coefficients of the SUWAN-1 variety that was listed in the IBSNAT database (IBSNAT 1989). This variety has genetic characteristics similar to some of the Mexican varieties grown at both Tlaltizapan and Poza Rica. We compared the predicted values for anthesis date, maturity date, yield, kernel weight, grains per square meter, grains per ear, and total biomass, with experimental data from CYMMIT at both stations. Coefficients P5 and G3 modify the grain-filling duration and kernel-filling rate, respectively. We repeatedly ran the model and adjusted P5 (within the ranges suggested by the CERES-Maize User's Guide) to obtain as close a match as possible between the simulated and predicted phenologies. We reduced the coefficients G2 (maximum number of kernels per plant) and G3 (kernel-filling rate) to get closer to observed yields. Since we had data for more than one experimental plot at each station, we validated our calibrated variety with data from a second plot and made small modifications to the coefficients based on the results. The results of the validations are shown in Table 2.

RESULTS

Sensitivity Analysis of the Baseline Yield to Inputs

Table 3 shows the influence of management variables on simulated maize yields under the baseline climate. Simulated yields at the two sites were rather sensitive to our assumptions about soil, fertilizer use, management practices, sowing date, and initial conditions. Our baseline results for 16 years at Tlaltizapan produced an average rainfed yield of 4.02 t ha^{-1} with nutrient stress conditions. Without nitrogen constraints, rainfed yields are 4.55 t ha^{-1}. At Poza Rica, 17 years of baseline climate produced an average rainfed yield of 3.18 t ha^{-1} with nutrient stress. Without nitrogen constraints, rainfed yields average 3.91 t ha^{-1}. The sensitivity of yields to our assumptions of nutrient-poor, dry soils and limited fertilizer use is clear. Yields increased at both sites with increases in fertilizer application and with deeper, moister, more fertile soils.

A delay in the planting date produced lower yields at both sites, while planting 10 days earlier reduced yields at Tlaltizapan, but slightly increased yields at Poza Rica. The unmodified SUWAN variety produced slightly higher yields at both sites than the calibrated variety. Yields were lower with a planting density of two plants per square meter and higher at Tlaltizapan with four plants per square meter.

These variations in responses to current practices suggest that a full set of practices should be tested for better projections of the impacts of climate change. Due to lack of detailed site information, we made some rather arbitrary decisions about soils, initial conditions, planting dates, and genetic coefficients.

Sensitivity Analysis of Maize Yields to Climate and CO_2 Changes

We also conducted a sensitivity analysis of the CERES-Maize model to changes in climate of +2°C and +4°C, +20% and -20% precipitation, and 330 ppm and 555 ppm of CO_2 (Table 4). At Poza Rica, base yields decreased with temperature increases and rainfall decreases; base yields increased under the +20% rainfall scenario. The simulation of the physiological CO_2 effects results in a slight increase of scenario yields in all cases.

Maize Yields under GCM Climate Change Scenarios

The effect of GCM climate change scenarios on simulated maize yields at Tlaltizapan and Poza Rica is presented in Table 5. For each climate scenario, yields were simulated under conditions with nutrient stress (to represent the actual situation) and under conditions without nutrient limitations. The physiological effects of elevated atmospheric CO_2 (555 ppm) were evaluated in all simulations. In this experiment we assumed that the planting dates and varieties remain unchanged under the climate change scenarios.

In Tlaltizapan, base rainfed yields decreased under all climate change scenarios, even when the physiological effects of CO_2 were included in the simulation. The decreases in yield ranged from 20% for the GFDL scenario, to 61% for the UKMO scenario. These low scenario yields occurred because the higher temperature accelerates the phenology and the crop matures faster with less time for gain-filling. There is also drought stress early in the growing season under the scenario conditions.

Baseline rainfed yields of maize at Poza Rica also decreased with global warming, even with the physiological effects of 555 ppm CO_2. The yield decreases at this site were smaller than those at Tlaltizapan, but nevertheless, they are significant ranging from -6% (GISS) to -26% (UKMO).

Maize Yields under the GISS Transient Scenarios

Yields of rainfed maize have also been simulated at Tlaltizapan and Poza Rica for three GISS transient scenarios, corresponding to the decades of the 2010s, 2030s, and 2050s (Table 6). At Tlaltizapan, yields decreased consistently as the climate changes, while at Poza Rica the yield responses varied through time. The latter result indicates that the trajectory of agricultural response to climate change may be non-linear.

Adaptive Responses

The sensitivity analyses of the baseline yields to management variables indicate the importance of some of the current uncertainties in estimating the impacts of future climate changes. In the previous sections we have presented results assuming no change in the average planting date or in the varieties used. But clearly, as climate changes, farmers and governments will try to adapt to change. In this section, we examine whether changes in maize varieties and nutrient levels may offset the negative impacts of a warmer climate.

The amount of fertilizer used is critically important to the maize yields predicted by the CERES-Maize model (Tables 3 and 5). At present, many Mexican producers can only afford to use small doses of nitrogen fertilizer at planting. If more fertilizer becomes available to more farmers, some of the yield reductions under the climate change scenarios might be offset (Table 5). With full fertilization, simulated maize yields increased under irrigation at Poza Rica, but the increase does not fully offset the negative effects of climate change on maize yields. However, given the environmental and economic constraints and trends in agricultural inputs in Mexico, unlimited water and nutrients are extremely unlikely.

We also simulated planting varieties more suited to the new climate conditions, since changing the variety or the genetic characteristics of crops may also help farmers to adapt to global warming. For example, planting the unmodified SUWAN or PIONEER varieties, rather than the calibrated varieties, produced slightly higher yields under the GISS scenario at both sites.

CONCLUSION

In this study we found that rainfed and irrigated maize yields in Mexico decreased with global warming, in spite of differences among the climate model results. Sensitivity analyses indicated that the decreases in crop yields will be severe under global warming unless irrigation expands, use of fertilizer increases, or new varieties of plants are developed.

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Table 1. Temperature differences (°C) and precipitation changes (%) between GCM 1xCO2 and $2xCO_2$ climate change scenarios.

	Temp. Diff. (°C)					Precip. Changes (%)				
Site/GCM	Spr.	Sum.	Fall	Win.	Annual	Spr.	Sum.	Fall	Win.	Annual
Tlaltizapan										
GISS	4.1	4.1	4.3	4.5	4.2	-6	-6	-2	-3	-4
GFDL	2.3	2.5	2.9	2.9	2.7	14	-19	-16	10	-9
UKMO	3.7	3.5	2.9	3.0	3.3	-33	42	11	-24	5
Poza Rica										
GISS	4.1	4.1	4.3	4.5	4.2	-6	-6	-2	-3	-4
GFDL	2.3	2.5	2.9	2.9	2.7	14	-19	-16	10	-9
UKMO	4.1	4.0	4.0	3.6	3.9	-5	-13	16	-29	-6

Table 2. Simulated and observed (1989) yield and season length at Tlaltizapan and Poza Rica.

		Yield (T/Ha)		Season Length (days)	
Site	Experiment	Obs.	Sim.	Obs.	Sim.
Tlaltizapan	1	6.20	6.58	122	127
Tlaltizapan	2	5.83	5.72	122	127
Poza Rica	1	5.27	9.12	112	109
Poza Rica	2	6.98	6.53	138	133
Poza Rica	3	6.56	7.50	138	133

Coefficients of SUWAN maize variety and modified coefficients of the varieties used at Tlaltizapan (TLA) and Poza Rica (PR):

SUWAN: P1 (380); P2 (0.6); P5 (780); G2 (750); G3 (7.0)
TLA: P1 (320); P2 (0.6); P5 (780); G2 (500); G3 (8.0)
PR: P1 (350); P2 (0.6); P5 (780); G2 (550); G3 (8.5)

Table 3. Sensitivity of CERES-Maize yield to changes in management variables.

Management variables	Simulated Yield (T/Ha)	
	Tlaltizapan	Poza Rica
Base scenario*	4.02	3.18
Planting 10 days later	1.41	1.12
Planting 10 days earlier	3.94	3.26
Variety SUWAN	4.75	3.31
100 kg ha^{-1} N fertilizer	4.56	3.81
200 kg ha^{-1} N fertilizer	4.55	3.91
More productive soil**	4.05	4.75
V. good initial conditions	4.66	4.53
Medium initial conditions	4.38	3.66
2 plants m^{-2}	2.86	2.70
4 plants m^{-2}	4.41	3.16

*Tlaltizapan planting date May 20; Poza Rica planting date June 15.

**Medium silt clay at Tlaltizapan; Deep sand at Poza Rica.

Table 4. Sensitivity of CERES-Maize yield to changes in temperature, precipitation, and atmospheric CO_2.

Scenario	Poza Rica (t ha^{-1})
BASE	3.18
T+2 C, 330 ppm CO_2	2.90
T+2 C, 555 ppm CO_2	3.10
T+4 C, 330 ppm CO_2	2.58
T+4 C, 555 ppm CO_2	2.89
P+20%, 330 ppm CO_2	3.26
P+20%, 555 ppm CO_2	----
P-20%, 330 ppm CO_2	3.06
P-20%, 555 ppm CO_2	3.30

Table 5. Effect of GCM climate change scenarios on CERES-Maize yield.

	Simulated Yield (T/Ha)			
	Nutrient stress*		No nutrient limitations	
Scenario	Tlaltizapan	Poza Rica	Tlaltizapan	Poza Rica
BASE	4.02	3.18	4.49	3.98
GISS, 330 ppm CO_2	3.11	2.76	3.49	2.80
GISS, 555 ppm CO_2	---	2.97	3.77	3.30
GFDL, 330 ppm CO_2	2.74	2.26	3.07	2.62
GFDL, 555 ppm CO_2	3.20	2.70	3.47	3.18
UKMO, 330 ppm CO_2	2.34	1.83	3.92	1.98
UKMO, 555 ppm CO_2	---	2.35	3.93	2.67

*Actual conditions

Table 6. Effect of GISS transient scenarios on CERES-Maize yield.

Scenario	Simulated Yield (T/Ha) Tlaltizapan	Poza Rica
BASE, 330 ppm CO_2	4.02	3.18
GISS 2010s, 405 ppm CO_2	3.67	3.27
GISS 2030s, 460 ppm CO_2	3.32	2.48
GISS 2050s, 530 ppm CO_2	2.95	2.95

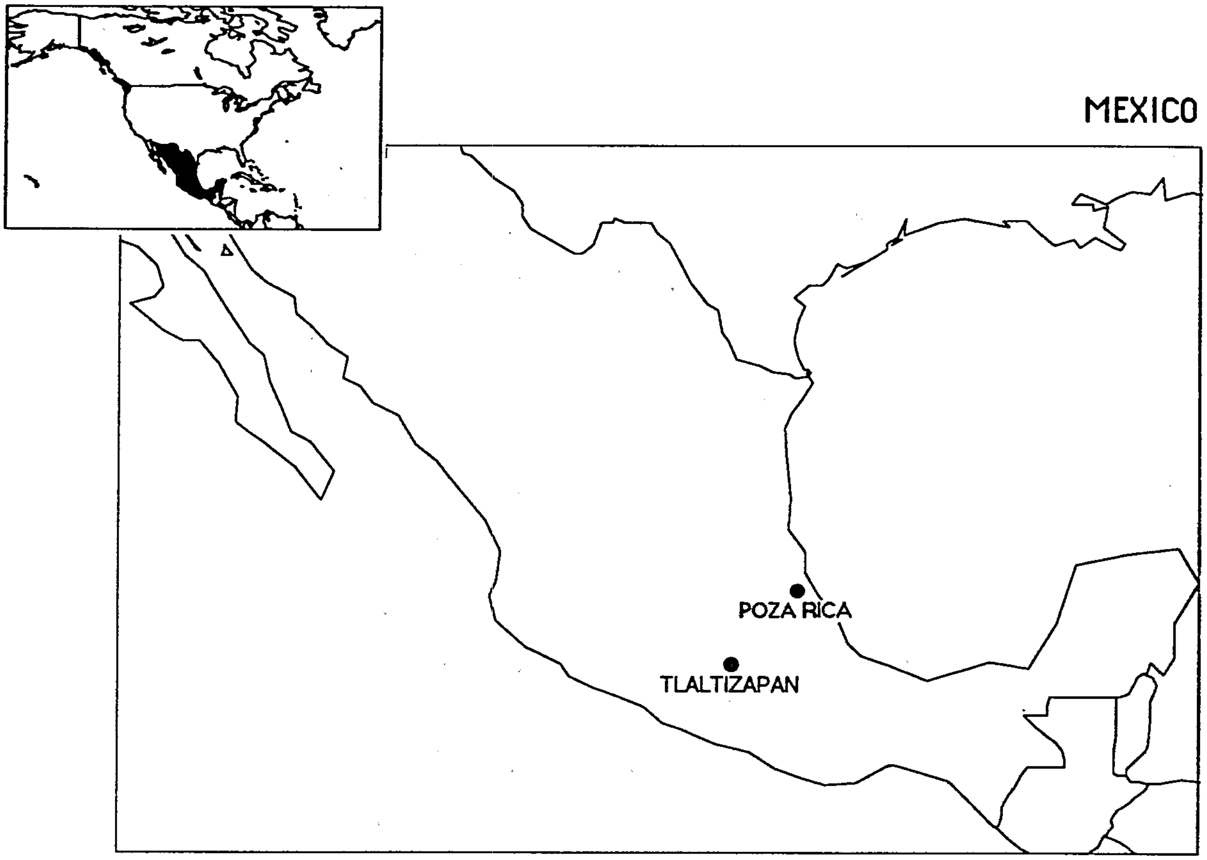
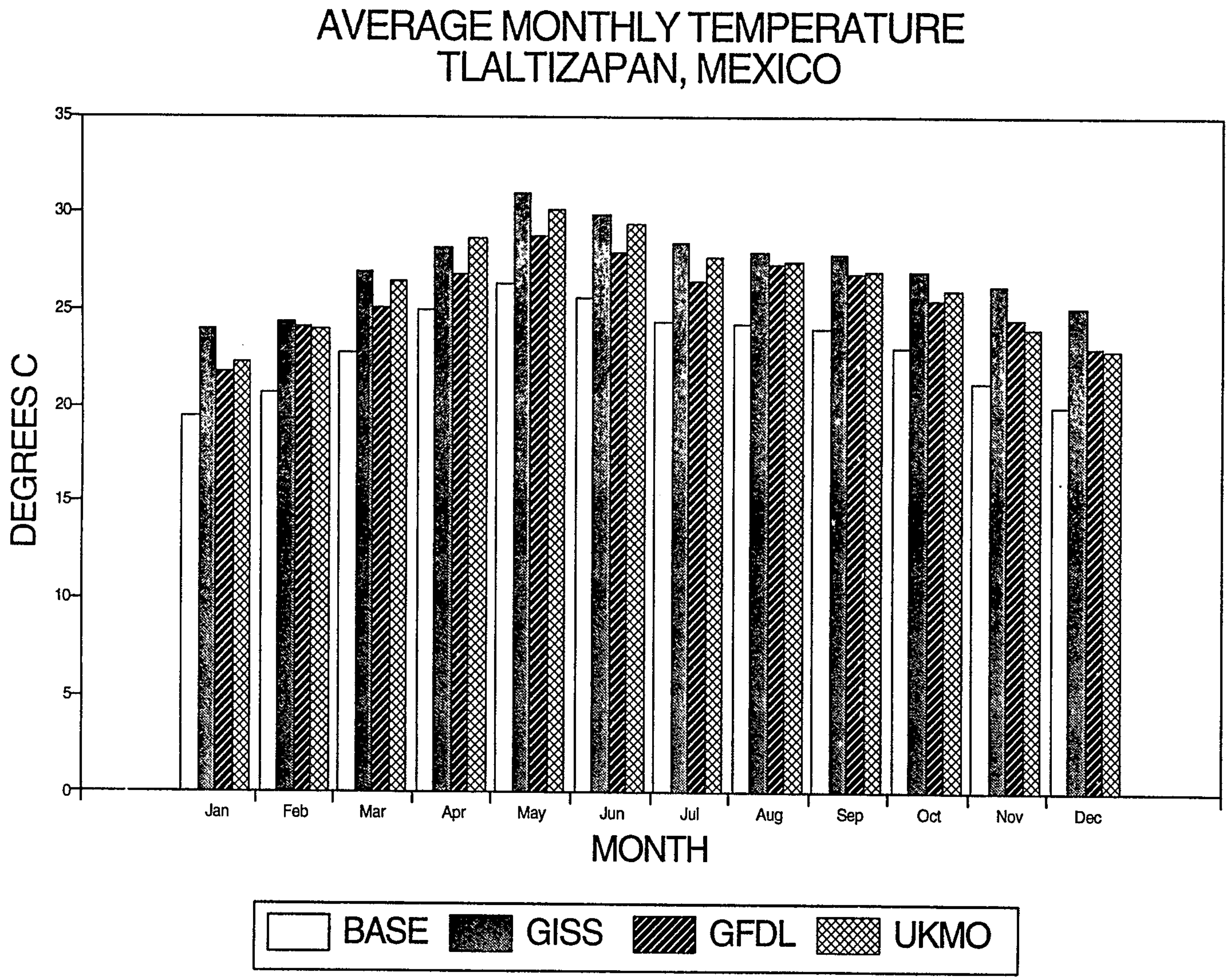


Figure 1. Map of Mexico and location of the sites selected for the study.


AVERAGE MONTHLY TEMPERATURE
TLALTIZAPAN, MEXICO
DEGREES C
35
30
25
20
15
10
5
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Jan
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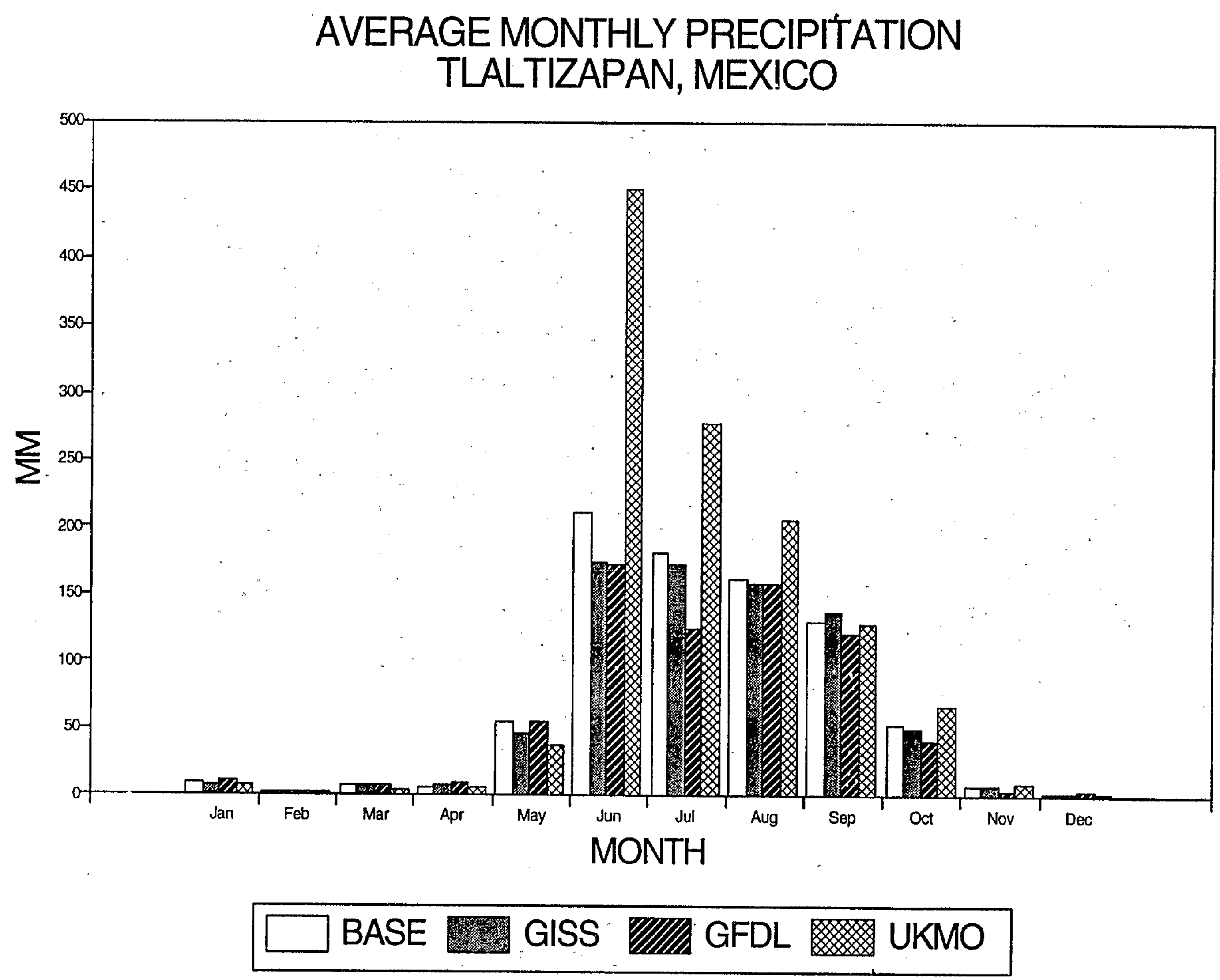
MONTH
BASE
GISS
GFDL
UKMO

Figure 2a.


AVERAGE MONTHLY PRECIPITATION
TLALTIZAPAN, MEXICO
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May
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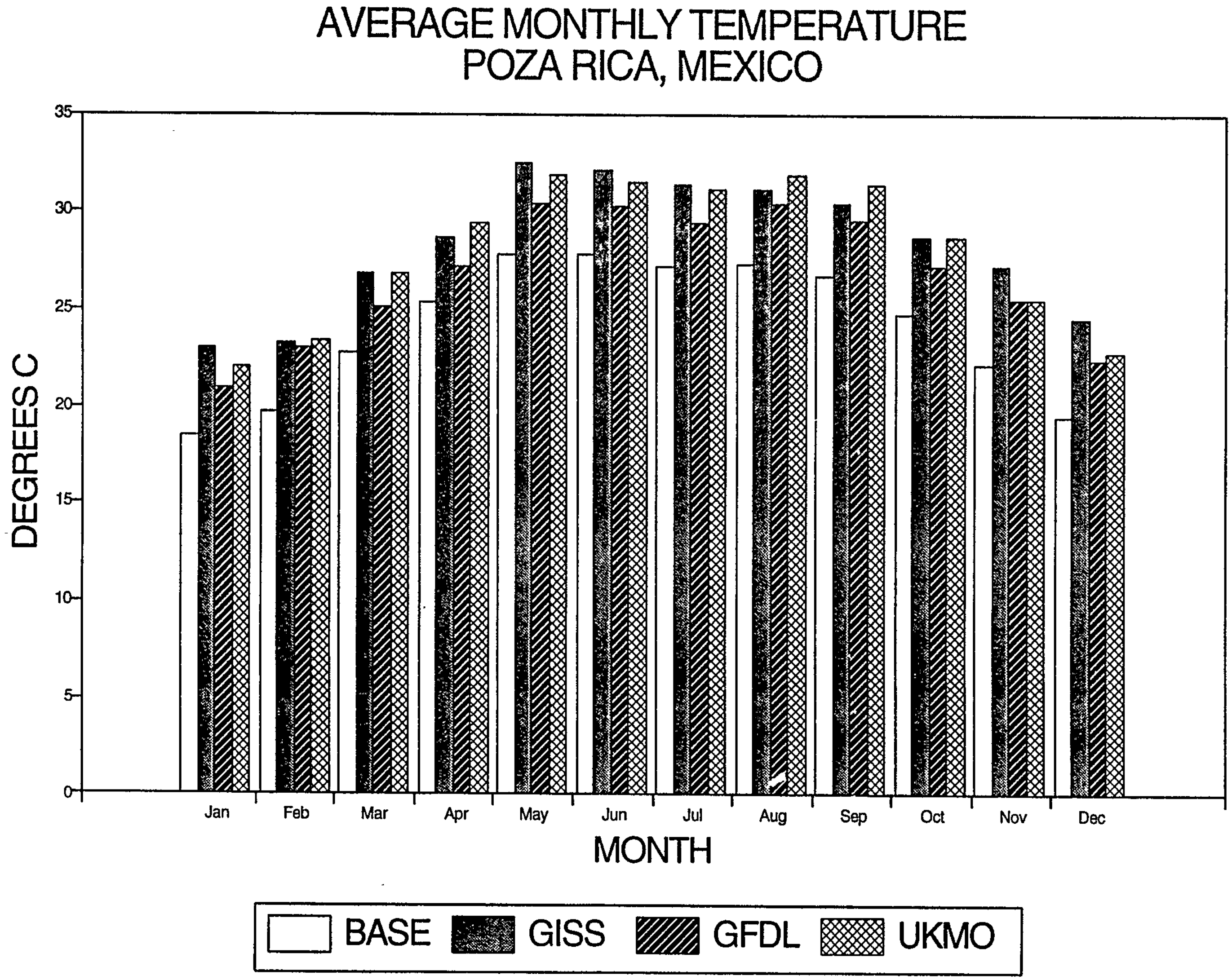
MONTH
BASE
GISS
GFDL
UKMO

Figure 2b.


AVERAGE MONTHLY TEMPERATURE
POZA RICA, MEXICO
DEGREES C
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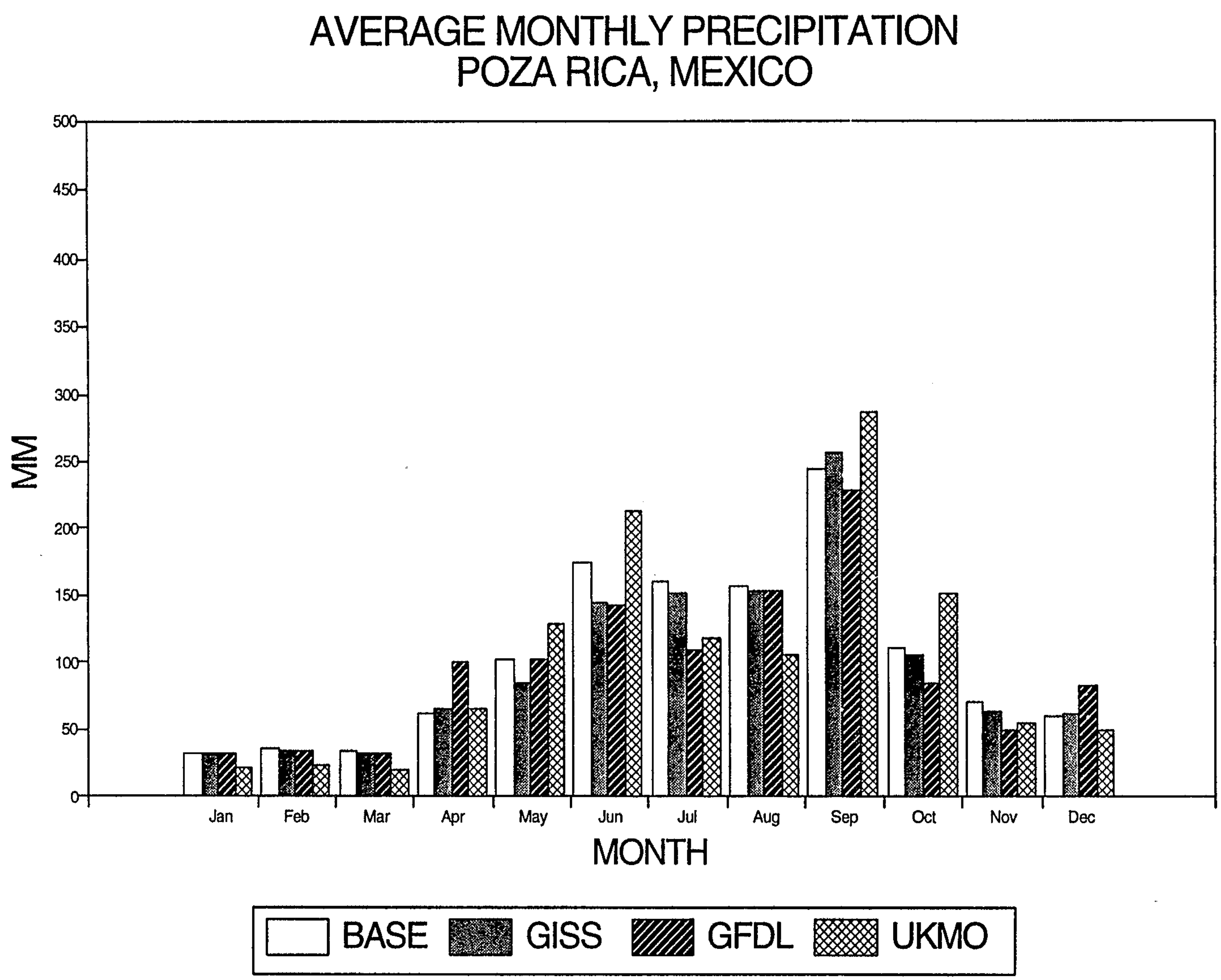
GISS
GFDL
UKMO

Figure 2c.


AVERAGE MONTHLY PRECIPITATION
POZA RICA, MEXICO
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Nov
Dec
MONTH
BASE
GISS
GFDL
UKMO

Figure 2d.

SECTION 3: SOUTH AMERICA

POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE FOR BRAZILIAN AGRICULTURE: APPLIED SIMULATION STUDIES FOR WHEAT, MAIZE, AND SOYBEANS

Otavio João Fernandes de Siqueira

National Research Center for Wheat
CPACT/EMBRAPA, Brazil

Jose Renato Boucas Farias

National Research Center for Soybean
CNPS/EMBRAPA, Brazil

Luis Marcelo Aguiar Sans

National Research Center for Maize and Sorghum
CNPMS/EMBRAPA, Brazil

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SUMMARY

Wheat, maize and soybean production were simulated with the CERES-Wheat, CERES-Maize and SOYGRO crop models to estimate the possible impact of global climate change at 13 sites in Brazil. Climate change scenarios for each site were created by combining observed climate data with the output of the GISS, GFDL and UKMO General Circulation Models (GCMs). Historical climate data were used as the base scenarios. The three GCMs project temperature increases, changes in precipitation, and small variations of solar radiation. The sensitivity of the simulated crop yield to changes in temperature, precipitation, and atmospheric CO_2 was also tested.

Temperature increases resulted in lower grain yield, biomass, and season length for wheat and maize, but soybean was less affected. The simulated physiological effects of CO_2 partially compensated for the yield decreases under the scenarios of climate change alone in wheat and maize, and fully compensated in the case of soybean. Wheat yields declined at all sites under the three GCM climate change scenarios, although the magnitude of the decreases varied with scenario and region; the largest decreases occurred in the Central region (24 and 46% under the GFDL and UKMO scenarios respectively) and in the Central South region (43% under the GISS scenario). Maize yields also declined at all sites. The largest decreases were in the Northern region (26% under the GISS scenario), while the decreases in the South and Central South region varied but were less than 20%. In contrast to wheat and maize, simulated soybean yield remained the same (in the Northern regions) or increased under the GCM climate change scenarios.

Adaptation strategies such as irrigation, changes in planting date, and increased nitrogen fertilization helped improve yields, but not enough to compensate for all of the losses under climate change. The crop simulation model was used to design a hypothetical more heat-resistant cultivar that showed promising results for potential adaptation to warmer climates, but the feasibility of this strategy still needs to be tested through breeding programs.

INTRODUCTION

The rising concentration of greenhouse gases in the atmosphere may lead to increased global temperatures (IPCC 1990) and the study of the potential impacts of global climate change on ecosystems and agriculture is a relatively new area of research (Smith and Tirpak 1989a, 1989b). In Brazil, very few studies have been conducted in this area. Some results have been presented by Mota *et al.* (1984) using statistical models. In this study, we analyze the possible impact of global climate change on wheat, maize, and soybean production in Brazil using crop growth simulation models and climate change scenarios created with GCM results. These crops are the major agricultural commodities in Brazil (along with rice), and cover approximately 25 million ha of cultivated land. In addition, this study analyzes adaptation strategies to minimize the impact of the projected climate changes on crop production.

Agroecological Regions and Sites

Thirteen sites were selected for the simulation study (Figure 1 and Table 1). The locations of the sites range from latitude 30 degrees South to close to the equator. Nine sites are concentrated in the subtropical and tropical/high-elevation regions and the other four sites are distributed among the tropical, semi-arid, and equatorial/sub-equatorial regions. The sites represent the main agricultural regions of Brazil, and they were selected based on previous agroclimatic studies (Mota

1989; Mota and Agendes 1986; Alfonsi *et al.* 1981; Queiroz *et al.* 1979). Nine sites are located in the most important agricultural region of the country, the South and Central-South regions. Almost 99% of the national wheat production and more than 80% of the maize and soybean production are concentrated in these regions.

METHODS

Baseline Climate

The baseline climate is represented by the historical data available for each site during the period 1951-1980 (Table 2) and includes daily maximum and minimum temperatures, precipitation, and hours of sunshine. Daily solar radiation data were generated using hours of sunshine, and the results were compared to actual data where available.

The lowest mean annual temperature is found in Vacaria, which has the most significant seasonal temperature variation. In contrast, Belem shows the highest mean annual temperature with the smallest variation during the year. Precipitation varies among the sites, with the highest precipitation occurring in the northern sites and the lowest in the northeast. There is also variability in seasonal precipitation in some central sites, where the lowest monthly rainfall occurs during the winter. Seasonal differences in solar radiation are more apparent in the southern sites.

Sensitivity Scenarios

To analyze the sensitivity of the crop models to temperature, precipitation, and CO_2 levels, sensitivity scenarios were created by combining step changes in the climate variables (0, +2°C, +4°C temperature changes; 0, +20%, -20% precipitation changes). The physiological effects of 555 ppm CO_2 were also considered for each scenario.

Climate Change Scenarios

This study used climate change scenarios generated by three equilibrium general circulation models: Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1983), Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), and United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987). These GCMs are three-dimensional models which incorporate physical knowledge of the processes involved in the transfer of the energy among the earth, oceans, and atmosphere.

The climate change scenarios for each site were created by applying the changes between the $1xCO_2$ and $2xCO_2$ monthly GCM-simulated climate variables (differences were used for temperatures and ratios for precipitation and solar radiation) to the corresponding daily baseline climate variables. The scenario changes in mean annual temperature, precipitation and solar radiation are shown in Table 3 for each site.

The annual temperature increases range from +2°C to +6°C, but there are significant differences among the scenario projections. In general, the largest increases correspond to the UKMO scenario. The sites included in the Central-South region show the largest temperature changes from March to November, which is the growing period of wheat. For the sites in the Northeast region, the UKMO scenario projects higher temperatures in the winter (June to August).

Under the climate change scenarios, precipitation projections vary greatly, especially for the more southern sites. For the most part, the projected annual precipitation increased in comparison with the current (observed) climate. The GFDL scenario projects the largest precipitation increases for sites in the South region from September to November, and for sites in the Central-South region from March to May. The precipitation projected by the GFDL and UKMO scenarios for December for most of the Southern sites is lower than the current precipitation, indicating a higher probability of drought problems for summer crops. Smaller annual increases in precipitation are projected for the sites in the Northeast and North regions, where the UKMO scenario projects decreases of about 10% to 15%. The precipitation reductions projected by the UKMO scenario during the summer (December to February) and winter (June to August) might bring additional stress for the crops in the northern sites, especially considering the currently low water supply in the winter.

GISS Transient Scenarios

The GISS transient scenarios were used to assess the effect of gradual changes in climate for the decades of the 2010s, 2030s, and 2050s on crop production (Hansen et al. 1988). The atmospheric CO_2 concentrations considered were 405 ppm, 460 ppm, and 530 ppm, respectively, for these decades.

Crop Models and Inputs

Crop-growth models developed by IBSNAT (Jones *et al.* 1990) were selected for this simulation study: CERES-Wheat version 2.10 (Godwin *et al.* 1989; Ritchie and Otter 1985), CERES-Maize (Jones and Kiniry 1986), and SOYGRO (Jones *et al.* 1988). The IBSNAT crop models simulate plant development and growth by integrating soil, plant, climate (daily maximum and minimum temperatures, precipitation, and solar radiation), and management factors.

The IBSNAT crop models include an option to simulate the direct physiological effects of CO_2 atmospheric concentrations on plant photosynthesis and water use, based on experimental results (Rose 1989; Curry *et al.* 1990). The photosynthetic enhancement of 555 ppm CO_2 is 1.17 for wheat, 1.21 for soybeans, and 1.06 for maize. Increases in stomatal resistance are also simulated.

Soil data were obtained from regional soil survey studies (Brasil 1971, 1973; Larach *et al.* 1984; Oliveira *et al.* 1984; Mothei *et al.* 1979; Santos *et al.* 1983). Soils were chosen to represent the local soils of the sites selected. The soil profile for Passo Fundo (crop model calibration site) was created with local data.

The cultivars, plant population, and planting date used as input for the crop growth simulation models are shown in Appendix A. The information was obtained from published crop management reports (Queiroz *et al.* 1979; Miyasaka and Medina 1981; Vernetti 1983; Reuniao 1987; CSBPT 1988; CCSBPT 1989; CCBPT 1988).

Although there are water deficits in some regions, almost all maize and soybean crops are cultivated without irrigation. For winter wheat, irrigation is recommended for some regions, including Campinas, Campo Grande, and Sete Lagoas. In Campo Grande, wheat could be produced in a rainfed system, if it is planted at a different planting date.

Calibration and Validation of the Crop Models

CERES-Wheat. The local wheat cultivar BR 14 was chosen for most dryland sites, and its genetic coefficients were determined using experimental field data. The cultivar ANZA, with the original genetic coefficients included in the DSSAT database, was selected for the irrigation sites. The model was validated in Passo Fundo with data from several field experiments, (Figure 2) and there is a satisfactory agreement between the observed and estimated grain yields (Siqueira 1991). In Brazil, the CERES model has also been validated for wheat in Sao Paulo (South region) (Anunciacao and Liu 1991).

CERES-Maize. The genetic coefficients for the local cultivar used in the South and Central-South regions (PIO 3230) were determined by comparing data from a field experiment conducted in Taquari involving irrigation, nitrogen, and population levels (Matzenauer et al. 1988). Figure 2 shows selected results of the validation. Cultivar SUWAN-1, with the original genetic coefficients included in the DSSAT data base, was used for the other regions because the simulated results are in agreement with the regional observed crop parameters.

SOYGRO. The genetic coefficients of the cultivar DAVIS were calibrated using data from a field experiment conducted in Passo Fundo in 1989, and the model was validated with data from several field experiments (Siqueira and Berg 1991) (Figure 2). The cultivars VICOJA and JUPITER were used for the sites in the Northeast and North regions. In Belem, simulated and observed yields and anthesis dates show a close relationship.

Limitations of the Study

The crop models have not been validated in all of the regions in this study. Technology and land use are assumed to be constant, even though it is certain that they will change in the future. The direct physiological effects of CO_2 on crop development and yield may be different than the simulated effects.

The GCM climate change scenarios do not include changes in climatic variability that might represent a very important factor for crop production, especially in the more vulnerable regions. The spatial resolution of the climate change scenarios as created in this study is low.

RESULTS AND DISCUSSION

Sensitivity Analysis

A sensitivity analysis was conducted at each site to evaluate the effect of step changes in temperature and precipitation on wheat, maize, and soybean (Tables 4, 5, and 6). For wheat, an increase in temperature resulted in significant reductions in crop season length and grain yields (Table 4). An increment of +4°C resulted in a shortening of the crop season length by about 15%, and a 40% to 50% decrease in grain yields. With the physiological effects of 555 ppm CO_2 on the crop included in the +4°C scenario, wheat yield increased in comparison with the +4°C scenario alone, but the effects did not completely compensate for the negative impact of higher temperature on yields.

For maize, the effect of warmer temperatures on grain yield varied among the regions (Table 5), ranging from about -20% in the South and Central-South to -28% in the Northeast region. Warmer temperatures reduced the maize crop season length by an average of 15%, but the effect was greater for the more southern latitude sites. There were no significant effects on maize grain yield from increased precipitation except in the Northeast region. Lower precipitation may be beneficial for maize in the North region and detrimental in the Northeast. The physiological effects of 555 ppm of CO_2 were smaller on maize grain yields than on wheat yields, as expected from the lower response of maize, a C4 crop, to higher CO_2.

Temperature and precipitation changes had a different effect on soybean yields than on maize and wheat yields (Table 6). A 2°C temperature increase with the physiological effects of doubled CO_2 resulted in small increases in yield. In addition, the temperature increase did not significantly affect the length of the crop season. With the physiological effects of CO_2, soybean yields generally increased under the scenarios with higher temperatures.

Crop Changes under GCM Climate Change Scenarios

The results of the simulation of wheat, maize, and soybean growth under the GCM climate change scenarios are shown in Table 7. Tables 8, 9, and 10 and Figure 3 show the results for each region.

Wheat. GCM scenarios projected wheat biomass, grain yield, and season length decreases in comparison with baseline data for all sites (Table 7). Wheat yield reductions were the largest with the UKMO scenario. All scenarios projected a shorter wheat crop season, especially for the South region. These changes were driven by the temperature increases of the scenarios, as described in the sensitivity analysis.

Figure 3 shows the percent change in wheat grain yield for each region under the different climate scenarios. With the physiological effects of CO_2, the negative effect of the climate change alone was partially diminished (Figure 3). Wheat yields in the Central region were most vulnerable to future climate changes under the GFDL and the UKMO scenarios: yield reductions were near 24 and 46%. Under the GISS scenario, losses were projected to be about 43% for the Central-South region. For the most part, the South region appeared to be less vulnerable to the climate changes, with projected average losses in yield of 22%.

Maize. All GCM scenarios projected reductions in maize biomass production, grain yield, and season length, when compared to the present climate (Tables 7 and 9 and Figure 3). Decreases in season length under the climate change scenarios varied in each region, but they averaged about 15%.

The effect of climate change on crop season length and yield was a consequence of the increases in temperature projected by the GCMs. With the physiological effects of CO_2, the projected reductions in grain yield were diminished in comparison with the yields projected under the climate change scenarios alone. Under the GFDL and the UKMO scenarios with physiological CO_2 effects, the largest decreases in yield were in the South and the Central-South regions, ranging from 11% to 20%. Under the GISS scenario, the largest reductions were found in the North region (24%).

Soybean. In general, reductions in soybean biomass and grain yield were smaller than reductions in wheat and maize projected by the GCM scenarios (Tables 7 and 10 and Figure 3). With the GCM scenarios alone, there were soybean yield and biomass reductions in almost all of the regions. Mean reductions in grain yield varied from 5% to 31% (Table 7). With the physiological effects of CO_2 on yield, the SOYGRO model simulated significant yield increases: gains averaged 22% (Table 7). The results were consistent in all regions except the Northeast where yields decreased, even when the physiological effects of CO_2 were considered (Figure 4). A slightly shorter crop season length was simulated for soybean with all GCM scenarios for the sites in the South and the Central-South regions, but this effect was very small in comparison with the shorter crop season of wheat and maize under the same conditions.

These results agree with the aforementioned sensitivity analysis and indicate that soybean production in Brazil might not be as adversely affected by climate change as wheat or maize. The more positive results projected for soybean, however, were dependent on the beneficial physiological effects of CO_2 concentration.

National Grain Yields

The effects of the climatic changes on national crop production wheat, maize, and soybean yields were estimated by aggregating the regional results weighted by cultivated area. For example, the yield changes from a region that represents 50% of the national cultivated wheat area was given a weight of 50% in the national results (Table 11). All results reported include the beneficial physiological CO_2 effects on crop yield. Crop management, technology, and distribution of cultivated land were assumed to be constant, although these will change in the future.

Wheat is currently grown on 3.6 million ha in Brazil. Using the changes in regional wheat yields under the GCM scenarios and the contribution of these regions to the national wheat area, we estimate that the possible impact of climate change scenarios on national wheat production would be large (reductions of 33%, 18% and 34% under the GISS, GFDL, and UKMO scenarios, respectively). Although significant reductions in wheat yield are projected for the Central region, the impact of these regional reductions on the national yield is not highly significant because of the small acreage that is cultivated (1%) in that region. Maize is the most widely cultivated crop in Brazil, now cultivated on about 22 million ha. National maize yields were reduced 11%, 11%, and 16% under the GISS, GFDL, and UKMO scenarios, respectively.

Soybean is the second most widely cultivated crop in Brazil, occupying about 15.5 million ha. Only in the Northeast region under UKMO were losses projected for simulated soybean yields. In all other regions, soybean yields increased under the conditions of climate change, as simulated in this study. The estimated changes in national yields under the GISS, GFDL, and UKMO climate scenarios are +26%, +23%, and +18%, respectively. The 17% decrease in yield under the UKMO scenario in the Northeast region did not have a large impact on the national yield estimate since that region only contributes about 1% of the total soybean cultivation area in the country.

Transient Results

Wheat and maize yields and season lengths were simulated under the GISS transient scenarios in Passo Fundo (South region) (Figure 4). Linear increases in temperature were projected from 1990 to the year 2050. Wheat yield and season length decreased under GISS transient scenarios; the rate of reduction decreased after the year 2030. In contrast to wheat, the simulated maize grain yield increased until the year 2030 with the physiological effects of CO_2 (460 ppm) and then decreased. The length of the maize crop season decreased linearly over this same period.

Adaptation Strategies to Climate Change

Wheat and maize development and yield were affected by the climate changes projected by the GCM scenarios, and the changes were largest under the UKMO scenario. This part of the study aims to define possible alternatives that would compensate for the negative impact of the climate changes on wheat and maize. The simulation was carried out in Passo Fundo because of the careful calibration and validation of the CERES model at that site. Additional and preliminary strategies were also simulated for maize and soybeans in

Petrolina in the Northeast region, a vulnerable area to climate change.

Crop management alternatives (irrigation, new cultivars, and nitrogen management) were evaluated as possible adaptation strategies for wheat under the climate change conditions (Figure 13). The UKMO scenario was run at Passo Fundo with various combinations of wheat genetic coefficients and management practices. When tested separately, the adaptation strategies failed to improve yields significantly. Only when several high-cost adaptation strategies (irrigation and nitrogen management) were combined were wheat yields restored to 90% of their baseline values.

The changes in maize crop management that were tested (irrigation and changes in planting date) did not compensate for the decrease in maize yield under the UKMO scenario in Passo Fundo (South region). The crop growth model can test the performance of a hypothetical new cultivar under the conditions of climate change. The development of a hypothetical new cultivar with a different P5 "genetic coefficient" would improve maize yield production under the climate change scenarios. The P5 coefficient is the growing degree days from flowering to maturity (Ritchie *et al.* 1989). A higher P5 coefficient extends the simulated duration of the grain-filling period under warmer climate conditions. An increase of 20% in the actual value of the P5 coefficient compensated for the projected grain yield losses caused by the UKMO scenario at Passo Fundo. The feasibility of breeding for extended grain-filling periods should be further explored by crop geneticists.

At Petrolina, an improvement in the crop management practices such as irrigation and increased nitrogen fertilization could compensate for the yield decreases under the UKMO scenario. However it is important to notice that in this case, base yields also increase substantially. At this site, irrigation also increases soybean yields under the base case and the UKMO scenario and would fully compensate for any negative impact of climate change on soybean yields in the vulnerable Northeast region.

CONCLUSIONS

Projected climate change with the physiological effects of CO_2 reduced modeled wheat and maize yields significantly, while soybean yields increased. Most of the wheat and maize yield losses were associated with a significant shortening of the growing season due to increased temperatures, which allowed less time for biomass accumulation. In contrast, soybean growing season was not reduced significantly, because soybean responds to temperature either positively or negatively depending on phenological stage. The variable season length response probably contributed to the more positive soybean yield responses to climate change. Soybean temperature responses at a wide range of sites require further study.

Adaptation strategies such as irrigation, changes in planting date, and increased nitrogen fertilization helped improve wheat and maize yields, but not enough to compensate for all of the losses projected for the climate change scenarios. The development of a hypothetical new, more heat-resistant cultivar showed promising results, although the feasibility of this strategy still needs to be tested through breeding programs.

These results imply substantial reduction in the national production of wheat and maize and increases in the production of soybean under climate change. Differential impacts on the country's regions are projected, with the Northeast especially vulnerable to maize and soybean yield decreases and the Central region vulnerable to wheat yield declines.

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Table 1. Characteristics of sites selected for the simulation study.

Site	Lat.	Long.	Elevation (m)	Weather Data	Soil
Pelotas, RS	31.47S	52.29W	13	52/80	Hapludult
Passo Fundo, RS	28.15S	52.24W	667	51/80	Haplorthox
Sao Borja, RS	28.39S	56.00W	99	56/80	Paleudalf
Vacaria, RS	28.33S	50.42W	955	51/80	Haplohumox
Ponta Grossa, PR	25.06S	50.10W	868	54/80	Haplorthox
Londrina, PR	23.19S	51.19W	566	58/80	Haplorthox
Campinas, SP	22.53S	47.06W	669	51/80	Eutrorthox
Campo Grande, MS	20.27S	54.37W	530	74/80	Haplorthox
Sete Lagoas, MG	19.28S	44.15W	732	60/80	Haplusthox
Cruz das Almas, BA	12.40S	39.06W	226	71/80	Haplorthox
Petrolina, PE	9.23S	40.30W	366	65/80	Eutrusthox
Manaus, AM	3.08S	60.01W	48	71/80	Acrorthox
Belem, PA	1.28S	48.27W	24	67/80	Haplorthox

Table 2. Observed baseline climate at selected sites.

TEMPERATURE (°C)	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
Pelotas	22.9	18.7	13.5	17.5	18.2
Passo Fundo	22.6	18.4	14.2	18.4	18.4
Sao Borja	25.0	20.5	15.5	20.0	20.2
Vacaria	20.2	15.9	11.8	15.9	15.9
Ponta Grossa	22.0	18.6	15.1	18.8	18.6
Londrina	24.3	21.4	18.0	21.8	21.4
Campinas	24.0	21.6	18.9	22.1	21.6
Campo Grande	25.3	23.3	21.6	24.0	23.6
Sete Lagoas	23.4	21.8	19.1	22.6	21.7
Cruz das Almas	25.9	24.9	22.1	24.2	24.3
Petrolina	26.6	25.6	24.0	27.0	25.8
Manaus	26.6	26.6	26.6	27.6	26.8
Belem	27.0	27.0	27.2	27.4	27.2

PRECIPITATION (mm)	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
Pelotas	297	264	366	315	1,242
Passo Fundo	474	348	441	501	1,764
Sao Borja	348	372	306	399	1,425
Vacaria	384	291	369	408	1,452
Ponta Grossa	480	309	276	381	1,446
Londrina	627	324	213	420	1,584
Campinas	648	267	114	330	1,359
Campo Grande	678	390	123	507	1,698
Sete Lagoas	738	201	33	393	1,365
Cruz das Almas	273	342	303	243	1,161
Petrolina	255	255	24	69	603
Manaus	708	903	348	420	2,379
Belem	960	1101	450	366	2,877

SOLAR RAD. (MJ/m^2)	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
Pelotas	18.4	11.2	8.0	14.6	13.0
Passo Fundo	17.7	11.6	8.6	14.7	13.1
Sao Borja	17.8	11.5	8.2	15.0	13.1
Vacaria	17.1	11.4	8.5	14.4	12.8
Ponta Grossa	15.1	11.4	9.6	13.7	12.4
Londrina	16.3	13.3	11.3	15.2	14.0
Campinas	16.1	13.4	11.6	15.3	14.1
Campo Grande	16.2	13.7	12.1	15.6	14.4
Sete Lagoas	15.9	14.5	13.6	15.0	14.7
Cruz das Almas	15.7	13.2	11.3	14.3	13.6
Petrolina	16.3	14.3	13.4	17.2	15.3
Manaus	11.7	11.2	13.7	14.3	12.7
Belem	13.1	12.7	15.6	16.2	14.4

Table 3. Annual GCM scenario changes in temperature, precipitation, and solar radiation at selected sites.

	CHANGES IN TEMPERATURE (°C)			PRECIPITATION RATIOS			SOLAR RADIATION RATIOS		
SITE	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Pelotas	4.0	4.2	4.5	1.00	1.00	1.14	1.06	1.01	1.03
Passo Fundo	4.5	3.5	6.1	0.98	1.20	1.05	1.02	0.99	1.04
Sao Borja	4.8	3.5	5.6	1.65	1.20	1.15	0.98	0.99	1.02
Vacaria	4.5	3.5	6.0	0.98	1.20	1.05	1.02	0.99	1.04
Ponta Grossa	4.5	3.1	6.0	0.98	1.21	1.05	1.02	0.99	1.04
Londrina	4.5	3.1	4.8	1.24	1.21	1.20	1.00	0.99	1.03
Campinas	4.5	3.2	4.8	1.24	1.25	1.20	1.00	0.96	1.03
Campo Grande	4.5	3.0	5.7	1.24	1.17	1.08	1.00	0.98	1.03
Sete Lagoas	4.1	4.2	6.0	1.08	1.07	1.26	1.05	0.98	1.14
Cruz das Almas	4.3	2.5	4.5	1.03	1.08	0.83	1.02	1.01	1.02
Petrolina	4.3	2.5	4.6	1.03	1.08	0.84	1.02	1.01	1.04
Manaus	3.5	2.7	3.9	1.25	1.20	0.97	1.02	1.01	1.11
Belem	4.0	2.7	3.9	1.09	1.00	0.80	1.02	1.01	1.00

Table 4. Sensitivity of the CERES-Wheat model to changes in temperature, precipitation, and CO_2 levels (330 ppm and 555 ppm CO_2). Simulated yields and season length for different regions.

SIMULATED GRAIN YIELD (t ha^{-1})

		SOUTH		C. SOUTH		CENTRAL	
Precip. Diff. (%)	Temp. Diff. (°C)	330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm
0%	+0	2.30	2.66	2.36	2.91	2.93	3.36
0%	+2	1.88	2.27	1.63	2.22	2.18	2.71
0%	+4	1.47	1.87	1.03	1.54	1.44	2.00
+20%	0	2.26	2.61	2.35	2.90	2.93	3.34
+20%	+2	1.86	2.24	1.64	2.21	2.17	2.70
+20%	+4	1.46	1.85	1.04	1.54	1.44	2.00
-20%	0	2.32	2.71	2.36	2.96	2.94	3.32
-20%	+2	1.89	2.30	1.63	2.24	2.18	2.67
-20%	+4	1.48	1.89	1.03	1.54	1.44	1.97

SIMULATED SEASON LENGTH (DAYS)*

	SOUTH	C. SOUTH	CENTRAL
Temp. Diff (°C)	330 ppm	330 ppm	330 ppm
0	124	103	100
+2	116	95	91
+4	108	89	85

*Season length changes (as simulated with the CERES-Wheat model) were affected only by temperature.

Table 5. Sensitivity of the CERES-Maize model to changes in temperature, precipitation, and CO_2 level (330 ppm and 555 ppm of CO_2). Simulated yields and season length for different regions.

SIMULATED GRAIN YIELD (t ha^{-1})

Precip. Diff. (%)	Temp. DIff. (°C)	SOUTH		C.SOUTH		N.EAST		NORTH	
		330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm
0%	0	7.78	8.49	6.66	7.05	4.87	5.44	4.39	4.36
0%	+2	7.14	7.81	6.15	6.56	4.11	4.68	3.90	3.91
0%	+4	6.31	6.90	5.36	5.75	3.49	4.14	3.42	3.43
+20%	0	7.92	8.51	6.58	6.94	5.04	5.52	4.19	3.99
+20%	+2	7.26	7.85	6.10	6.47	4.32	4.74	3.72	3.60
+20%	+4	6.41	6.95	5.33	5.70	3.67	4.18	3.28	3.19
-20%	0	7.57	8.37	6.70	7.14	4.54	5.30	4.64	4.67
-20%	+2	6.92	7.63	6.17	6.62	3.79	4.52	4.10	4.15
-20%	+4	6.11	6.70	5.35	5.78	3.16	3.98	3.55	3.62

SIMULATED SEASON LENGTH (DAYS)*

Temp. Diff. (°C)	SOUTH 330 ppm	C.SOUTH 330 ppm	N.EAST 330 ppm	NORTH 330 ppm
0	134	117	106	104
+2	118	106	98	96
+4	103	98	94	92

*Season length changes (as simulated with the CERES-Maize model) were affected only by temperature.

Table 6. Sensitivity of the SOYGRO model to changes in temperature, precipitation, and CO_2 levels (330 ppm and 555 ppm of CO_2). Simulated yields and season length for different regions.

SIMULATED GRAIN YIELD (t ha^{-1})

Prec. Diff. (%)	Temp. Diff. (°C)	SOUTH		C.SOUTH		N.EAST		NORTH	
		330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm
0%	0	2.91	3.92	3.10	4.60	3.26	4.08	2.17	3.08
0%	+2	2.99	4.14	2.83	4.36	3.06	3.81	1.94	2.93
0%	+4	2.79	3.77	2.35	3.88	2.79	3.45	1.79	2.82
+20%	0	3.08	4.26	3.29	4.71	3.36	4.18	2.21	3.10
+20%	+2	3.18	4.17	2.98	4.48	3.18	3.92	2.00	2.96
+20%	+4	3.00	3.95	2.46	4.01	2.92	3.60	1.85	2.88
-20%	0	2.63	3.68	2.90	4.43	3.06	3.86	2.10	3.05
-20%	+2	2.67	3.72	2.65	4.18	2.84	3.56	1.88	2.89
-20%	+4	2.47	3.46	2.16	3.70	2.54	3.19	1.71	2.76

SIMULATED SEASON LENGTH (DAYS)*

Temp. Diff. (°C)	SOUTH		C.SOUTH		N.EAST		NORTH	
(°C)	330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm	330 ppm	555 ppm
0	143		125		110		91	
+2	137		118		112		90	
+4	134		114		116		92	

*Season length changes (as simulated with the SOYGRO model) were affected only by temperature.

Table 7. Effects of GCM climate change scenarios on wheat, maize, and soybean yields in selected sites.

	Simulated Yield (t ha^{-1})							
	Climate Scenario Alone				Climate Scenario + Physiological CO_2 Effects			
Site	BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO
				WHEAT				
Pelotas	2.54	1.73	1.52	1.62	2.85	2.14	1.94	2.05
Passo Fundo	1.99	1.21	1.25	0.91	2.32	1.62	1.65	1.32
Vacaria	2.66	1.89	1.94	1.69	2.89	2.18	2.22	2.02
Sao Borja	2.01	0.93	1.21	1.01	2.54	1.33	1.62	1.44
Ponta Grossa	2.28	1.50	1.52	1.17	2.70	1.91	1.88	1.57
Londrina	2.02	0.93	1.35	0.95	2.42	1.33	1.78	1.34
Campinas (*)	2.93	1.14	1.57	1.17	3.52	1.72	2.24	1.74
Campo Grande (*)	2.12	0.59	1.23	0.76	2.79	1.00	1.84	1.23
Sete Lagoas (*)	2.93	1.51	1.72	1.10	3.36	2.04	2.24	1.57
				MAIZE				
Pelotas	6.26	5.01	3.93	5.01	7.58	6.06	5.12	6.02
Passo Fundo	8.17	6.83	6.91	5.85	8.93	7.42	7.54	6.64
Vacaria	9.20	7.49	7.24	6.93	9.64	7.92	7.68	7.39
Sao Borja	7.60	5.54	5.24	4.21	8.25	5.99	5.94	5.10
Ponta Grossa	7.64	5.88	6.08	5.29	8.07	6.26	6.42	5.72
Londrina	7.36	6.21	5.78	5.76	7.77	6.59	6.10	6.17
Campinas	7.16	6.34	5.93	5.78	7.56	6.72	6.33	6.18
Campo Grande	6.72	5.34	5.83	4.28	7.08	5.63	6.17	4.56
Sete Lagoas	5.41	4.46	4.66	4.67	5.79	4.92	5.12	5.05
Cruz das Almas	5.10	3.77	3.94	4.07	5.64	4.49	4.92	4.73
Petrolina	4.64	2.59	3.09	2.81	5.25	3.06	3.73	3.36
Belem	4.00	3.02	3.45	3.64	3.65	2.54	3.94	3.65
Manaus	4.79	3.82	3.92	3.96	5.06	4.10	4.23	4.30
				SOYBEAN				
Pelotas	2.84	2.20	2.12	3.66	2.95	2.99	3.35	3.30
Passo Fundo	3.03	2.38	2.39	1.71	4.38	3.67	3.76	2.82
Vacaria	2.94	3.68	3.52	3.65	3.78	4.64	4.48	4.76
Sao Borja	2.48	2.36	1.83	1.55	3.52	3.23	2.73	2.36
Ponta Grossa	3.28	3.24	3.23	2.76	4.28	4.38	4.37	4.18
Londrina	2.16	1.73	1.60	0.94	4.64	4.12	4.01	3.76
Campinas	3.77	3.44	3.10	3.22	4.80	4.36	4.07	4.20
Campo Grande	3.43	2.97	2.91	1.76	4.92	4.41	4.29	3.63
Sete Lagoas	3.05	2.53	2.62	2.66	4.05	3.62	3.50	3.57
Cruz das Almas	3.01	2.57	2.63	2.33	3.74	3.19	3.28	2.93
Petrolina	3.52	3.18	2.83	2.51	4.42	3.44	3.99	3.17
Belem	1.87	2.38	3.17	2.36	3.14	3.16	3.02	3.14
Manaus	1.89	1.49	1.50	1.19	3.01	2.84	2.80	2.55

SOUTH REGION: Pelotas, Passo Fundo, Sao Borja, Vacaria, and Ponta Grossa. CENTRAL SOUTH REGION: Londrina, Campinas, Campo Grande, and Sete Lagoas (S.L. in the CENTRAL region for wheat). NORTHEAST REGION: Cruz das Almas and Petrolina. NORTH REGION: Manaus and Belem. (*) Irrigated simulation.

Table 8. Effect of the GCM climate change scenarios on simulated wheat.

Region	Climate Scenario Alone			Climate Scenario + Physiological CO_2 Effects		
	South	C.South	Central	South	C.South	Central
BIOMASS (t ha^{-1})						
BASE	8.82	7.30	7.72	10.30	9.04	8.76
GISS	6.18	3.01	4.21	7.87	4.55	5.63
GFDL	6.33	4.51	4.74	7.96	6.37	6.10
UKMO	5.50	3.28	3.22	7.27	4.89	4.57
GRAIN YIELD (t ha^{-1})						
BASE	2.30	2.36	2.93	2.66	2.91	3.36
GISS	1.43	0.89	1.51	1.84	1.35	2.04
GFDL	1.49	1.38	1.72	1.86	1.95	2.24
UKMO	1.28	0.96	1.10	1.68	1.43	1.57
SEASON LENGTH (Days)						
BASE	124	103	100	124	103	100
GISS	107	87	85	107	87	85
GFDL	109	93	89	109	93	89
UKMO	104	87	82	104	87	82
EVAPOTRANSPIRATION (mm)						
BASE	274	264	303	248	233	260
GISS	247	248	294	227	219	253
GFDL	243	250	277	222	224	238
UKMO	246	252	305	227	222	259

Table 9. Effect of the GCM climate change scenarios on simulated maize.

	Climate Scenario Alone				Climate Scenario + Physiological CO_2 Effects			
Region	South	CSouth	NEast	North	South	CSouth	NEast	North
BIOMASS (t ha^{-1})								
BASE	14.03	13.32	10.64	10.82	14.73	13.72	11.50	10.70
GISS	12.54	11.85	7.62	8.78	13.27	12.32	8.75	8.60
GFDL	12.06	12.03	7.86	8.52	12.90	12.46	9.34	9.33
UKMO	11.60	11.42	8.28	9.72	12.63	11.94	9.34	10.17
GRAIN YIELD (t ha^{-1})								
BASE	7.78	6.66	4.87	4.39	8.50	7.05	5.45	4.36
GISS	6.15	5.59	3.16	3.42	6.73	5.96	3.78	3.32
GFDL	5.88	5.55	3.52	3.68	6.54	5.93	4.32	4.08
UKMO	5.46	5.12	3.44	3.80	6.18	5.49	4.04	3.97
SEASON LENGTH (days)								
BASE	134	117	106	104	134	117	106	104
GISS	105	100	88	92	107	100	88	92
GFDL	109	101	94	94	109	101	94	94
UKMO	101	97	90	92	101	97	90	92
EVAPOTRANSPIRATION (mm)								
BASE	448	414	316	305	377	347	268	254
GISS	407	378	258	306	347	318	264	256
GFDL	394	378	268	294	339	318	233	244
UKMO	405	400	381	297	353	338	244	249

Table 10. Effect of the GCM climate change scenarios on simulated soybean.

Region	Climate Scenario Alone				Climate Scenario + Physiological CO_2 Effects			
	South	CSouth	NEast	North	South	CSouth	NEast	North
BIOMASS (t ha^{-1})								
BASE	6.53	5.69	6.06	3.86	7.77	7.02	6.17	4.82
GISS	5.89	5.04	5.18	3.37	8.19	7.80	6.76	5.21
GFDL	5.44	4.74	5.33	3.33	7.72	7.52	6.91	5.12
UKMO	5.08	3.92	4.28	3.08	7.41	7.05	5.81	4.95
YIELD (t ha^{-1})								
BASE	2.92	3.10	3.20	2.17	3.63	3.70	3.56	2.76
GISS	2.83	2.71	2.60	1.94	3.84	4.13	3.32	3.00
GFDL	2.70	2.55	2.75	1.90	3.74	3.95	3.47	2.91
UKMO	2.44	2.02	2.01	1.78	3.48	3.63	2.80	2.85
SEASON LENGTH (days)								
BASE	143	123	109	91	135	121	110	92
GISS	133	119	110	92	133	121	110	92
GFDL	135	120	109	90	135	122	109	90
UKMO	133	114	110	92	133	122	110	92
EVAPOTRANSP. (mm)								
BASE	462	432	381	302	454	446	334	324
GISS	495	453	433	345	494	462	432	330
GFDL	453	442	400	324	454	446	396	310
UKMO	496	462	407	336	502	500	408	322

Table 11. Aggregated yield changes under GCM climate change scenarios. Results include the physiological effects of CO_2 on yield.

Region	Crop	Production (t x 1000)	Simulated Yield Change (%) GISS	GFDL	UKMO
SOUTH	WHEAT	1,573	-21	-19	-27
CENTRAL-SOUTH	WHEAT	2,028	-43	-17	-39
CENTRAL	WHEAT	24	-30	-24	-46
NATIONAL	WHEAT	3,625	-33	-18	-34
SOUTH	MAIZE	6,695	-13	-16	-20
CENTRAL-SOUTH	MAIZE	11,131	-10	-11	-18
CENTRAL	MAIZE	2,495	**	**	**
NORTHEAST	MAIZE	1,126	-22	-11	-17
NORTH	MAIZE	330	-24	-7	-10
NATIONAL	MAIZE	21,778	-11	-11	-16
SOUTH	SOYBEAN	6,408	30	25	20
CENTRAL-SOUTH	SOYBEAN	6,943	32	28	22
CENTRAL	SOYBEAN	2,135	**	**	**
NORTHEAST	SOYBEAN	96	9	12	-6
NORTH	SOYBEAN	0	38	34	31
NATIONAL	SOYBEAN	15,582	30	23	18

Source of Production data: IBGE and Bank of Brazil

(**) not simulated

Table 12. Adaptation strategies.

(A) Effect of changes in planting date, irrigation, and nitrogen stress on simulated maize and soybean yields. The climate change scenario simulations include the physiological effects of CO_2 on yield.

Site	Crop	Strategy	Simulated Yield (t ha^{-1}) BASE	UKMO	Yield Change from Base (%)
Passo Fundo	Maize	Oct 15, rainfed(*)	8.17	6.69	-18
		Sep 15, rainfed		6.54	-20
		Nov 15, rainfed		5.75	-30
		Dec 15, rainfed		5.72	-30
		Jan 15, rainfed		6.62	-19
		Oct 15, irrig.	8.48	6.79	-17
Petrolina	Maize	Rainfed, N stress(*)	4.64	3.98	-14
		Rainfed, N	6.72	5.34	15
		Irrig., N stress	5.37	5.10	10
		Irrig., N	7.05	6.37	37
Petrolina	Soybean	Rainfed	3.39	2.64	-22
		Irrig.	3.73	4.19	24

(*) current practice
N stress: 80 Kg N/Ha
N: N for maximum yield (N balance off in the model)

(B) Sensitivity of the CERES-Maize model to changes in the P5 coefficient of the cultivar PIO 3230. Scenario simulations include the physiological effects of CO_2 on yield.

Site	Crop	Strategy	Simulated Yield (T/Ha) Base	UKMO	Yield Change from Base (%)
Passo Fundo	Maize	Change in P5			
		P5=995*	8.18	6.86	-16
		P5=795		5.21	-36
		P5=1195		8.51	4
		P5=1395		10.09	23

(*) calibrated coefficient for the cultivar PIO 3230 in Passo Fundo.

Appendix A. Cultivars and crop management data used to run the crop models.

Crop	Region	Site	Cultivar	Plant Pop. (pl/m^2	Planting Date
WHEAT	SOUTH	PELOTAS	BR 14	330	JUN. 15
	SOUTH	PASSO FUNDO	BR 14	330	JUN. 15
	SOUTH	SAO BORJA	BR 14	330	MAY. 31
	SOUTH	VACARIA	BR 14	330	JUL. 15
	SOUTH	PONTA GROSSA	BR 14	330	JUN. 15
	C.SOUTH	LONDRINA	BR 14	330	APR. 15
	C.SOUTH	CAMPINAS	ANZA*	350	APR. 30*
	C.SOUTH	CAMPO GRANDE	BR 14/ANZA*	350	APR.30*
	CENTRAL	SETE LAGOAS	ANZA*	350	APR. 30*
MAIZE	SOUTH	PELOTAS	PIO-3230	5	OCT. 15
	SOUTH	PASSO FUNDO	PIO-3230	5	OCT. 15
	SOUTH	SAO BORJA	PIO-3230	5	OCT. 15
	SOUTH	VACARIA	PIO-3230	5	NOV. 15
	SOUTH	PONTA GROSSA	PIO-3230	5	OCT. 15
	C.SOUTH	LONDRINA	PIO-3230	5	OCT. 15
	C.SOUTH	CAMPINAS	PIO-3230	5	OCT. 15
	C.SOUTH	CAMPO GRANDE	PIO-3230	5	OCT. 30
	C.SOUTH	SETE LAGOAS	PIO-3230	5	OCT. 30
	N.EAST	CRUZ D.ALMAS	SUWAN-1	5	OCT. 15
	N.EAST	PETROLINA	SUWAN-1	5	OCT. 15
	NORTH	MANAUS	SUWAN-1	5	NOV. 15
	NORTH	BELEM	SUWAN-1	5	NOV. 15
SOYBEAN	SOUTH	PELOTAS	DAVIS	40	NOV. 15
	SOUTH	PASSO FUNDO	DAVIS	40	OCT. 15
	SOUTH	SAO BORJA	DAVIS	40	NOV. 15
	SOUTH	VACARIA	DAVIS	40	NOV. 15
	SOUTH	PONTA GROSSA	DAVIS	40	NOV. 15

C.SOUTH	LONDRINA	DAVIS	40	NOV. 15
C.SOUTH	CAMPINAS	DAVIS	40	NOV. 15
C.SOUTH	CAMPO GRANDE	DAVIS	40	NOV. 15
C.SOUTH	SETE LAGOAS	DAVIS	40	OCT. 15
N.EAST	CRUZ D.ALMAS	VICOJA	40	NOV. 30
N.EAST	PETROLINA	VICOJA	40	NOV. 30
NORTH	MANAUS	JUPITER	40	NOV. 30
NORTH	BELEM	JUPITER	40	NOV. 30

*Irrigated. Others: rainfed.

Local cultivars: BR 14: P1V=1.9; P1D=1.5; P5=6.0; G1=3.2; G2=0.6; G3=3.9.
PIO-3230: P1=220; P2=0.85; P5=995; G2=720; G3=5200.

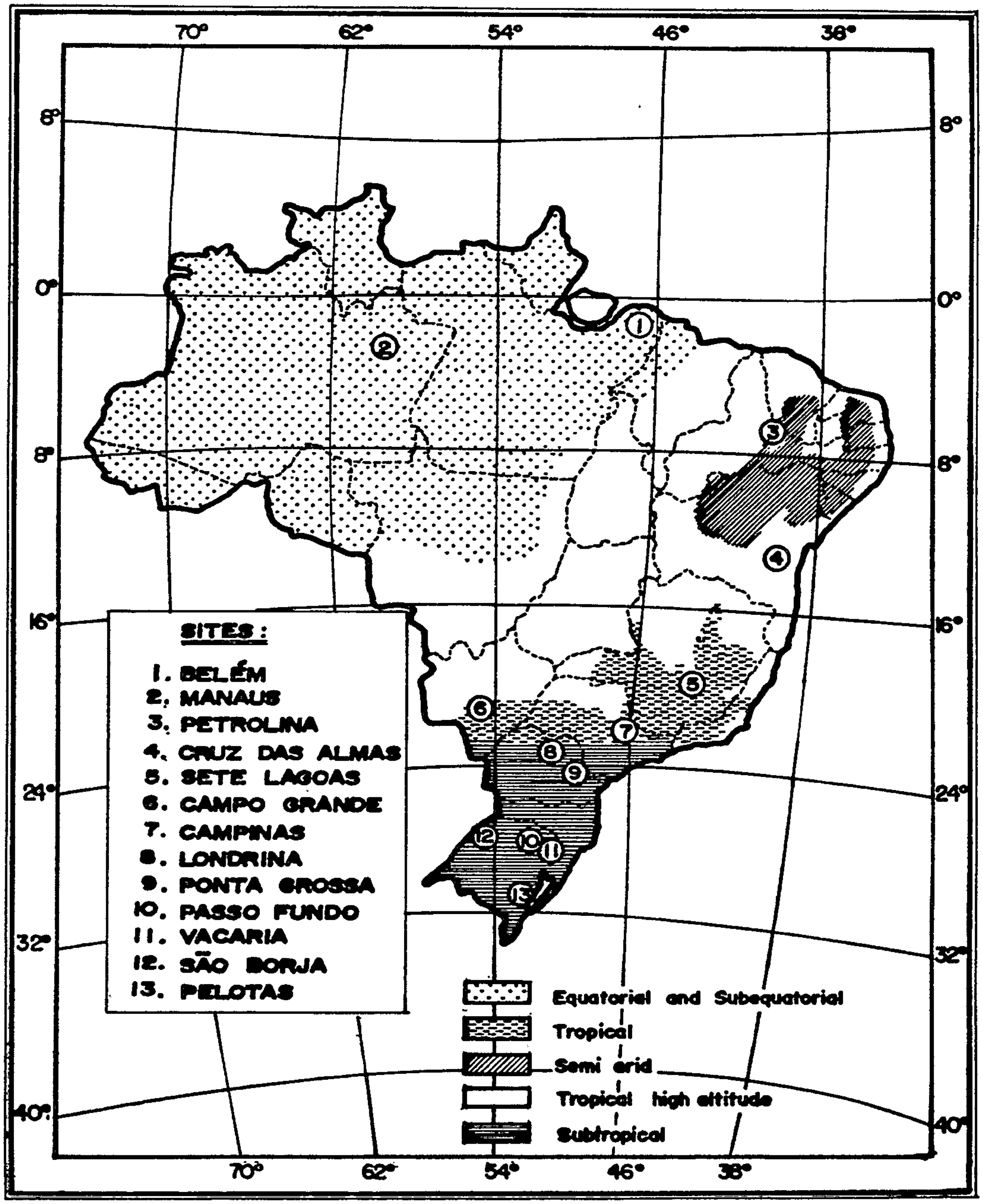

Figure 1a. Map of Brazil; climatic regions and sites selected for the study.

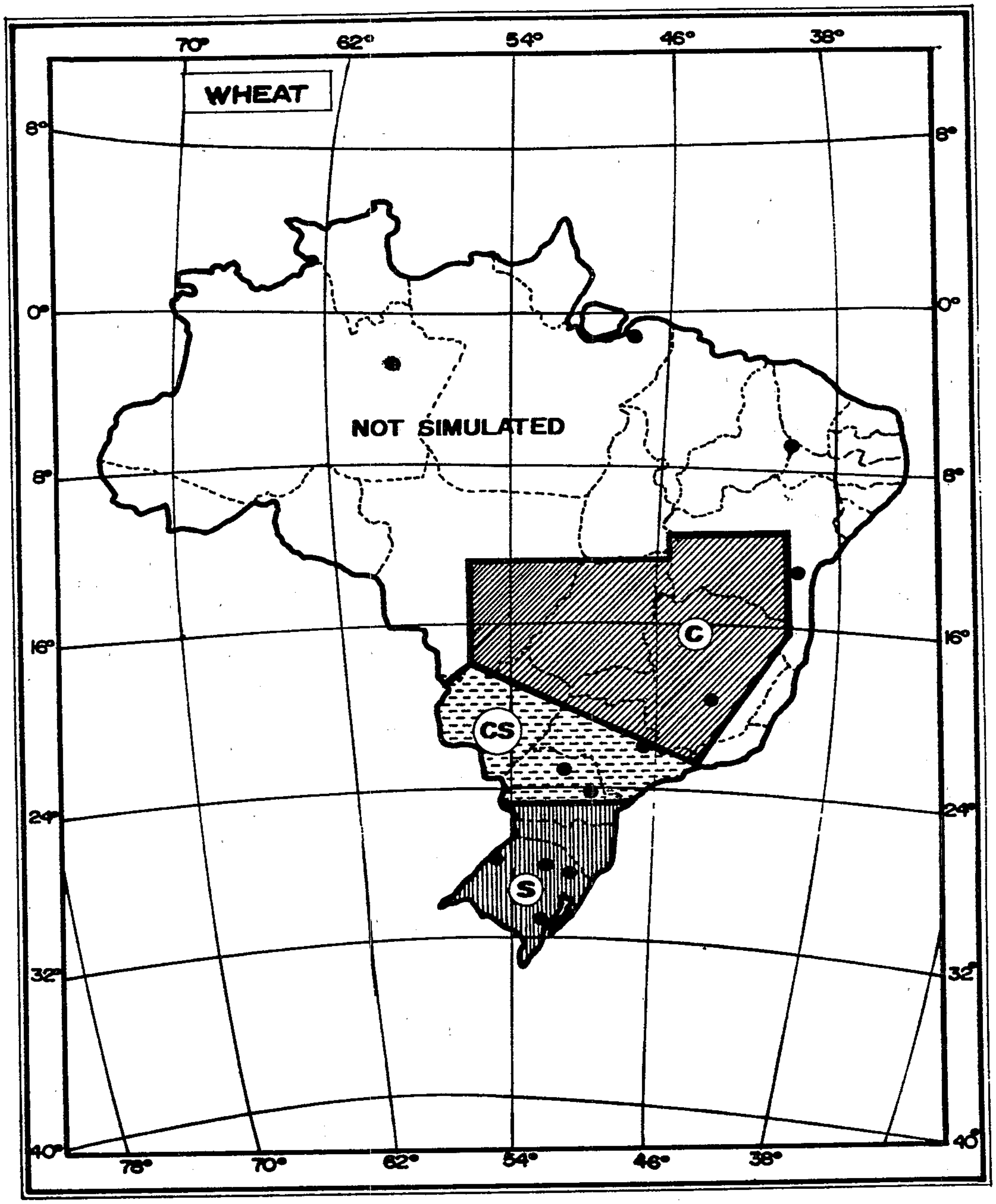

Figure 1b. Wheat agroecological regions; C=Central, CS=Central-South, S=South.

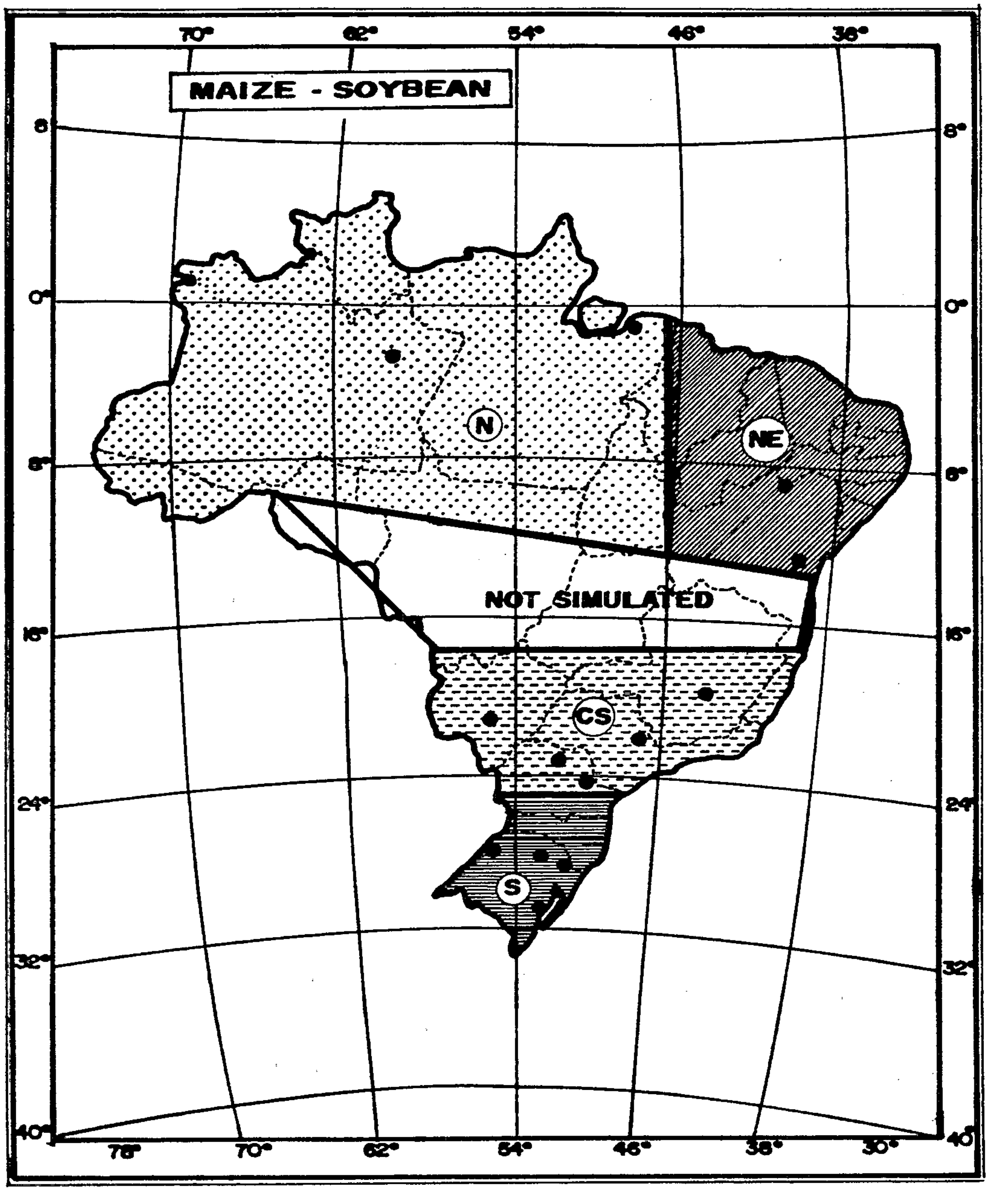

Figure 1c. Maize and soybean agroecological regions; N=North, NE=Northeast, CS=Central-South, S=South.

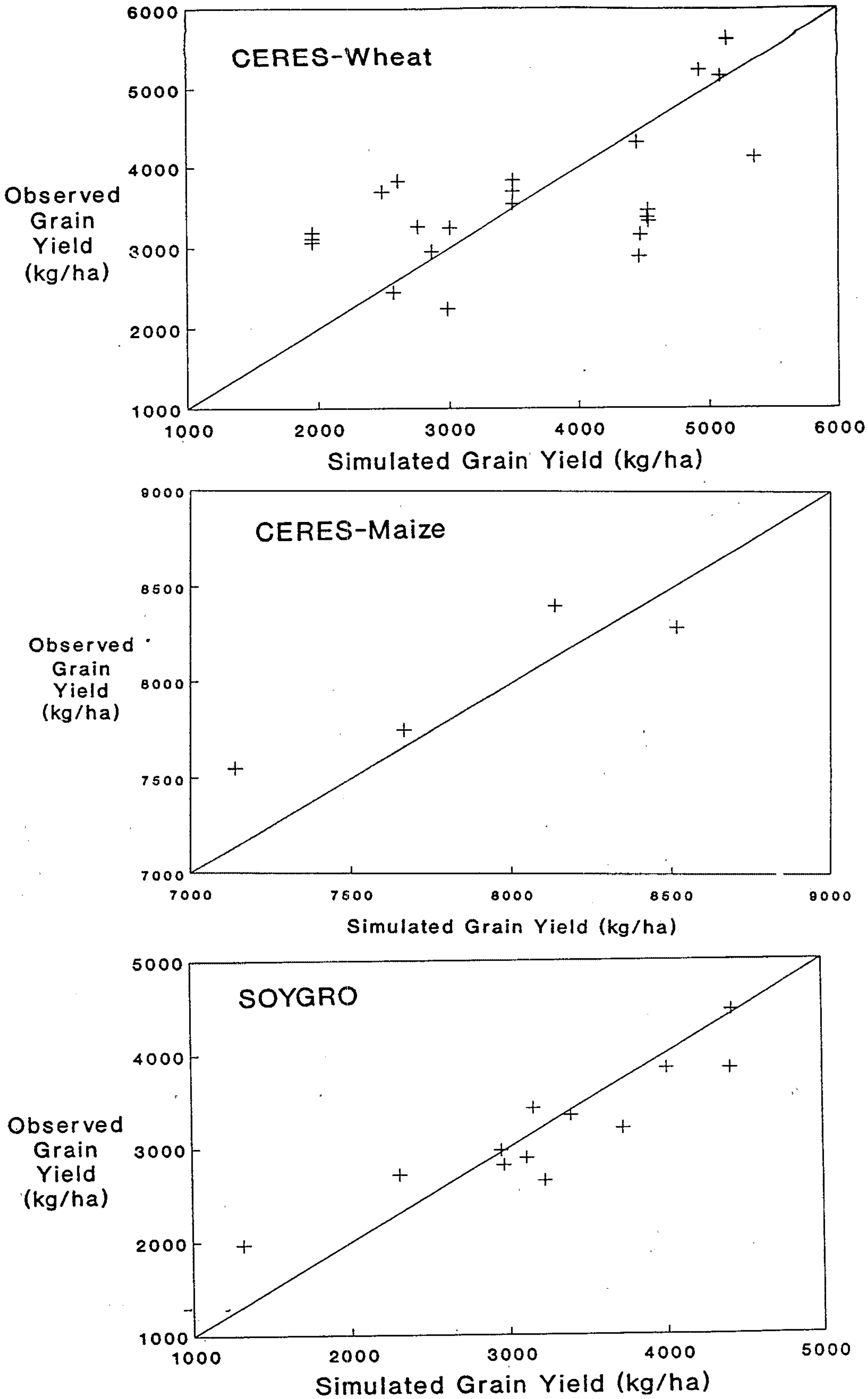

Figure 2. Observed and simulated grain yields (kg ha^{-1}) using the CERES-Wheat (Siqueira 1991), CERES-Maize (adapted from Matzenauer et al. 1988), and SOYGRO (Siqueira and Berg 1991) at Rio Grande do Sul.

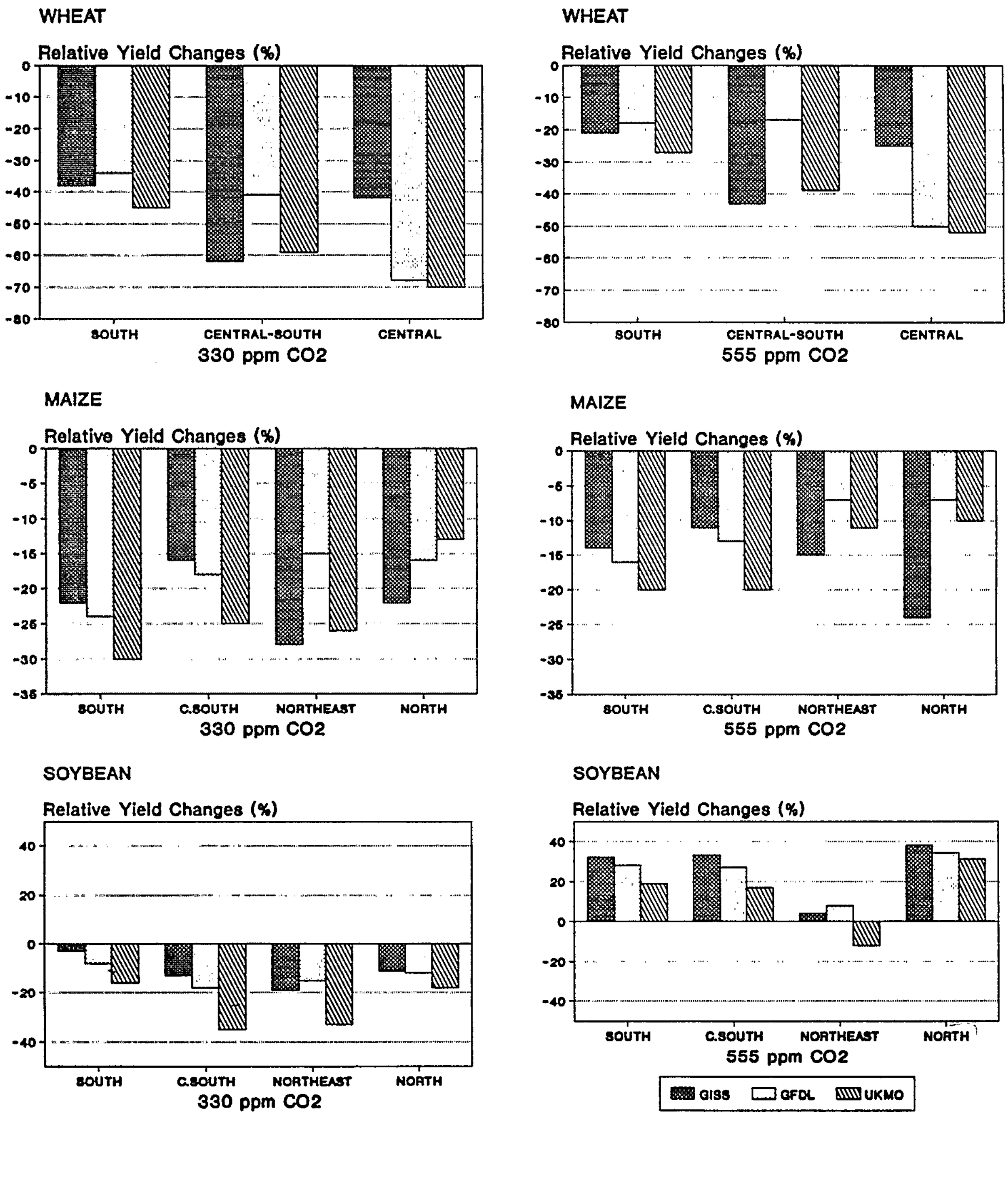

Figure 3. Regional yield changes for wheat, maize, and soybean under GCM climate change scenarios.

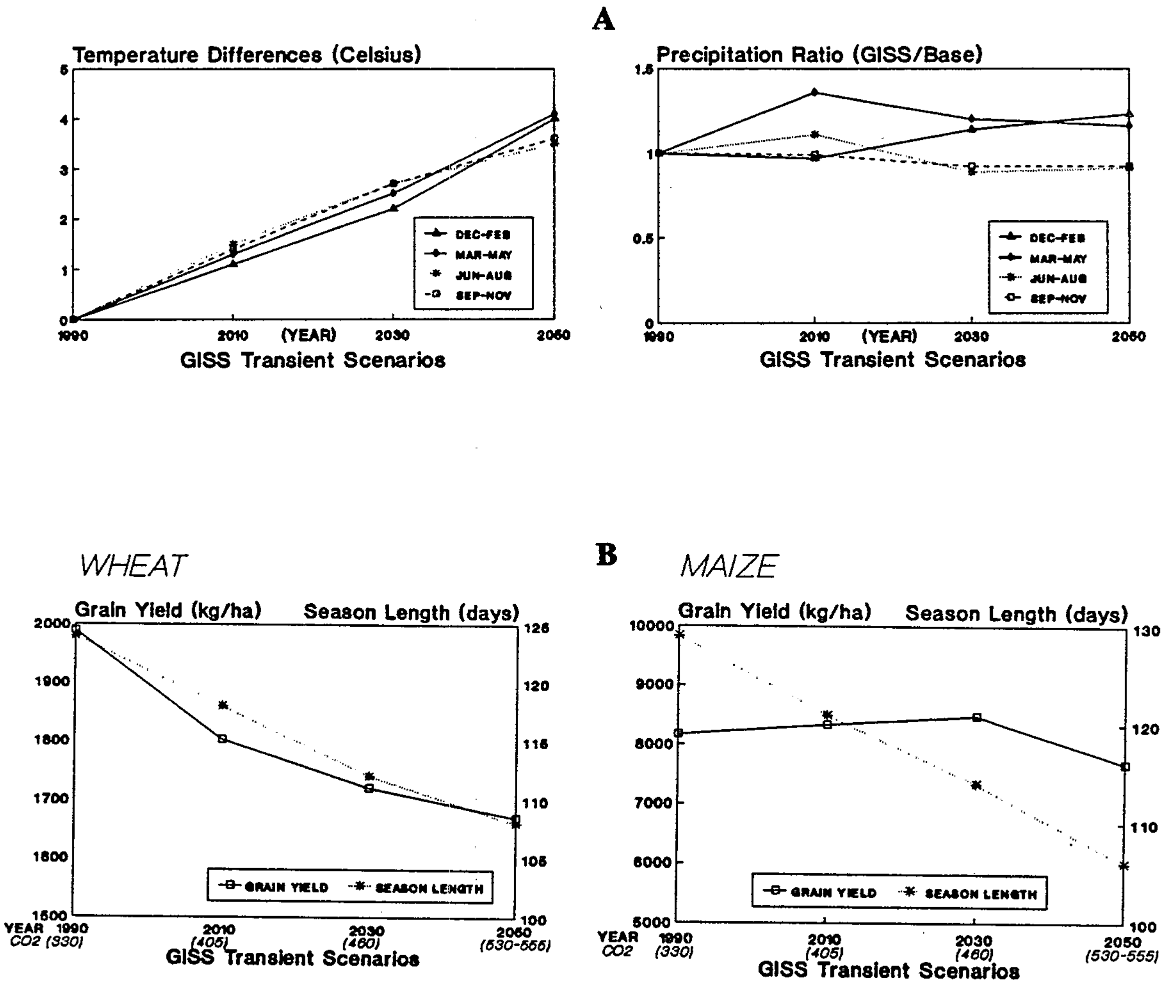

Figure 4. (A) Temperature and precipitation changes with the GISS transient scenarios at Passo Fundo. (B) Wheat and maize yield and season length under the GISS transient scenarios for Passo Fundo.

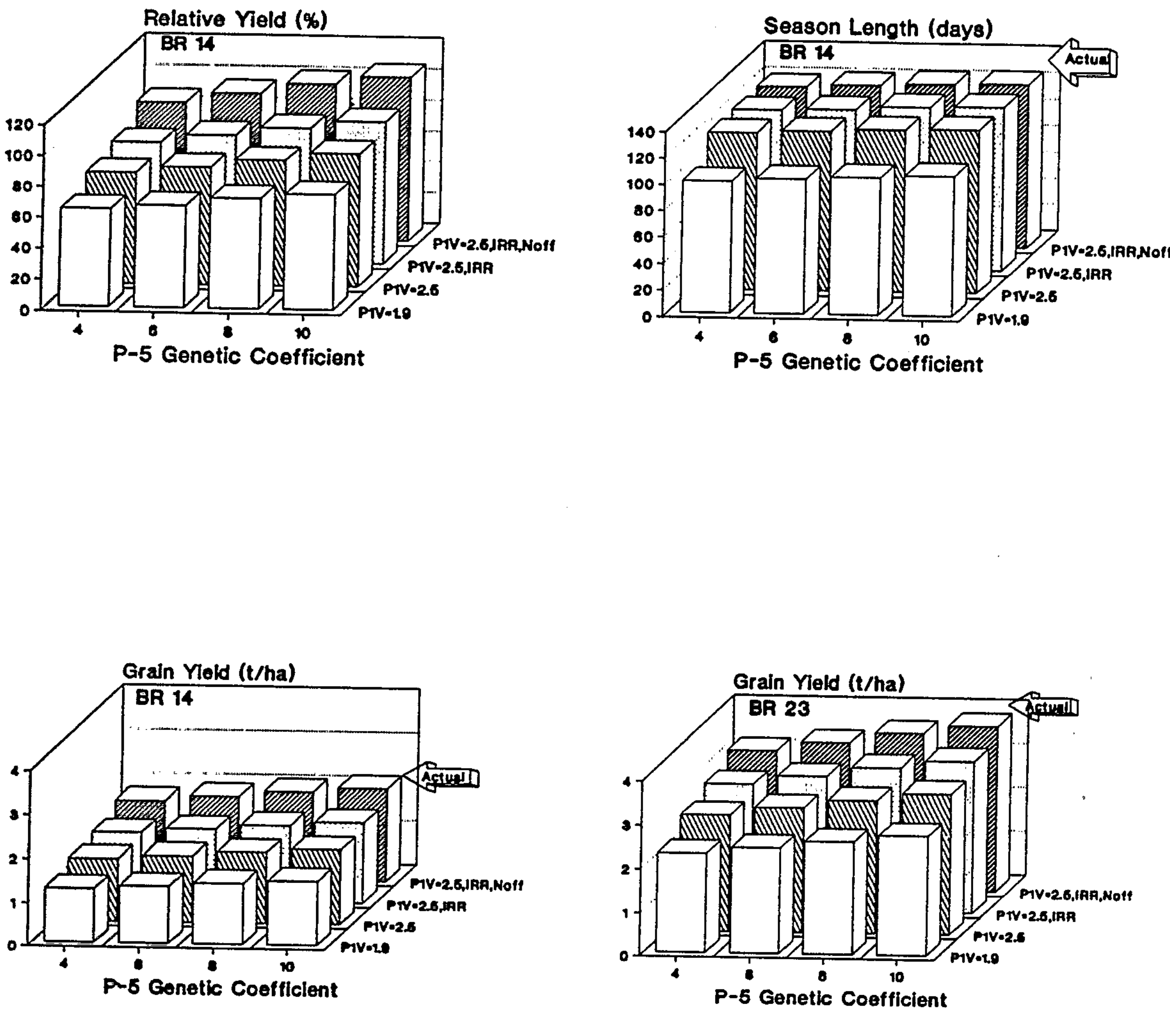

Figure 5. Adaptation studies for two cultivars of wheat (BR 14 and BR 23) in Passo Fundo to the UKMO climate change scenario. The results include the physiological CO_2 effects. Changes in the genetic coefficients and crop management. IRR: Irrigation; Noff: full nitrogen fertilization.

IMPACTS OF GLOBAL CLIMATE CHANGE ON MAIZE PRODUCTION IN ARGENTINA

O. E. Sala and J.M. Paruelo

Universidad de Buenos Aires
Buenos Aires, Argentina

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SUMMARY

Climate change is predicted by three GCMs to increase temperature and precipitation in the Rolling Pampa. These climatic changes may decrease maize yields, if all other variables remain constant. The simulation results suggest that decreases in maize yields may be offset by (1) changing the sowing date of current maize varieties, or (2) using hybrids more adapted to the climate change conditions. However, at the warmer boundaries of the Pampa, it is unlikely that decreases in maize yields could be completely offset by changes in management practices. Under climate change conditions, maize production may also be constrained in the northern edge of its current distribution due to extreme high temperatures. At the same time, maize production could expand into areas to the south that are currently limited by frost.

INTRODUCTION

Agricultural Systems in Argentina

The Pampa region (Figure 1) covers approximately 34 million hectares of agricultural land (Hall et al. 1991). One-third of the area is used to grow grain crops; the rest, which is comprised of meadows and natural grasslands, is used to fatten steers and conduct cow/calf operations. The Pampa region has been subdivided according to ecological criteria (León *et al.* 1991). Of these subregions, the Rolling Pampa is the most productive. Here, 50 - 75% of the region is devoted to grain crops.

The Pampa region has a temperate, humid climate and lacks a fully developed dry season. There is a gradient of rainfall from 1,000 mm in the NE of the region to 600 mm in the SW. Mean annual temperatures range from 17°C in the northern part of the region to 14°C in the SE. Similarly, there is a gradient of the frost-free period which ranges from 180 to 260 days.

Soils in the region are mainly Mollisols developed on a deep mass of Pampean loess (Frenguelli 1925). This is a quaternary sediment which was originally transported by wind and later redistributed by water. There is a clear gradient of soil texture, from coarse soils in the West to fine-textured soils in the East.

Maize is one of the most important crops of the Pampa, occupying 2.3 millon hectares (Hall et al. 1991), with production concentrated in the Rolling Pampa in the NE portion of the region. Maize is alternated with wheat and soybean crops. Sunflower and grain sorghum are also important (1.5 and 1.1 millon hectares, respectively, from 1983 to 1985). The average yield of maize in the region from 1980 to 1986 was 4.2 t ha^{-1}.

Objectives

The objective of this work is to assess the possible effect of climate change on maize yields in the Pampa of Argentina. Climate change driven by an increase of greenhouse gases, mainly CO_2, will affect crops in two ways. One, an elevated CO_2 level may enhance net photosynthesis and change stomatal conductance (making the water use per unit leaf area more efficient). These responses are called the "direct CO_2 effects". Two, the expected temperature increases and changes in precipitation patterns would alter the growth and development of the crop. In this study, we explore the effects of climate change alone and climate change with the direct effects of increasing CO_2 on maize. We use climate change scenarios developed from three General Circulation Models (GCMs) and apply them to a dynamic process crop simulation model to determine the potential yield changes under future climate conditions.

METHODS

Baseline Climate Data and Climate Change Scenarios

The climatic data used for the modeling experiments are from the town of Pergamino in the Rolling Pampa (lat. 33°S, long. 60°W) (Figure 1). We used daily precipitation and maximum and minimum temperature data for the period 1960-1984. Daily radiation was estimated using sunshine hours data.

Climate change scenarios were generated from three GCMs: GISS (Goddard Institute for Space Studies, Hansen *et al.* 1983); GFDL (Geophysical Fluid Dynamics Laboratory Model, Manabe and Wetherald 1987); and UKMO (United Kingdom Meteorological Office Model, Wilson and Mitchell 1987). Changes in temperature, precipitation, and solar radiation projected by the GCMs were applied to the observed (baseline) climate to create the climate change scenarios for Pergamino.

The annual and seasonal changes in temperature and precipitation projected by the GCMs at Pergamino are shown in Table 1. The three scenarios predict significant increases in annual temperatures ranging from 4.5°C to 5.2°C; the temperature increases are larger during the summer months. The projected precipitation changes vary. The UKMO and GISS scenarios predict precipitation increases (29% and 10%, respectively), while the GFDL scenario predicts an annual decrease in precipitation (-5%).

Crop Model Calibration

The CERES-Maize crop model (Ritchie *et al.* 1989; Jones and Kiniry, 1986) was chosen for the simulations. This model has been widely validated in different agroecological conditions (Hodges et al. 1986). We further calibrated and validated the CERES-Maize model for the conditions of the Pampa to determine its suitability as a simulating tool. The calibration was performed for two single flint type hybrids, DAF11 and DAF12, from Dekalb Argentina. Table 2 presents the derived genetic coefficients that define the maize varieties. A summary of the simulated and observed validation results is presented in Table 3.

Soils and Management Variables

The main soil type of the Rolling Pampa is the Pergamino series. It is a typical argiudol with no serious constraints for agriculture. It is comparable to soils of the mid-western U.S. or the Ukraine, but it does not freeze in winter; thus tillage is feasible year-round (Hall *et al.* 1991) (Appendix 1).

Maize in the Rolling Pampa is mostly rainfed, and long-cycle hybrids account for 80% of the cultivated area. There are some medium-cycle hybrids grown. Maize is sown in early September and harvested in early February the following year. For this simulation, the sowing date of long-cycle hybrids was the 277th day of the Julian calendar and for medium-cycle hybrids, the 267th day. The duration of the fallow is directly correlated with maize yields in the region. A fallow period longer than 120 days is reported for 37% of the crops.

RESULTS AND DISCUSSION

The Effects of Climate Change

The changes in temperature and precipitation predicted for the doubled CO_2 scenarios produced decreases in maize yields (Table 4). Under the GISS scenario, yields simulated with nitrogen stress were reduced about 19% in comparison with base yields. Under the GFDL and UKMO scenarios, the yield reductions were larger (about 36% in both cases). These simulated yield reductions are mainly a result of a shorter growing period. The higher temperatures under the climate change scenarios trigger the onset of maturity stages earlier than under the present climate.

The direct effect of the increased atmospheric CO_2 on the crop resulted in very small yield increases. These did not compensate for the yield decreases simulated under the GCM scenarios alone.

Yearly variability of the yields decreased in the doubled-CO_2 runs. Since precipitation variability was not modified in this modeling exercise we suggest that the observed reduction in yield variability is a result of the shortened growing season, with the crop being constrained to a portion of the year where precipitation variability was lower. Results simulated without nitrogen stress are also shown in Table 4.

Sensitivity Analysis

The purpose of the sensitivity analysis is to assess the maize model responses to changes in temperature, precipitation, and CO_2. The experiment consisted of running the model for three temperature conditions (control, +2°C, and +4°C); three precipitation conditions (control, +20%, -20%); and two CO_2 conditions (330 ppm and 555 ppm). The response variables analyzed are yield, season length, and evapotranspiration (Table 5).

Yields decrease as a result of increases in temperature, due to a decrease in the season length which particularly affects the critical grain-filling period. The simulated increases in precipitation do not produce increases in simulated yields as we had expected. A possible explanation may be that the modeled crop was under more nitrogen stress under the higher precipitation scenario, due to nutrient leaching. Alternatively, with seasonal rainfall, percentage increases of precipitation may still be quite small. Further analysis of the nitrogen balance in the CERES-Maize model and the simulation conditions are needed.

The direct effects of 555 ppm CO_2 result in a small increase in simulated yield, but this yield increase did not compensate for the negative effects of a +2°C temperature increase. The direct effects of CO_2 on yield are larger under the lower precipitation conditions because the beneficial effect of CO_2 on simulated water use is more apparent under low precipitation conditions.

Adaptation Strategies

The major effect of climate change predicted by this modeling exercise is that temperature increases result in yield reductions due to a shortening of the growing period. We suggest two possible adaptive strategies to climate change: (1) a shift in the sowing date; and (2) a change in the hybrid.

Changes in the sowing date had large effects on simulated maize yields (Figure 3) and on the length of the growing period (Figure 2). Under the baseline climate, the optimum simulated sowing date is close to the date most frequently used in the region. However, under the GISS climate change scenario, the curve relating sowing dates and yields shows a bimodal response, with maxima occurring with very early or very late sowing dates. Both dates avoid the high-stress months of midsummer (January and February) and consequently decrease the water stress.

Therefore, one possible adaptive strategy to climate change conditions would be to sow maize very early so that the growing period occurs mostly during the cooler part of the year. Planting two months earlier than the present sowing date can fully compensate for the yield decreases under climate change conditions. An alternative strategy is to sow very late and avoid the hot months of midsummer.

These strategies have some risk associated with them. The yield variability increases markedly as the sowing date moves away from October/November (Figure 2), because of extremely low temperatures in some years. Although these strategies simulate an optimum yield under climate change conditions, they may not represent a practical optimum because of the biological uncertainties and the economic risks associated with them. Each of these alternatives implies major changes in the agricultural system of the region.

Simulations with Hypothetical New Hybrids

A possible strategy for adaptation to climate change could be to replace the currently available hybrid with a hypothetical new hybrid better adapted to climate change conditions. To analyze this alternative, hypothetical new hybrids were created under the GISS scenario by increasing the genetic coefficients, P_1, P_2, and P_5, from 10% to 50% (Figure 4). P_1 represents the time period during which the plant is not responsive to changes in the photoperiod. P_2 defines the photoperiod sensitivity of the cultivar. P_5 is the number of degree days above a base of 8°C from silking to physiological maturity.

The figure shows that an increase in the genetic coefficients of the potential new hybrids of between 10% and 20% is enough to restore the GISS climate change yields to their baseline level. This simulation exercise suggests that hypothetical new hybrids may be able to take advantage of a prolonged growing season and higher precipitation amounts. The extent to which this could be possible in practice needs to be further investigated with maize breeders.

IMPLICATIONS OF THE RESULTS

This study suggests that projected climate changes resulting from an increase in greenhouse gases may result in decreases in maize yields in the Rolling Pampa. The yield decreases may be compensated for by changing the planting date of the hybrids presently used. But in the warmer boundaries of the rolling Pampa, it is unlikely that maize yields could be fully restored to their previous level. Nevertheless, maize production could expand into areas that are currently limited by the length of the frost-free period.

Using the same tools that we used in this exercise, we plan to conduct further model simulations for different locations in order to estimate the geographical location of the potential new maize-producing region in Argentina under climate change conditions. A qualitative analysis suggests that a large portion of the maize-producing area will be located on soils of poorer quality than present soils. Therefore, the average soil fertility of the maize area may decrease, possibly resulting in decreased yields, unless additional fertilizer is added to the soil. These hypotheses can be tested further by using these same modeling tools on a larger number of sites.

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Table 1. Average seasonal changes of temperature and precipitation for the GISS, GFDL, and UKMO GCM climate change scenarios in Pergamino.

Scenario/variable	SPRING	SUMMER	FALL	WINTER	ANNUAL
GISS					
Temperature °C	3.8	5.4	5.5	4.5	4.8
Precip. (%)	-3	30	10	15	10
GFDL					
Temperature °C	4.0	5.5	4.3	4.4	4.5
Precip. (%)	0	20	-34	-25	-5
UKMO					
Temperature °C	4.8	5.9	5.1	5.0	5.2
Precip. (%)	51	14	40	33	29

Table 2. Genetic coefficients derived for single flint type hybrids.

Genetic coefficient		DAF11 hybrid	DAF12 hybrid
P1	(Juvenile)	260	260
P2	(Photoperiodism)	1.0	1.0
P5	(Grain filling duration)	700	700
G2	(Kernel number)	625	710
G3	(Kernel weight)	9.6	8.6

Table 3. Validation of the CERES-Maize model for Pergamino.

	DAF11 hybrid		DAF12 hybrid	
Crop variable	Sim.	Obs.	Sim.	Obs.
Emergence	3-11	3-11	3-11	3-11
Anthesis	10-1	13-1	10-1	9-1
Beginning grain filling	20-1	--	20-1	--
End grain filling	20-2	--	20-2	--
Yield (t ha^{-1})	10.12	9.96	10.15	10.25
Kernel weight (g)	0.275	0.281	0.246	0.251
Grain/ear	383	381	429	436
Biomass (t ha^{-1})	20.57	22.68	20.58	20.25

Table 4. Effects of climate change on simulated rainfed maize yield, season length, season precipitation, and evapotranspiration with and without nitrogen stress.

		Climate Scenario Alone				Climate Scenario With Physiological CO_2 Effects			
Management	Simulated Variable	BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO
Rainfed Nitrogen Stress	**Yield ($t\ ha^{-1}$)**	3.69	3.00	2.52	2.40	3.77	3.04	2.52	2.54
	SD	0.85	0.70	0.61	0.48	0.82	0.51	0.53	0.42
	S.Length (d)	126	102	101	99	126	102	101	99
	SD	8	4	4	3	8	4	4	3
	S. PP (mm)	611	498	530	594	611	498	530	594
	SD	142	102	134	115	142	102	134	115
	ET (mm)	487	460	458	448	398	387	408	367
	SD	20	21	25	22	16	24	18	27
Rainfed Fertilized	**Yield ($t\ ha^{-1}$)**	9.42	7.89	7.39	8.20	9.95	8.52	8.29	8.88
	SD	1.44	0.95	1.13	0.95	1.30	0.85	0.91	0.85
	ET (mm)	494	471	458	475	419	414	408	417
	SD	22	21	25	22	19	23	19	22

Table 5. Sensitivity analysis of CERES-Maize to climate and CO_2 changes.

		Simulated variable*					
		330 ppm CO_2			555 ppm CO_2		
Changes Precip.	Temp.	Yield	Season L.	ET	Yield	Season L.	ET
(%)	(°C)	(t ha^{-1})	(days)	(mm)	(t ha^{-1})	(days)	(mm)
0%	0	3.69	126	486	3.77	126	397
	2	3.35	113	457	3.38	113	376
	4	3.31	104	437	3.35	104	364
20%	0	3.52	126	487	3.49	126	395
	2	3.19	113	456	3.18	113	373
	4	3.18	104	437	3.12	104	360
-20%	0	3.76	126	482	3.92	126	399
	2	3.49	113	453	3.59	113	378
	4	3.35	104	433	3.52	104	366

* Simulations with nitrogen stress.

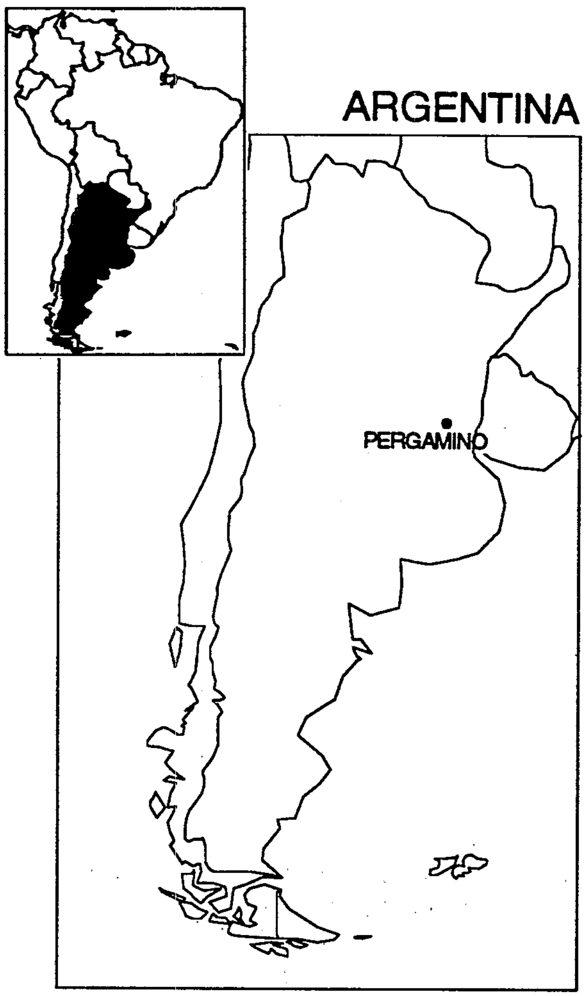

Figure 1. Map of Argentina and location of Pergamino

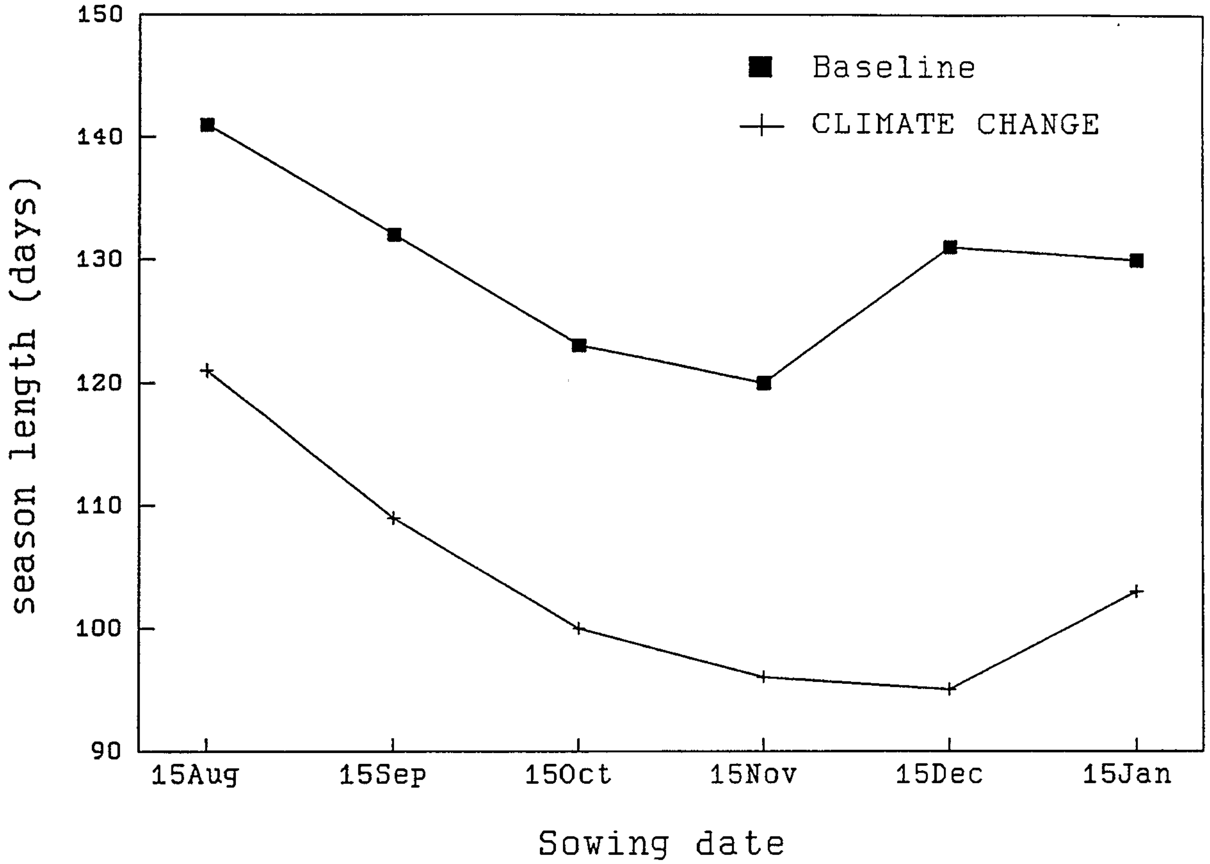

Figure 2. Effect of sowing date on maize yield for the baseline and the climate change conditions. Vertical bars represent standard deviations.

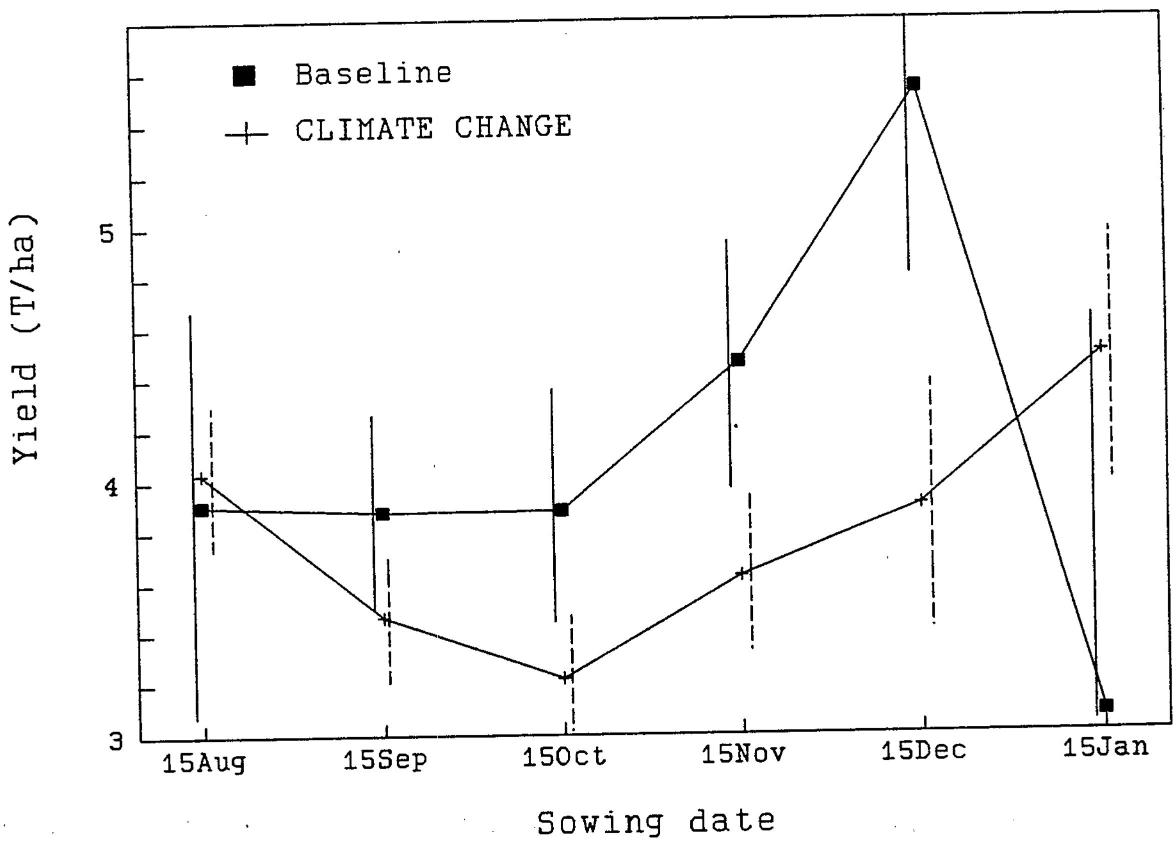

Figure 3. **Effects of sowing date on the season length of maize for the baseline and climate change conditions.**

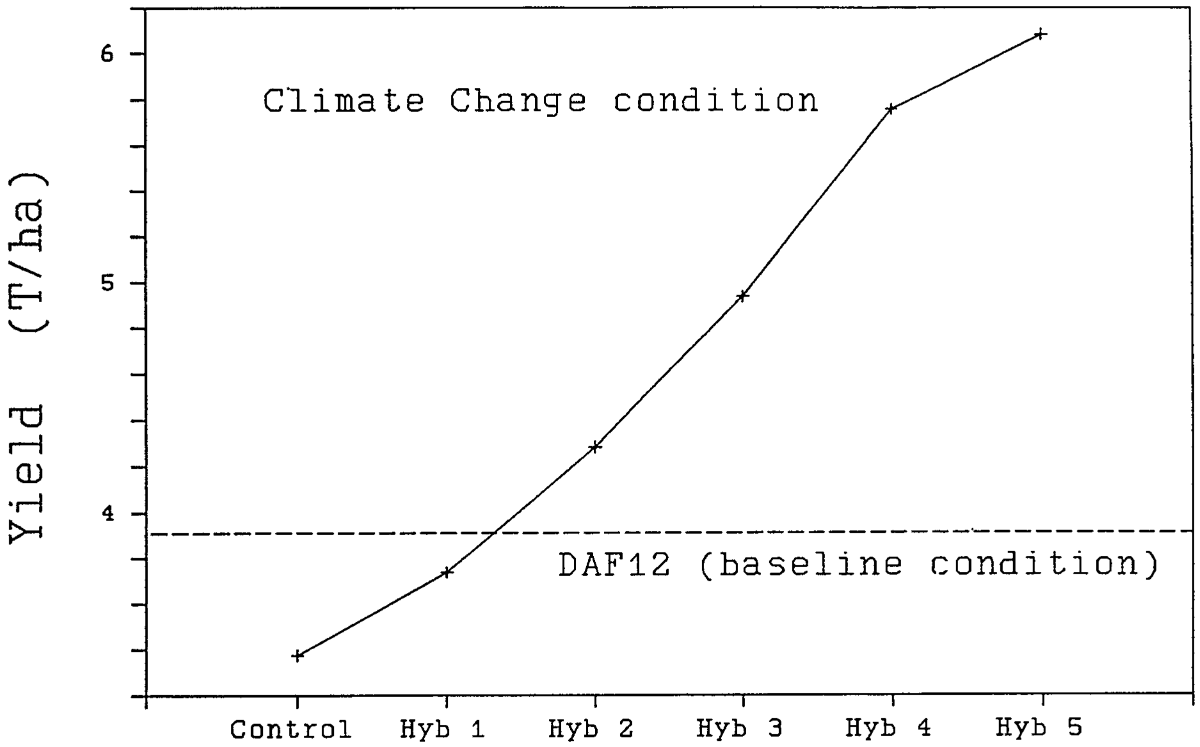

Figure 4. Simulated season length of hybrids with genetic coefficients P1, P2, and P5 ranging from 10% to +50% (Hyb1 to Hyb5) higher than the control hybrid.

IMPACT OF CLIMATE CHANGE ON BARLEY IN URUGUAY: YIELD CHANGES AND ANALYSIS OF NITROGEN MANAGEMENT SYSTEMS

Walter E. Baethgen

International Fertilizer Development Center (IFDC)
USA

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SUMMARY

This study utilized global climate models (GCMs) and dynamic crop growth models to estimate the potential agricultural effects of climate change on barley production and nitrogen management systems in Uruguay. The barley crop simulation model was calibrated and validated in great detail in the study, considering seven parameters of growth and development of the crop. Since barley management practices vary widely in Uruguay, several crop management scenarios were considered combining three planting dates and two levels of available nitrogen. Projected climate change caused simulated barley yields to decrease in all strategies considered. The decrease in modeled grain yields were caused primarily by temperature increases which shorten the duration of the crop life cycle, particularly the grain-filling period. These decreases were partially counteracted by the beneficial physiological CO_2 effects on crop growth and water use as simulated in this study. The negative effects of GCM climate change were worse when no nitrogen fertilizer was applied, and/or when planting was delayed. The variability of grain yields was larger under the GCM scenarios and when planting dates were delayed, but it was not affected by nitrogen fertilization. A possible adaptation of barley management systems in Uruguay to climate change conditions is an optimization of the soil nitrogen available for the crop, but even considering this adaptation strategy, significant production losses were still associated with the climatic conditions projected by the UKMO scenario.

INTRODUCTION

Background

The climatic characteristics of Uruguay (Table 1) allow the production of subtropical and temperate species. The most important crops in Uruguay are wheat, barley, rice, maize, sorghum and sunflower. The country is self-sufficient in food, and 30-40% of the country's total exports are textiles, beef, hides and cereals. Most of the wheat, maize, sorghum and sunflower are consumed in the country; barley and rice are primarily export crops. Due to the economic importance of barley as an export, it was selected for this study.

The enhanced greenhouse effect of increased atmospheric concentration of CO_2 and other trace gases could lead to higher global surface temperatures and changed hydrological cycles (IPCC 1990). Global climate change may affect crop production in some areas of the world, as previous impact studies have shown (Parry *et al.* 1988). A change in climatic conditions could affect crop production in Uruguay.

Barley crops in Uruguay are sometimes damaged by excess soil water that causes leaching and denitrification, with consequent increased requirements for nitrogen fertilization, lower economic returns, and greater potential for nitrate contamination of groundwater. A possible change in climatic conditions may have an important impact on barley production and on the environmental consequences of the use of nitrogen fertilizers.

Objectives

This study had two main objectives. One goal was to study the potential impact of global climate change on barley production in Uruguay under a wide range of management practices, in particular available nitrogen levels and planting dates. Another goal was to evaluate soil and crop management practices (nitrogen fertilizer use, cultivar characteristics, and planting dates) that may be better adapted to the possible climate change conditions.

Representative Climate and Soils

The crop-growing area of Uruguay is small (about 700,000 hectares) and the major agricultural regions are located in the west and southwest of the country; the barley production is concentrated in those regions. Given the relatively small size of the barley growing area in Uruguay, the climate variables recorded in the different meteorological stations within the area are very similar; therefore, one site was selected for the study: "La Estanzuela" Experimental Station (34° 27' S, 57° 46' W) (Figure 1).

The soils are heterogeneous and important variability exists with respect to soil water-holding capacity, the ability to supply nitrogen through mineralization, and the ease with which the soils can be tilled. The dominant soils in the area are Mollisols and Vertisols. Typical ranges of the most important chemical characteristics of unfertilized soils of the area are: pH 5.5-6.5; organic mater 25-60 g/kg; 2.0-4.0 mg/kg available phosphorus (Bray 1); 0.25-0.60 cmol(+)/kg of potassium. Most Mollisols in the area have more than 25% of clay in the superficial horizon and usually a heavy textured B horizon (more than 40% clay). The Vertisols are less differentiated and usually present more than 30% of clay through all the profile. Although soil variability in the region is important, for this simulation study we selected one representative soil profile that accurately represents the textures and water capacities of the main agricultural soils in the region. The available nitrogen content in the soil was varied to create different nitrogen conditions that represent the agricultural soils and management practices in the area.

Management Practices and Nitrogen Available for the Crop

Typical farms in the area produce crops and raise livestock. Consequently, the grain crops and pastures are rotated. For example, three years of crops (such as wheat, barley, sunflower and sorghum) alternate with three years of pasture (typically a mixture of white clover, red clover, birdsfoot trefoil and tall fescue). As a result of this system, soils have a variable ability to supply nitrogen to the crops, depending on: (a) time since the last pasture was plowed, (b) soil tillage, and (c) soil type. Soil tillage is especially important for barley production because the planting time of the recommended cultivars coincides with the time of the year when soil tillage is the most difficult (Figure 2). Thus, years with low rainfall during summer and fall usually result in good soil tillage, high nitrogen levels, and high yields. Years with heavy rainfall during soil preparation often result in inadequate seedbeds, low plant populations, poor natural soil nitrogen supply, and low grain yields.

Winter crops in the west and southwest can be planted as early as April (cultivars with photoperiod sensitivity) and as late as August. With the exception of a few newly developed cultivars, barley cannot be planted earlier due to lodging problems. This simulation study considered three possible planting dates and two levels of available nitrogen to construct simulations that represent the wide variety of conditions used for barley production in Uruguay.

METHODS

Baseline Climate Data

The baseline climate data were obtained from Mr. Ricardo Romero, Agrometeorologist of the La Estanzuela Experimental Station of INIA (National Agricultural Research Institute of Uruguay). The period included in the dataset was 1 January, 1966 to 31 December 1989. The solar radiation values were obtained from the sunshine hours based on the total possible hours and the observed hours using the WGEN program (Richardson and Wright 1984). Mean monthly temperature, precipitation and solar radiation for the period are shown in Table 1. The temperature regime is seasonal and the largest monthly precipitation corresponds to the late summer.

Climate Change Scenarios for the Region

Global Climate Models (GCMs) were used to derive climate scenarios. Runs of these models were used to estimate change in climate variables (temperature, precipitation, and solar radiation). These changes were then used to modify the baseline climate and produce the climate change scenarios at each site. The equilibrium GCMs used were: Goddard Institute for Space Studies (GISS, Hansen *et al.* 1983); Geophysical Fluid Dynamics Laboratory (GFDL, Manabe and Wetherald 1987); and United Kingdom Meteorological Office (UKMO, Wilson and Mitchell 1987). Transient scenarios were created from the GISS transient model simulations (Hansen *et al.* 1988).

The following climate scenarios were run: (a) baseline; (b) GCMs (GISS, GFDL, and UKMO) doubled CO_2 climate change; (both (a) and (b) with and without the direct effects of CO_2 on photosynthesis); (c) sensitivity studies with combinations of 0, +2°C, +4°C, and 0, +20%, -20% precipitation, over the baseline, each with and without direct CO_2 effects; (d) transient climate change for the 2010s, 2030s and 2050s using the GISS model; and (e) adaptive responses, e.g. the use of soil and crop management practices that are better adapted to the possible new climatic conditions.

The three GCMs used to predict climate changes under doubled CO_2 conditions show similar trends with respect to the average mean temperature (Figure 3a). All three models predict an increase in the monthly average of about 5°C. The UKMO model predict the largest increase (about 6°C); GFDL produces the smallest change (approximately 4°C).

The GCMs show contrasting trends for precipitation (Figure 4a). Both the GISS and UKMO models predict a general increase in total precipitation. Increases in rainfall are predicted for spring and fall, although the GISS model also predicts a considerable increase in rainfall for the winter months. The GISS and UKMO models predict higher means for annual precipitation than the baseline scenario - approximately 150 and 300 mm higher, respectively. In contrast, the GFDL model predicts a small decrease in total precipitation for most of the fall and winter months except for September (Figure 4). Excluding this month, the mean annual precipitation predicted with the GFDL model is about 50 mm lower than the baseline.

All three models predict very small changes in solar radiation (Figure 5a). The UKMO model projects a slightly larger solar radiation value for January and February, approximately 2 MJ/m_2.

Because the UKMO model predicts the most unfavorable climate changes (largest temperature and precipitation increases) for barley production in the area it was used for the adaptive response studies discussed earlier. It was also the only GCM included in this study in which a model gridbox included the entire land area of Uruguay.

The GISS model was also used to predict transient climate changes for the 2010s, 2030s, and 2050s. Figures 3b, 4b and 5b show the results of these predictions for temperature, rainfall, and solar radiation, respectively. The results indicate a gradual temperature increase through the 2010s, 2030s, and 2050s, reaching the maximum at the doubled CO_2 scenario. The variation in the total precipitation was less systematic and showed a very high rainfall value for March in the 2030s (GCM regional precipitation projections are highly uncertain). As expected, the predicted solar radiation values showed almost no change from the baseline data over the three decades.

Crop Model and Simulation Strategies

An International Fertilizer Development Center (IFDC) - United Nations Development Programme (UNDP) global project was started in 1990, which will include the validation and regional adaptation of the wheat, rice, maize, soybean, sunflower, and barley CERES models for further studies. The CERES-Barley model, based on the CERES generic model, was used for all the simulation activities reported here (IBSNAT 1989). The soil used for the modeling activities, (fine, messic, typic, Argiudoll) was the same soil that was used for the model validation. A complete description of the chemical and physical properties for 10 cm layers throughout the soil profile is shown in Table 2.

The simulations are described in Table 3. Three possible fertilization strategies were used: (a) no N fertilizer; (b) 60 kg N/ha at planting + 60 kg/ha at the end of tillering (a common practice in the region); and (c) optimal N fertilization. This last strategy simulates the situation of having a diagnostic tool available to ensure optimal N fertilizer application, one of the key objectives of the barley research mentioned above. Also, given the long planting season for winter crops, three different planting dates were used to run the model: 1 June (early), 21 July (normal), and 28 August (late).

Frequent rains in summer and in fall result in problems with the soil tillage for winter crops. Common consequences are inadequate seedbeds and a very compacted layer at 20-25 cm. The contraction is caused by numerous tillage operations performed in a short period of time. An attempt was made to simulate this situation by setting the value of the weighting factor to determine new root growth (WR in the CERES models) equal to zero for all soil layers below 30 cm. However, the model was insensitive to the simulated poor soil preparation. Setting the value of the weighing factor to determine new root growth (WR in the CERES model) equal to 0.0 for all soil layers below 30 cm did not affect the results in crop production (data not shown). Therefore, the model was not used to perform any further simulations changing soil preparation.

Since the climate change scenarios are associated with higher levels of CO_2 (designated as 555 ppm in the figures, representing an equivalent doubling of CO_2) than the current climate GCM simulations (330 ppm in the figures), the study includes simulations of the physiological effects of CO_2 on barley. Higher levels of atmospheric CO_2 have been found to increase photosynthesis and water use efficiency, resulting in yield increases in experimental settings (Acock and Allen 1985; Cure 1985).

Validation and Calibration of the Crop Model

A complete dataset is available in Uruguay that is suitable for calibrating and validating the CERES-Barley model. All the crop production variables (dry matter production, grain yield, kernel weight, grains/m_2, grains/ear, etc.) of the CERES model were validated with this dataset. However, the phenology variables (anthesis dates and maturity dates) were also tested with results from three years of cultivar trials conducted by the Department of Plant Breeding of INIA. The phenological variables were calibrated and validated for planting dates similar to the early, normal and late dates used in the simulation studies.

The CERES-Barley model validation procedures for this study were performed in two stages: (a) determination of the genetic coefficients and validation of the phenological variables of the model; and (b) validation of the crop production variables. Data from several barley planting date trials were used for the first stage. The genetic coefficients, P1V and P1D, were adjusted for the cultivar CLE-116, a newly developed cultivar from INIA, using three years of data. The model's accuracy in predicting anthesis and maturity dates was excellent. The difference between observed and simulated dates for all years and planting dates included in the study was always less than three days. The CERES model also accurately predicted the end of tillering in most situations.

The validation of the crop production variables was performed using data from 1991 research. The most relevant results of this validation are shown in Figures 2a-2g. For example, there was a high correlation ($r>0.9$, $P<0.01$) between the simulated and observed results for grain yield, total biomass production, straw production, grains/m_2, and kernel weight. However, the model did not simulate grains/ear or for nitrogen content of the grain as well. Considering the grains/ear, the principal problem was that the model did not correctly predict the number of spikes per m_2 (data not shown). In all treatments, the predicted number of spikes/m_2 was always lower than the observed data, indicating a problem with the model routines that calculate tiller production, or the number of tillers that produce spikes. Observation of the predicted number of tillers showed that, in most cases, the simulated values were similar to the ones observed, and in some cases, the predicted values were higher than those observed. This suggests that a problem may exist predicting the proportion of tillers that will produce spikes, a topic to be studied in further validation research.

The reason for the poor performance of the model in predicting the nitrogen content of the grain is not clear. Problems may exist during the grain-filling stage because the length of this stage greatly affects the N content of the grain. Finally, the kernel weight and the N content of the grain simulated by the model showed a smaller sensitivity to N fertilizer than that observed in the field research. The kernel weight depended only on the value of G2 (kernel weight genetic coefficient) and was constant for all the N treatments. Similarly, the N content of the grain observed in the field varied more than the values predicted by the model. Although these limitations of the model justify further work on the routines and in the validation procedures, the general performance of the CERES-Barley model was very good. This was particularly true for simulating grain yield, biomass production, and dates of anthesis and maturity.

RESULTS AND DISCUSSION

Effects of 2xCO_2 GCM Climate Change on Barley Production

Yield. Figures 6a and 6b show the effects of the climate change predicted with the three GCMs on barley production. Without nitrogen fertilization, the GCMs predicted a 50% mean decrease in grain yield. When nitrogen fertilizer was applied at rates and timings that are similar to Uruguayan farmers' practices (60 kg N/Ha at planting + 60 kg N/ha at tillering), the yield was reduced by 40%. In all of the climate scenarios tested, N fertilizer affected the grain yields, especially in the normal (NP) and late (LP) planting dates. Figure 6 indicates that normal planting date yields doubled and that late planting yields tripled with N fertilizer.

The interaction of planting date and nitrogen fertilizer for the baseline and the three GCMs resulted in a substantial difference between early planted (EP) and NP barley yields when no fertilizer was applied. In contrast, the yields of EP and NP were very similar when N fertilizer was used. A possible explanation of these results is that early planted barley remains in the vegetative growth stage for a longer period of time than NP barley. This gives the soil more time to supply larger quantities of N (through mineralization) at a stage when N requirements are relatively low. When barley is planted at a normal date, the crop is much more dependent on fertilizer N.

Direct CO_2 effects. Figure 6b shows the physiological effects of CO_2 on crop growth. The results indicate that the baseline yields increased by 20% and the GCM climate change scenario yields increased by 30%. The yields simulated with the GCM scenarios that included the direct effects of CO_2 were 30% lower than the yields of the baseline climate at 330 ppm of CO_2 concentration.

Yield variability. Baseline yields were less variable than yields simulated with three GCM scenarios (Figures 7a and 7b). However, the main source of variability in grain yields was planting date. Figure 7 shows that the CV increased from 20% to almost 50% when the planting time was delayed to a later date. Also, the CVs for the GCMs were much larger those for the baseline at late planting dates. Finally, N fertilization did not affect variability of the grain yield: the CVs with or without fertilizer were similar.

Biomass and season length. Decreases in barley grain yield can be caused by a reduction in the total biomass production (which is highly correlated with grain yields), and/or by a reduction in the grain filling period. To explain the observed reductions of grain yield, we studied the effect of the GCMs on the total production of barley biomass (Figures 8a and 8b). The experiments showed that the biomass production changed in proportion to grain yields, and as a result, the barley harvest index (grain yield/total biomass, expressed as a percent) did not change. Therefore, reductions in grain yield were mainly due to reductions in the production of total dry matter. The decrease in total biomass production was caused by a shorter growing season (Figure 9). The figure indicates that: (a) the period from emergence to maturity was shortened by a delay in the planting date; and (b) for any given planting date, all of the GCM scenarios caused a reduction of the period equal to 30 days for EP, 20 days for NP, and 15 days for LP - about 20% in all cases.

Sensitivity Analysis

The results in Figures 3 and 4 indicate that the GCMs predicted important changes in the temperature and total precipitation. A sensitivity analysis was performed to try to identify which of these variables was responsible for the negative effect on the grain yields (Figures 10a and 10b). The analysis indicates that the barley grain yields were much more sensitive to temperature changes than to precipitation changes. This is expected since Uruguay does not have periods of water shortages in the winter. As mentioned above, one factor causing reductions in winter crop yields is the excess of water in the soil. In all of the simulation runs, there were no years with periods of water stress in the vegetative stage and very few years with periods of mild water stress during the reproductive stage.

The results of the sensitivity analysis indicate that the mean grain yields were reduced by 0.45 t ha^{-1} for each 1°C of mean temperature increase. This reduction is similar for the three tested precipitation scenarios. Grain yields decreased 0.10 t ha^{-1} for each 10% decrease in total precipitation and did not decrease with the potential period of excess of water in the soil.

Figure 11 shows the results of the sensitivity analysis on total biomass production. The effects of temperature and precipitation changes were similar to the effects on the grain yields, suggesting that the reduction in grain yield - caused by an increase in the mean temperature - is a consequence of a reduction in the total biomass produced. Figure 12 shows the effect a of temperature increase on the length of the period from emergence to maturity. The results indicate that the crop growing season was shortened by five days for each 1°C increase in the mean temperature.

Transient Analysis

The analysis of the transient climate change using the GISS model indicates a gradual increase in the mean temperature through the 2010s, 2030s and 2050s. As expected, the transient analysis of barley production indicated a reduction in grain yields and an increase in yield variability (Figures 13a and 13b). Barley grain yields were reduced by 1.7 t ha^{-1} from the baseline for the 2010s, and by an additional 0.35 t ha^{-1} for each of the following decades. There is no apparent reason for this differential reduction since the temperature change predicted for the barley-growing season was gradual.

Adaptation Strategies to Climate Change

Adaptive responses were tested to mitigate the negative effects of the predicted climate changes of the UKMO model, including the improvement of nitrogen fertilizer management and the creation of a cultivar with a longer grain-filling period. An additional cultivar which is more adapted to earlier planting dates was also simulated. The results of these runs indicate the importance of the these alternatives (Figures 14a and 14b). The use of a more adequate fertilizer regime produced an increase in yield of 1 t ha^{-1} over the unfertilized crop. An additional 1 t ha^{-1} increase was achieved without N limitations. Finally, another 1 t ha^{-1} increase was gained by using the optimum N management with an improved "hypothetical cultivar" designed with a higher number of $kernels/m_2$, and a longer grain filling period.

The adaptive response analysis shows that using improved crop management practices would increase currently attainable grain yields of 2.5-3.0 T/Ha (baseline with 60 kg N/ha at planting + 60 kg N/ha at tillering, in Figure 14a), and results in a mean grain yield of 5.0 T/Ha, even under the unfavorable weather conditions predicted by the UKMO model. However, Figure 14a also shows that the mean grain yield achieved with these same crop management practices would be 6 t ha^{-1} with 330 ppm CO_2, or 7.5 T/ha with direct effects of doubling the CO_2 concentration - indicating a potential loss of 1.0-2.5 t ha^{-1} under the predicted climate changes.

A second set of simulation runs to compare the barley response to nitrogen fertilizer under baseline and UKMO conditions. For the baseline runs, CLE-116 was used at the normal planting date. The same cultivar was used for the UKMO runs at the early planting date. The planting date was changed for the UKMO runs because the model had predicted an increase in the mean temperature, which in turn resulted in a shorter growing season. The probable response of farmers to this change would be to plant at earlier dates and avoid high temperatures during the grain-filling period. The results presented for the climate change scenario included the physiological CO_2 effects.

Figure 15 shows the results of testing four nitrogen fertilizer rates. The response curve was adjusted with linear regression analysis. Because the baseline response curve was much steeper than the UKMO curve, the baseline maximum yield was more than 1 t ha^{-1} higher than the UKMO maximum yield. Also, the amount of N fertilizer needed to attain the maximum grain yield under UKMO was 2.6 times more than the amount required to attain the same yield under current climatic conditions.

CONCLUSIONS

The climate changes predicted by the three GCMs are increased mean temperature, unchanged or increased precipitation, and unchanged solar radiation. These climate conditions resulted in reduced crop growing seasons and lower total biomass production and grain yields for barley in Uruguay. The negative effects of the GCMs were worse when no nitrogen fertilizer was applied, and/or when the planting date was delayed. The variability of grain yields was greater under the GCM conditions and when the planting dates were delayed, but it was not affected by N fertilization.

The sensitivity analysis indicated that the decrease in grain yields is related to the reduction of the barley-growing season. This reduction results from the temperature increase predicted by the GCM climate change scenarios. In the major barley-growing region of Uruguay, the estimated yield effect of increasing the mean temperature by 1°C is equivalent to the estimated effect of a 40% reduction of the total precipitation. The adaptive response studies indicated that although there is a good potential for developing adaptive management practices for the predicted climate changes, significant losses in crop production can still be expected.

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Table 1. Mean temperature, precipitation, and solar radiation for baseline data in La Estanzuela, Uruguay (1966-1989).

Month	Mean Temperature	Total Precipitation	Solar Radiation
	°C	mm	MJ/m_2
JAN	21.1	77.6	23.0
FEB	20.3	85.8	20.8
MAR	18.5	107.0	16.9
APR	15.7	58.7	13.0
MAY	12.6	59.5	9.4
JUN	9.6	62.3	7.3
JUL	9.8	67.2	8.0
AUG	10.5	73.0	10.7
SEP	12.2	76.6	14.4
OCT	14.4	96.7	18.5
NOV	16.6	80.7	21.6
DEC	19.8	78.1	23.3

Table 2. Description of the soil used for modeling activities.

Layer	LL	DUL	SAT	SW	BD	OC	NH4	NO3	pH
cm		cm³/cm³			g/cm³	%		mg/kg	
0-5	0.124	0.320	0.350	0.320	1.28	2.08	5.0	20.0	5.6
5-10	0.124	0.320	0.350	0.320	1.28	2.08	5.0	15.0	5.6
10-20	0.119	0.290	0.320	0.290	1.32	2.08	5.0	10.0	5.6
20-30	0.127	0.300	0.350	0.300	1.32	2.08	2.0	5.0	5.6
30-40	0.186	0.290	0.350	0.290	1.36	.78	2.0	1.0	6.1
40-50	0.200	0.310	0.360	0.310	1.40	.78	1.0	1.0	6.1
50-60	0.199	0.310	0.360	0.310	1.40	.95	1.0	1.0	6.6
60-70	0.192	0.300	0.350	0.300	1.42	.95	1.0	1.0	6.6
70-80	0.193	0.290	0.340	0.290	1.42	.14	1.0	1.0	6.6
80-90	0.185	0.280	0.320	0.280	1.42	.14	1.0	1.0	6.8
90-100	0.186	0.270	0.310	0.270	1.42	.14	1.0	1.0	6.8

LL = Lower limit of soil extractable water
DUL = Drained upper limit of soil water content
SAT = Saturated water content
BD = Bulk density
OC = Organic Carbon
SW = Initial soil water content

Table 3. Management practices used in the simulations.

a) Baseline and GCMs (x2 CO_2) with and without direct effects of doubled CO_2 concentration TOTAL: 48 runs

Planting Date	N fertilizer
Early (1-June)	No N Fertilizer
Normal (21-July)	No N Fertilizer
Late (28-August)	No N Fertilizer
Early (1-June)	60 + 60 Kg N/ha (Plant. + Till.)
Normal (21-July)	60 + 60 Kg N/ha (Plant. + Till.)
Late (28-August)	60 + 60 Kg N/ha (Plant. + Till.)

b) Sensitivity analysis (0,+2,+4 °C X 0,-20,+20% mm) with and without 2xCO_2 TOTAL: 18 runs

Planting Date	N fertilizer
Normal (21-July)	60 + 60 Kg N/ha

c) Transient climate change with and without 2xCO_2 TOTAL: 6 runs

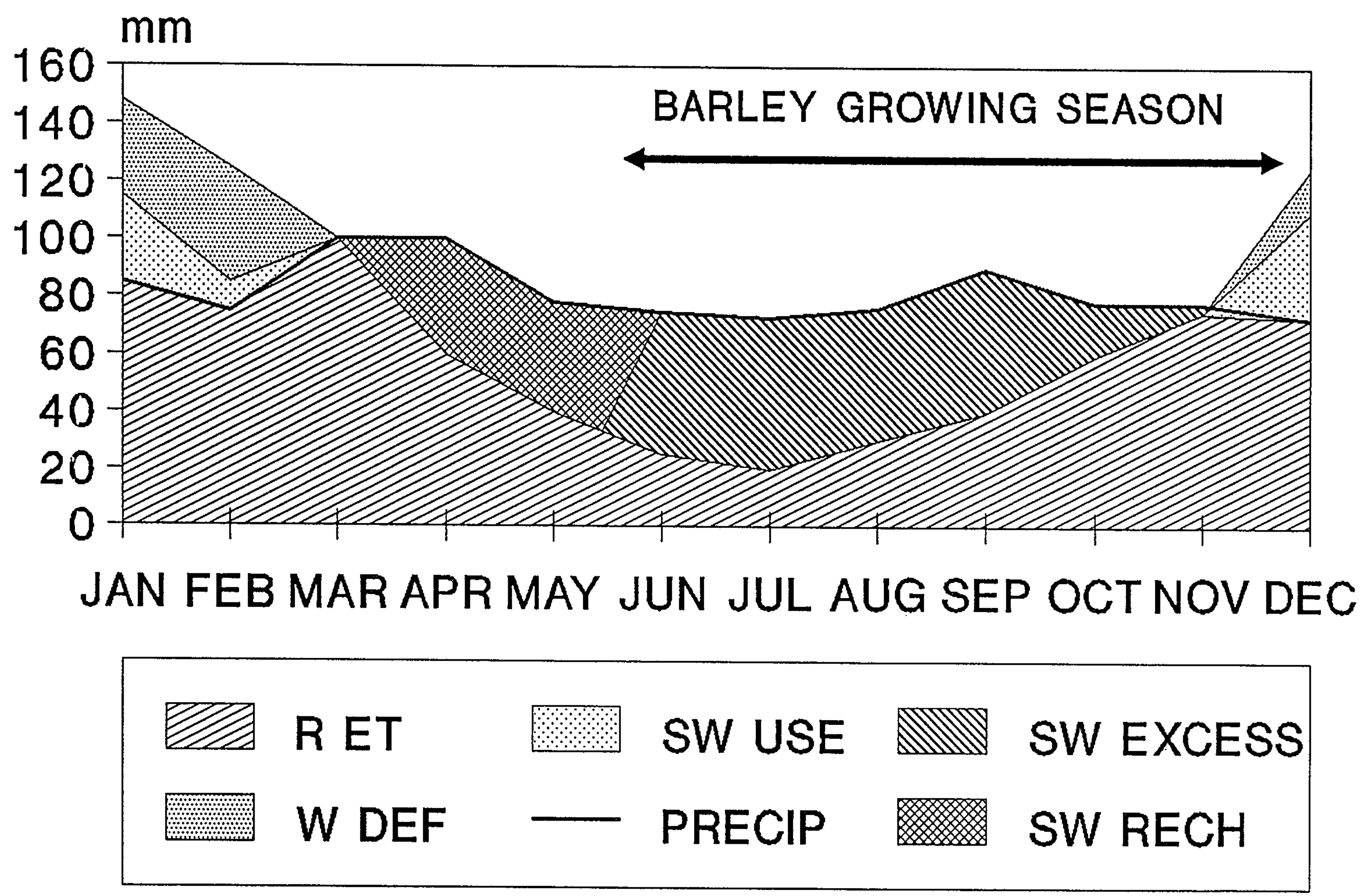
Planting Date	N fertilizer
Normal (21-July)	60 + 60 Kg N/ha

d) Adaptive Response with and without 2xCO_2 TOTAL 12 runs

Planting Date	N fertilizer	Cultivar
Normal (21-July)	60 + 60 Kg N/ha	CLE-116
Normal	Optimal	CLE-116
Early	Optimal	CLE-116
Normal	Optimal	Improved #1(*)
Normal	Optimal	Improved #2
Early	Optimal	Improved #3

Improved cultivar #1 = CLE-116 with increased grains/m_2
Improved cultivar #2 = Improved #1 with longer grain filling period
Improved cultivar #3 = Improved #2 better adapted to early planting

Fig 1: LONG TERM WATER BALANCE FOR SW URUGUAY



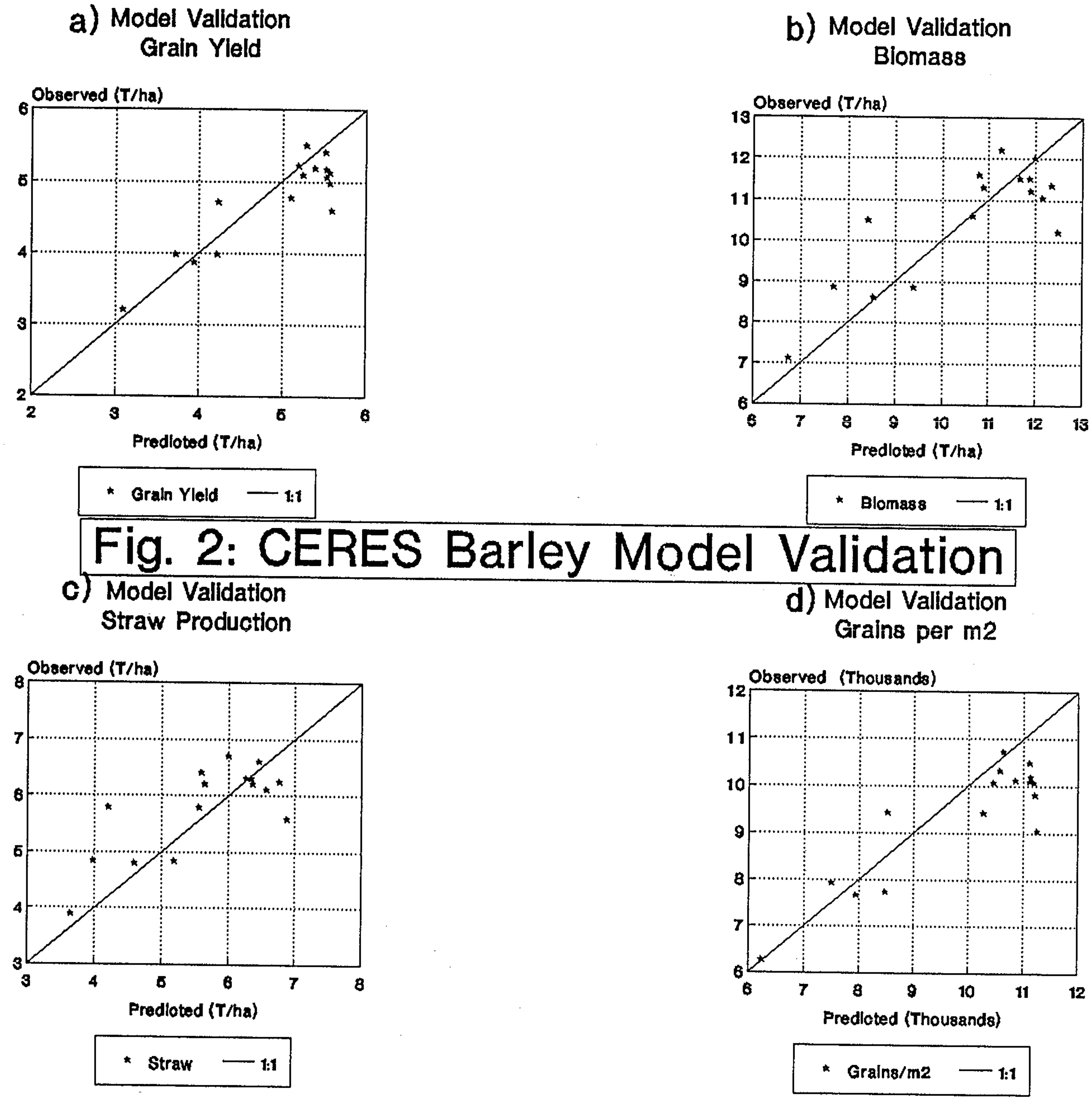


Fig. 2: CERES Barley Model Validation

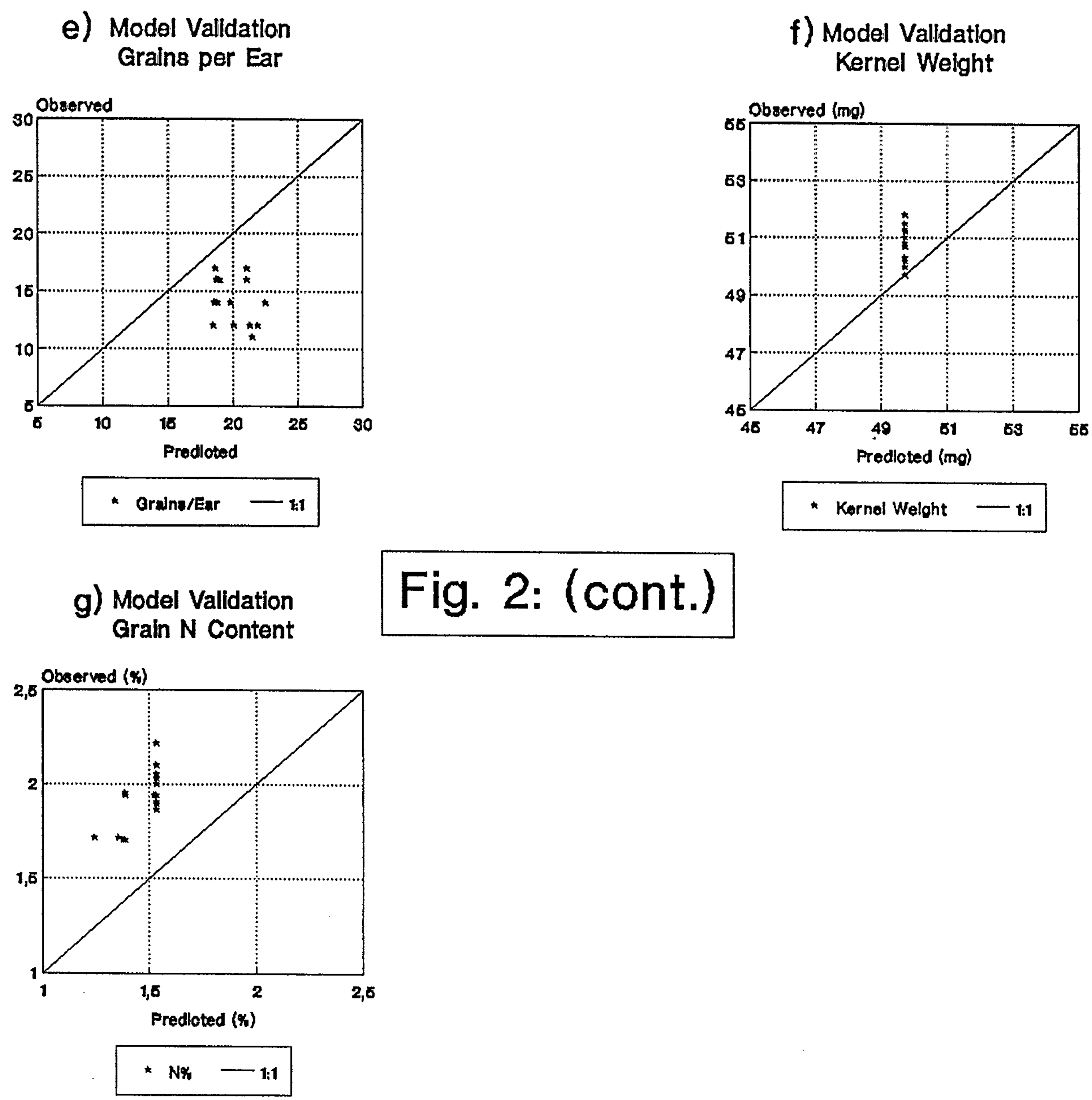

e) Model Validation
Grains per Ear
Observed
30
25
20
15
10
5
5
10
15
20
25
30
Predicted
* Grains/Ear
1:1
f) Model Validation
Kernel Weight
Observed (mg)
55
53
51
49
47
45
45
47
49
51
53
55
Predicted (mg)
* Kernel Weight
1:1
g) Model Validation
Grain N Content
Observed (%)
2,5
2
1,5
1
1
1,5
2
2,5
Predicted (%)
* N%
1:1

Fig. 2: (cont.)

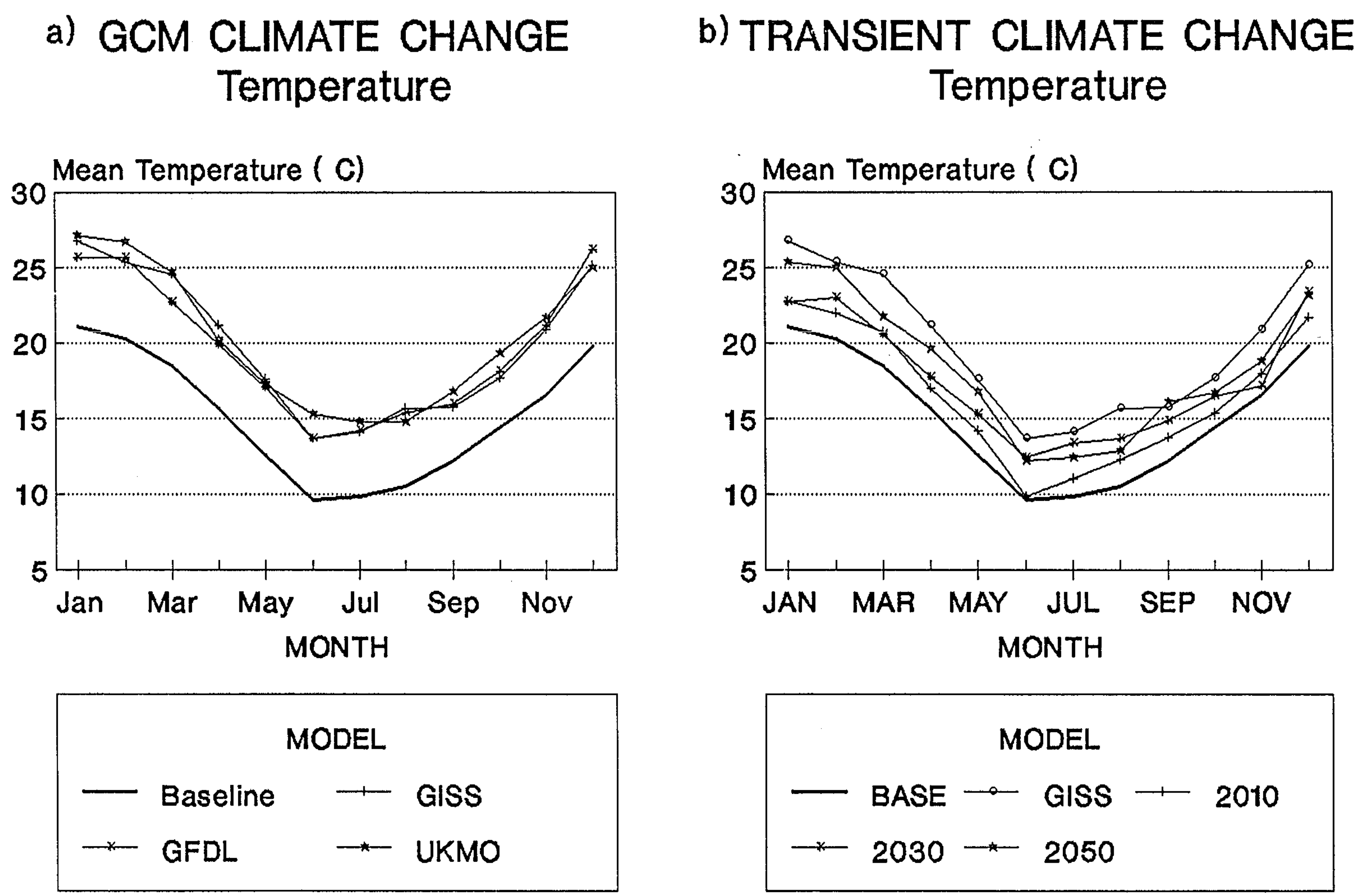


Fig. 3: Change in Mean Temperature (GCM and Transient)

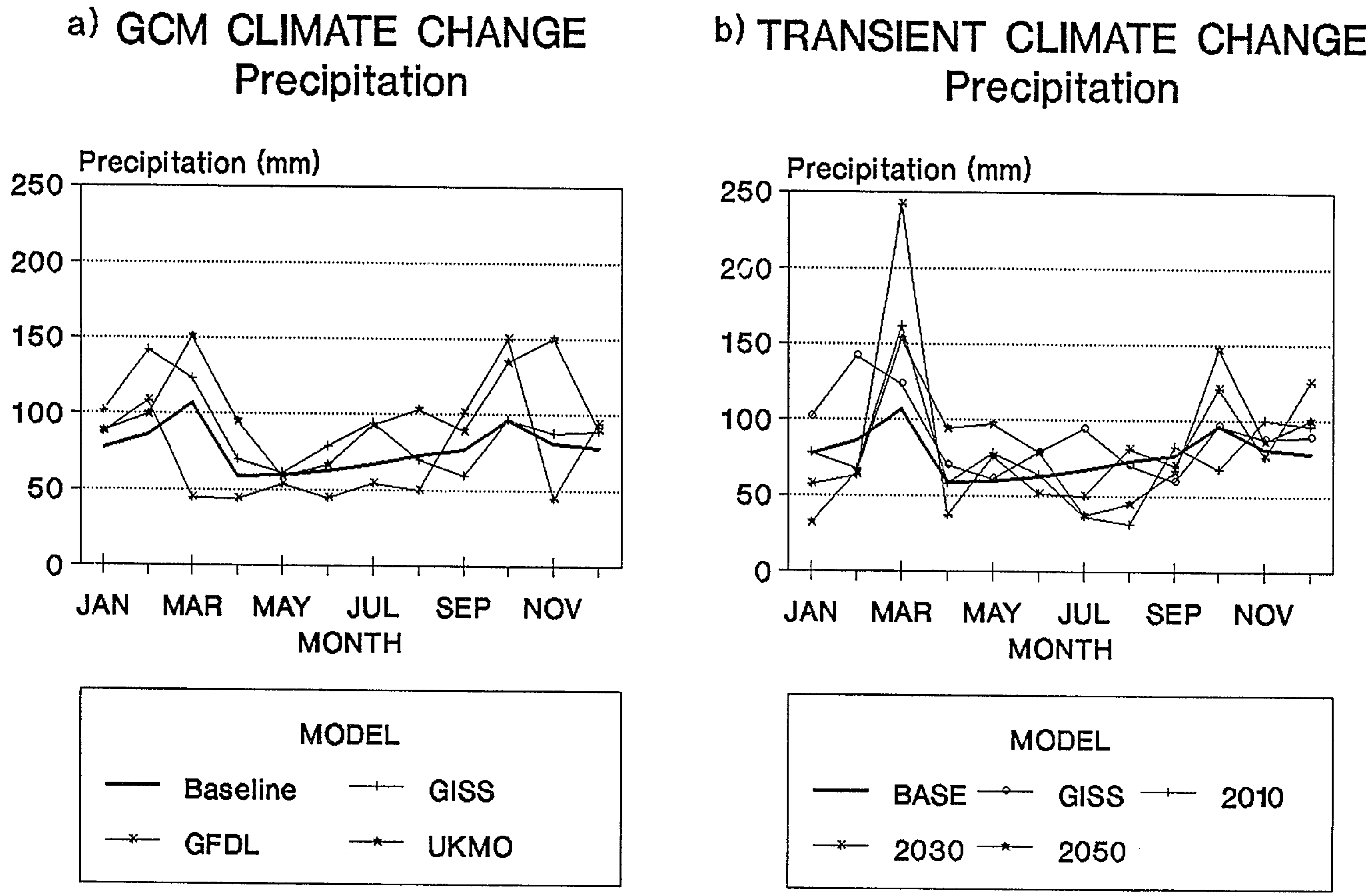


Fig. 4: Change in Precipitation (GCM and Transient)

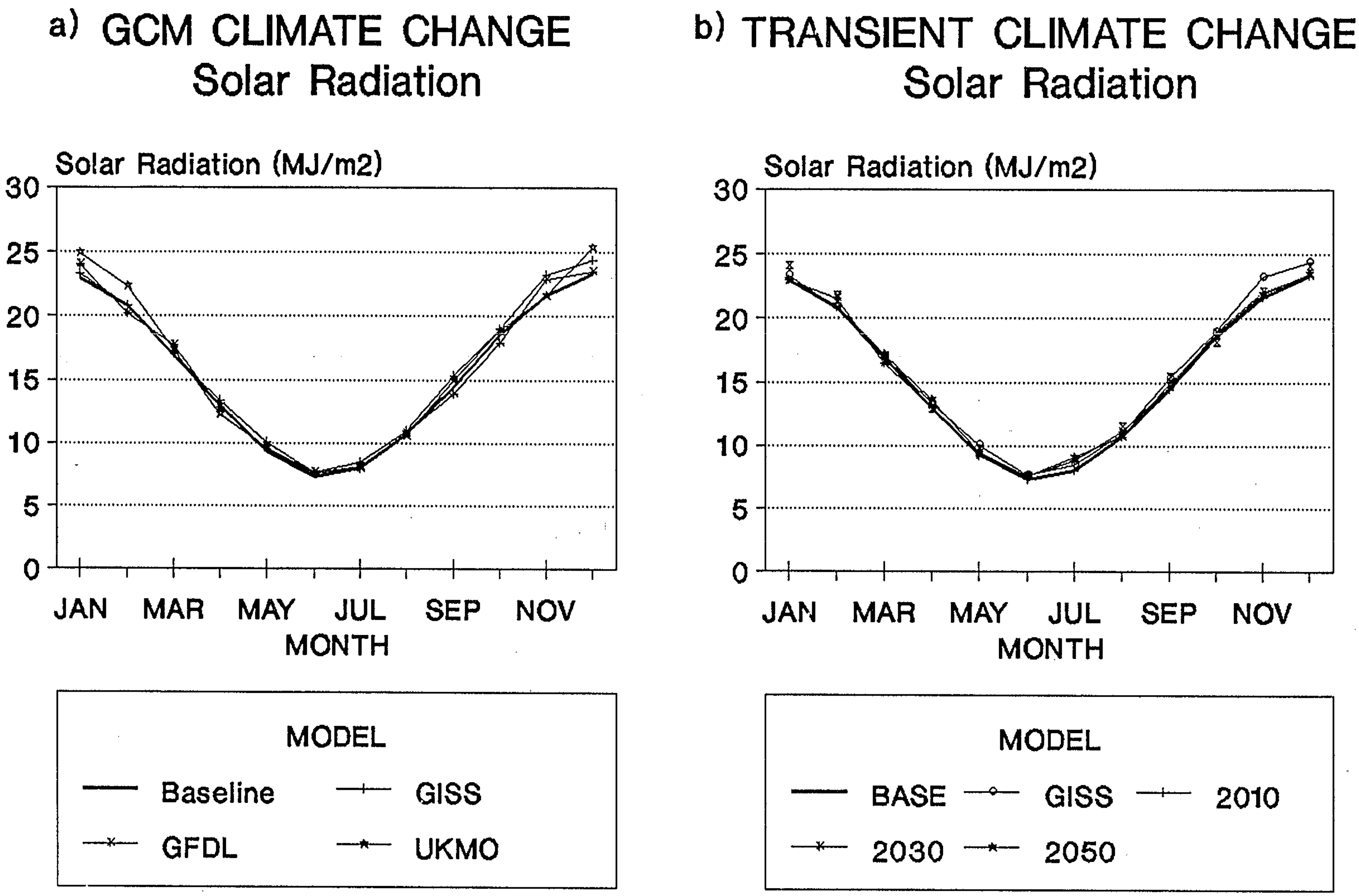


Fig. 5: Change in Solar Radiation (GCM and Transient)

Fig. 6a: BASELINE AND GCMs MEAN GRAIN YIELDS

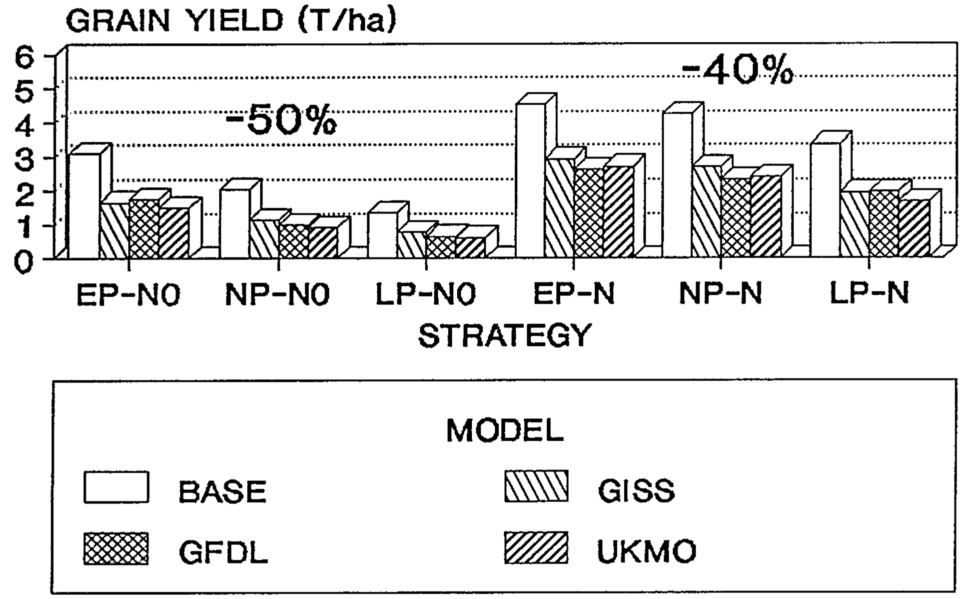


Fig. 6b: BASELINE AND GCMs MEAN GRAIN YIELDS

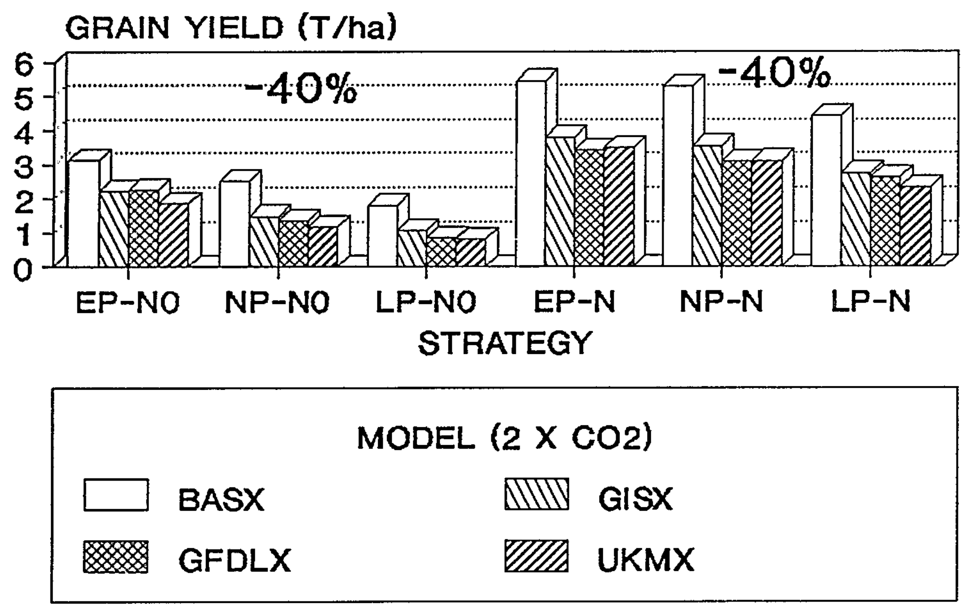


Fig. 7a: BASELINE AND GCMs CV % GRAIN YIELDS

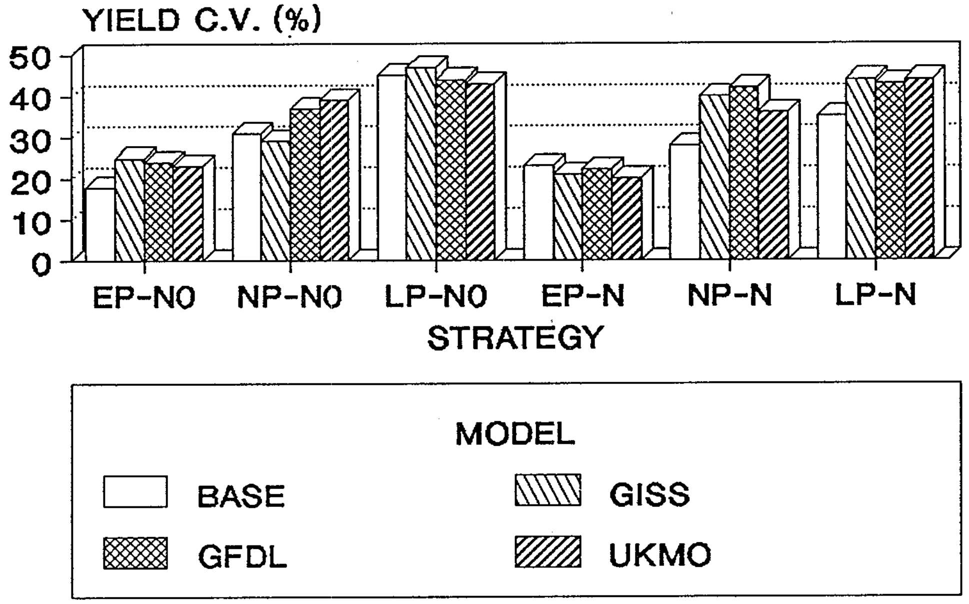


Fig. 7b: BASELINE AND GCMs CV % GRAIN YIELDS

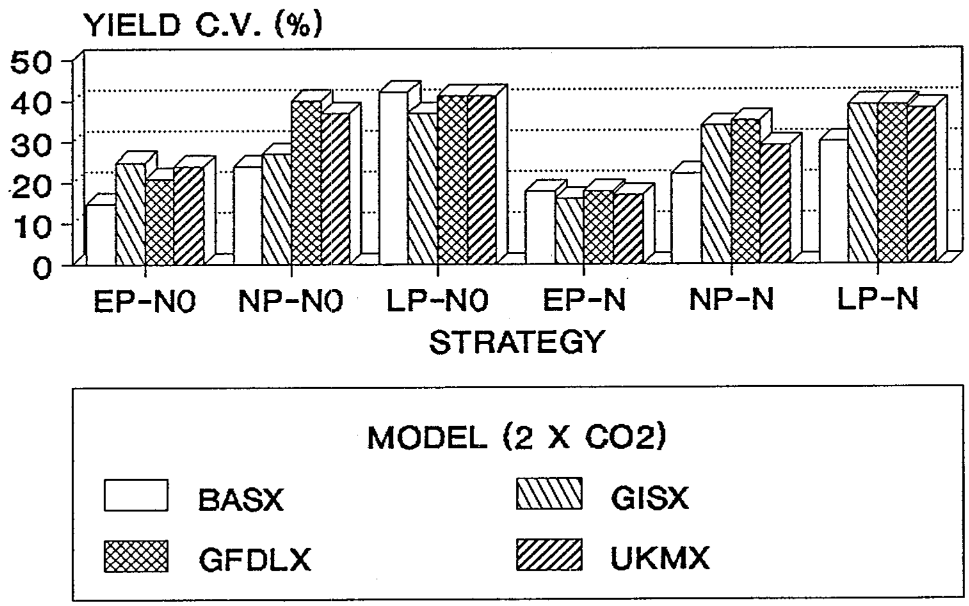


Fig. 8a: BASELINE AND GCMs MEAN BIOMASS PRODUCTION

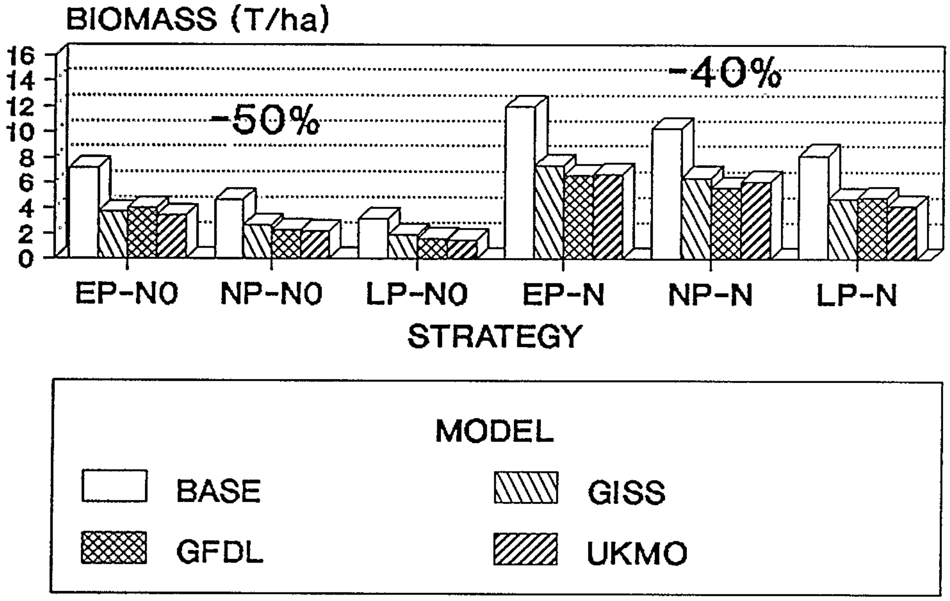


Fig. 8b: BASELINE AND GCMs MEAN BIOMASS PRODUCTION

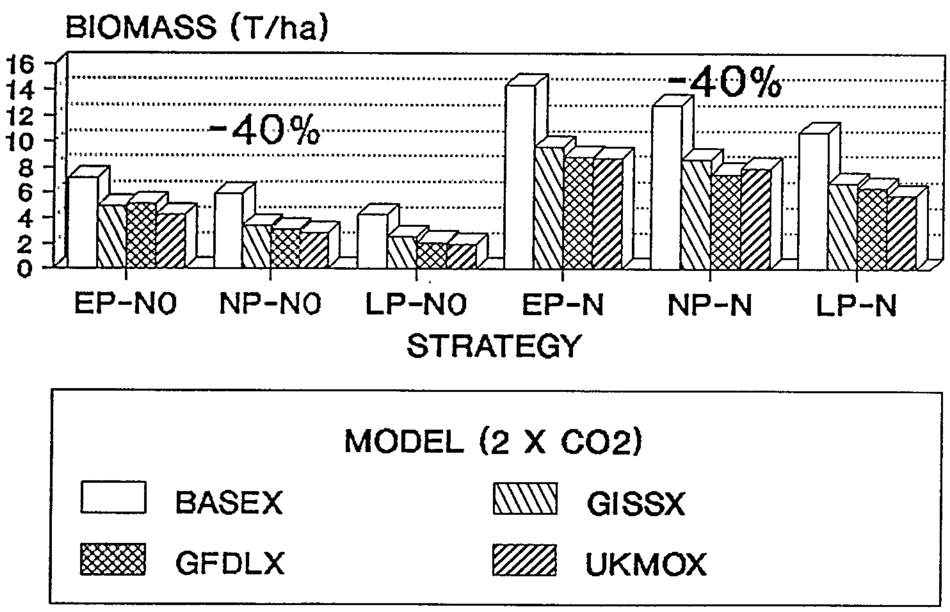


Fig. 9: BASELINE AND GCMs EMERGENCE - MATURITY LENGTH

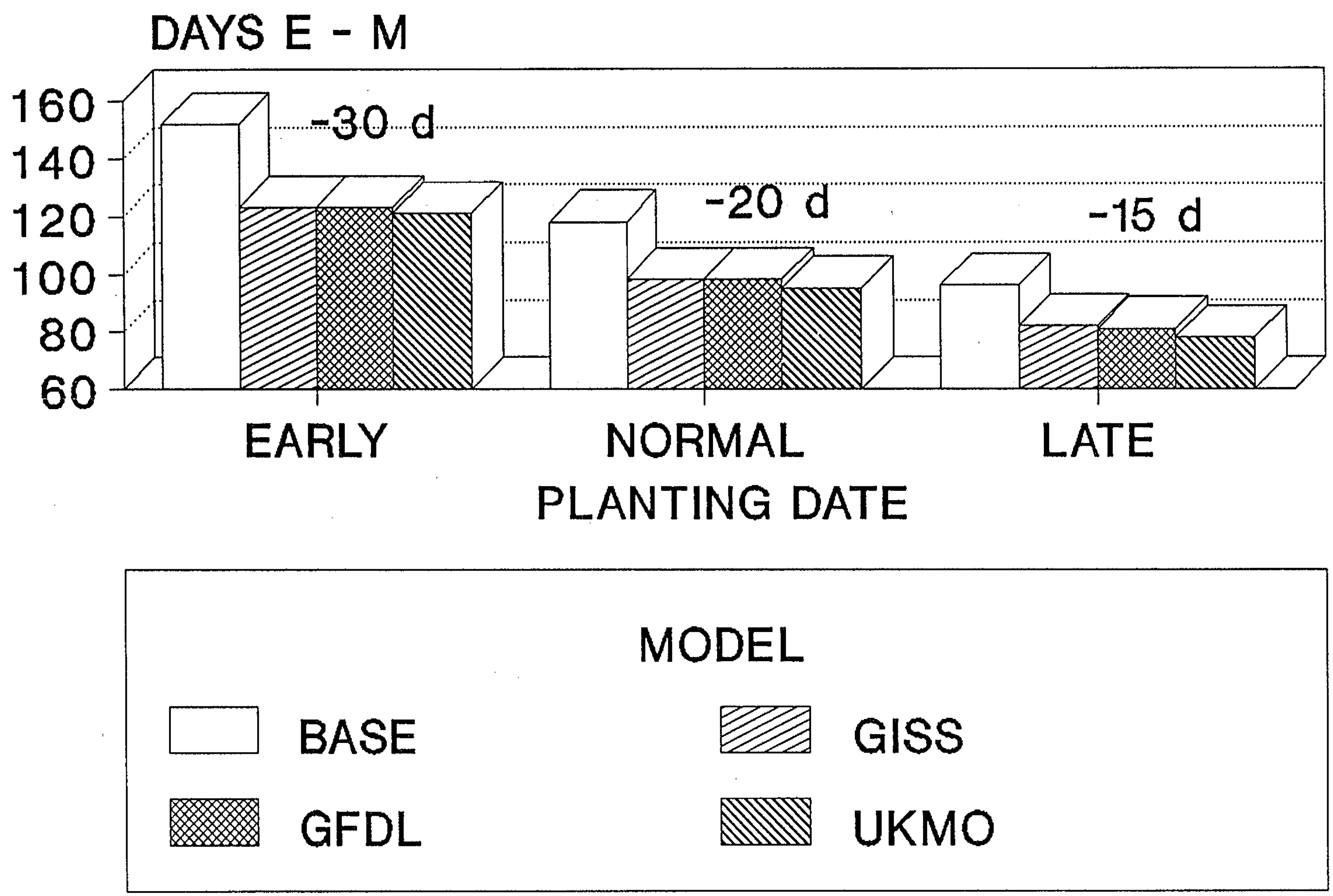


Fig. 10a: SENSITIVITY ANALYSIS MEAN GRAIN YIELDS

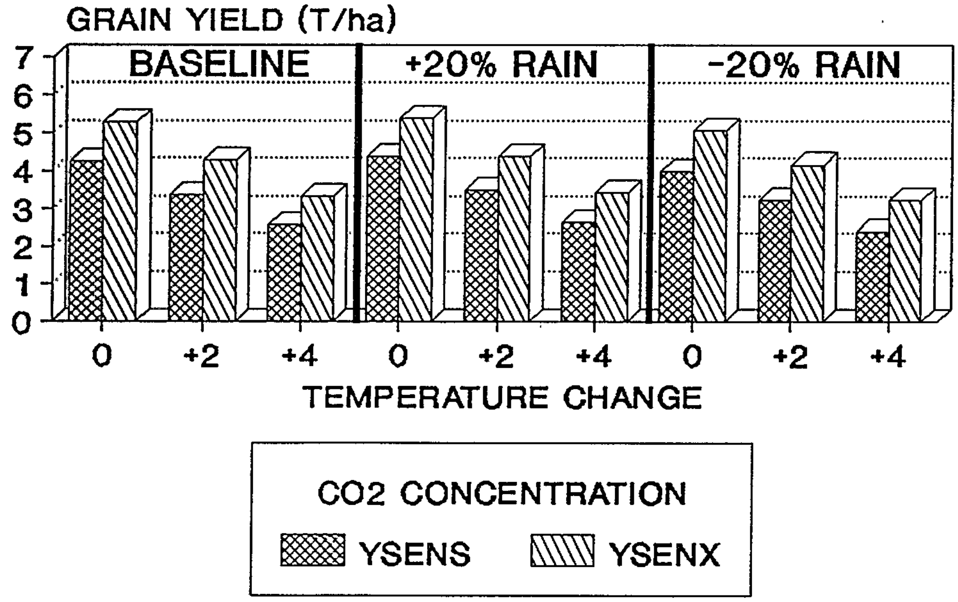


Fig. 10b: SENSITIVITY ANALYSIS C.V. GRAIN YIELDS

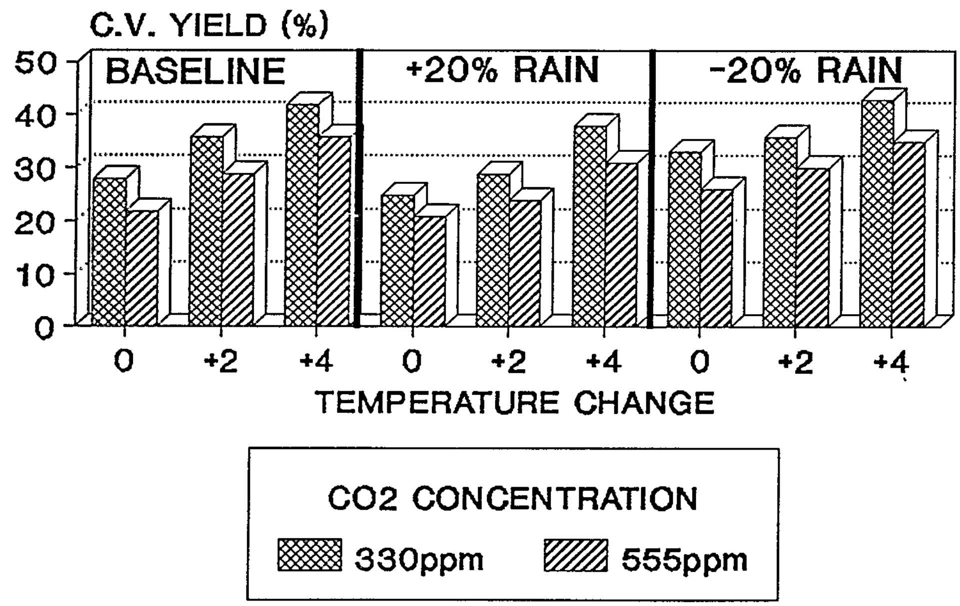


Fig. 11: SENSITIVITY ANALYSIS
MEAN BIOMASS PRODUCTION

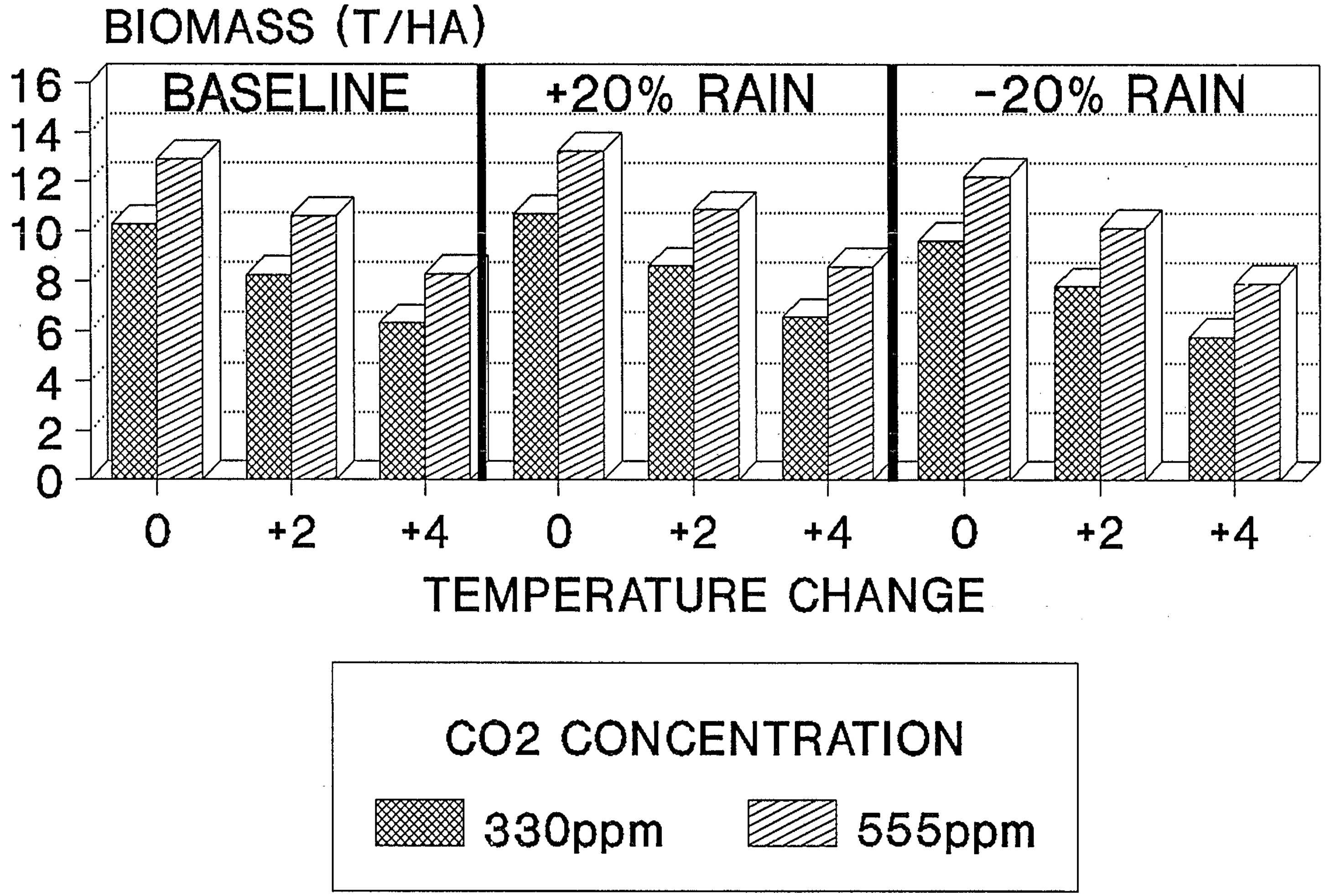


Fig. 12: SENSITIVITY ANALYSIS
EMERGENCE - MATURITY LENGTH

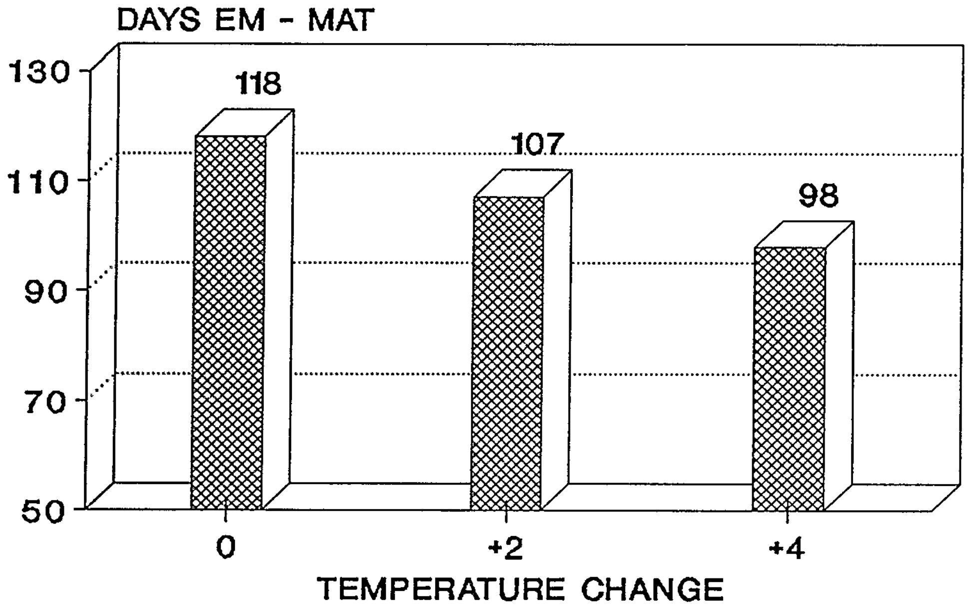


Fig. 13a: TRANSIENT ANALYSIS (GISS) MEAN GRAIN YIELDS

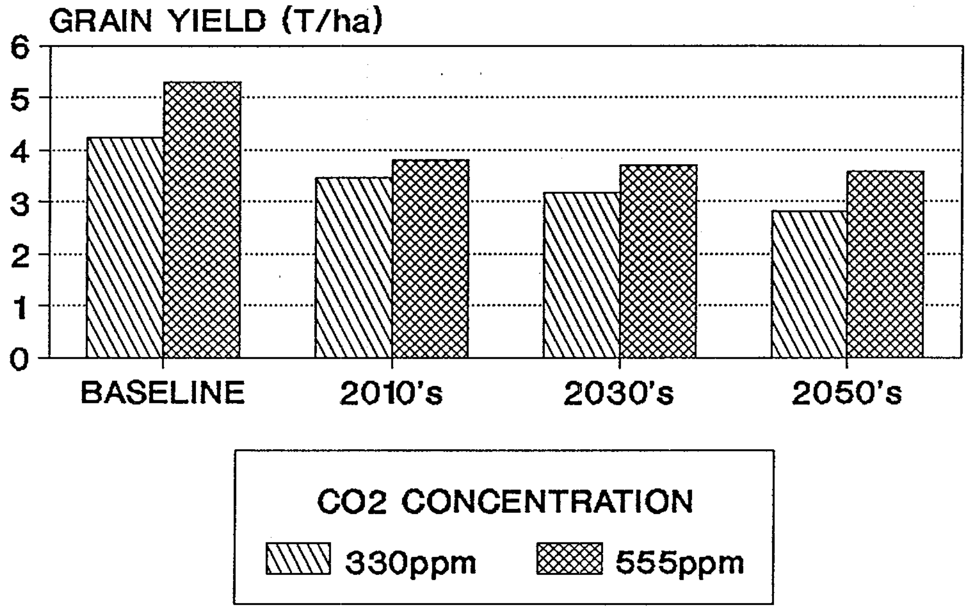


Fig. 13b: TRANSIENT ANALYSIS (GISS) C.V. GRAIN YIELDS

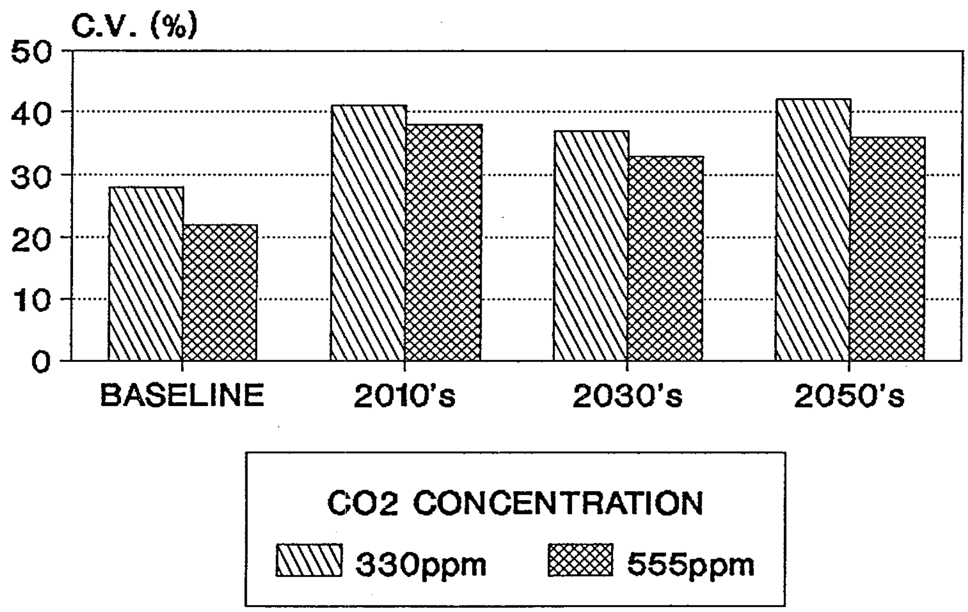


Fig. 14a: ADAPTIVE RESPONSE (UKMO) MEAN GRAIN YIELDS

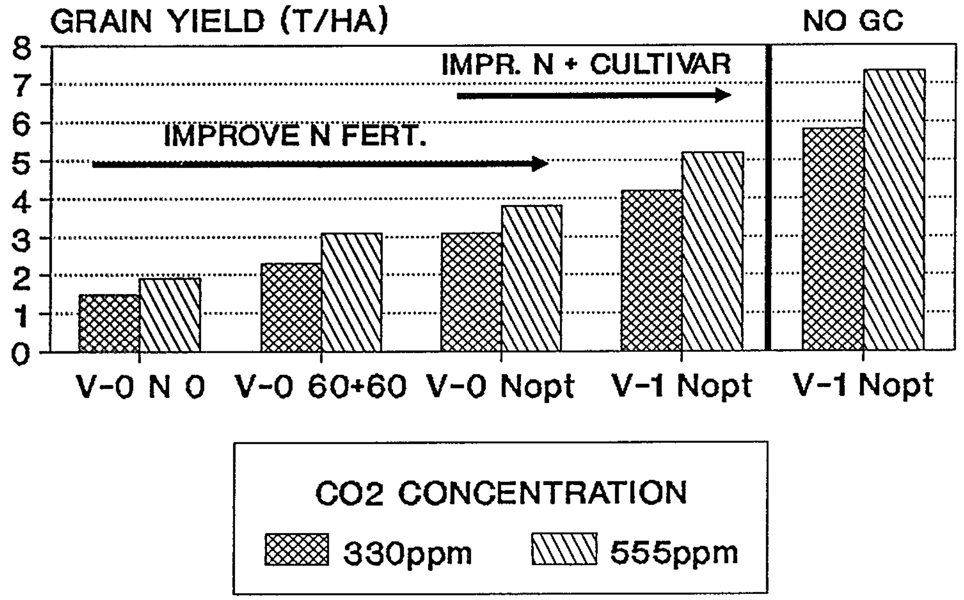


Fig. 14b: ADAPTIVE RESPONSE (UKMO) C.V. GRAIN YIELDS

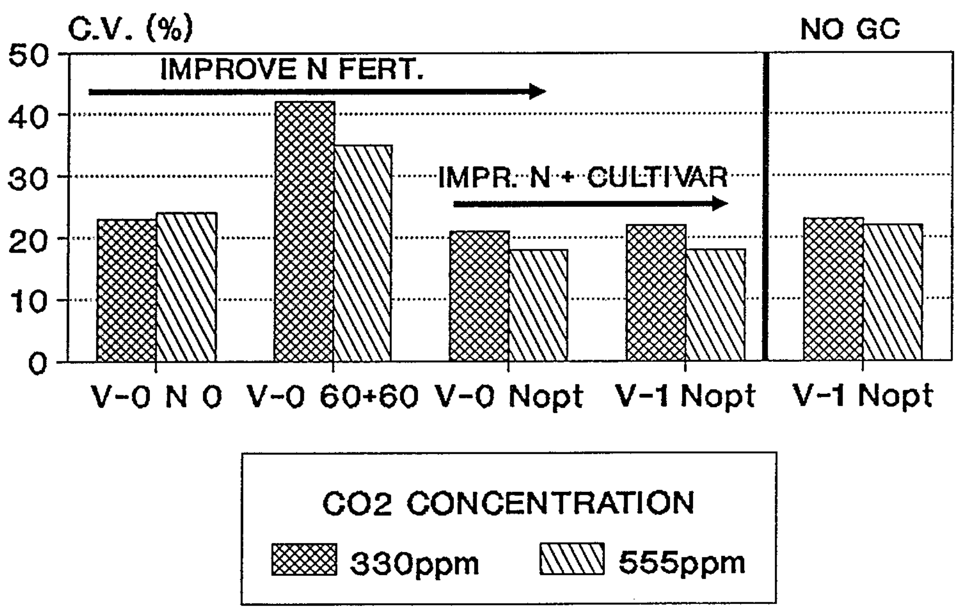
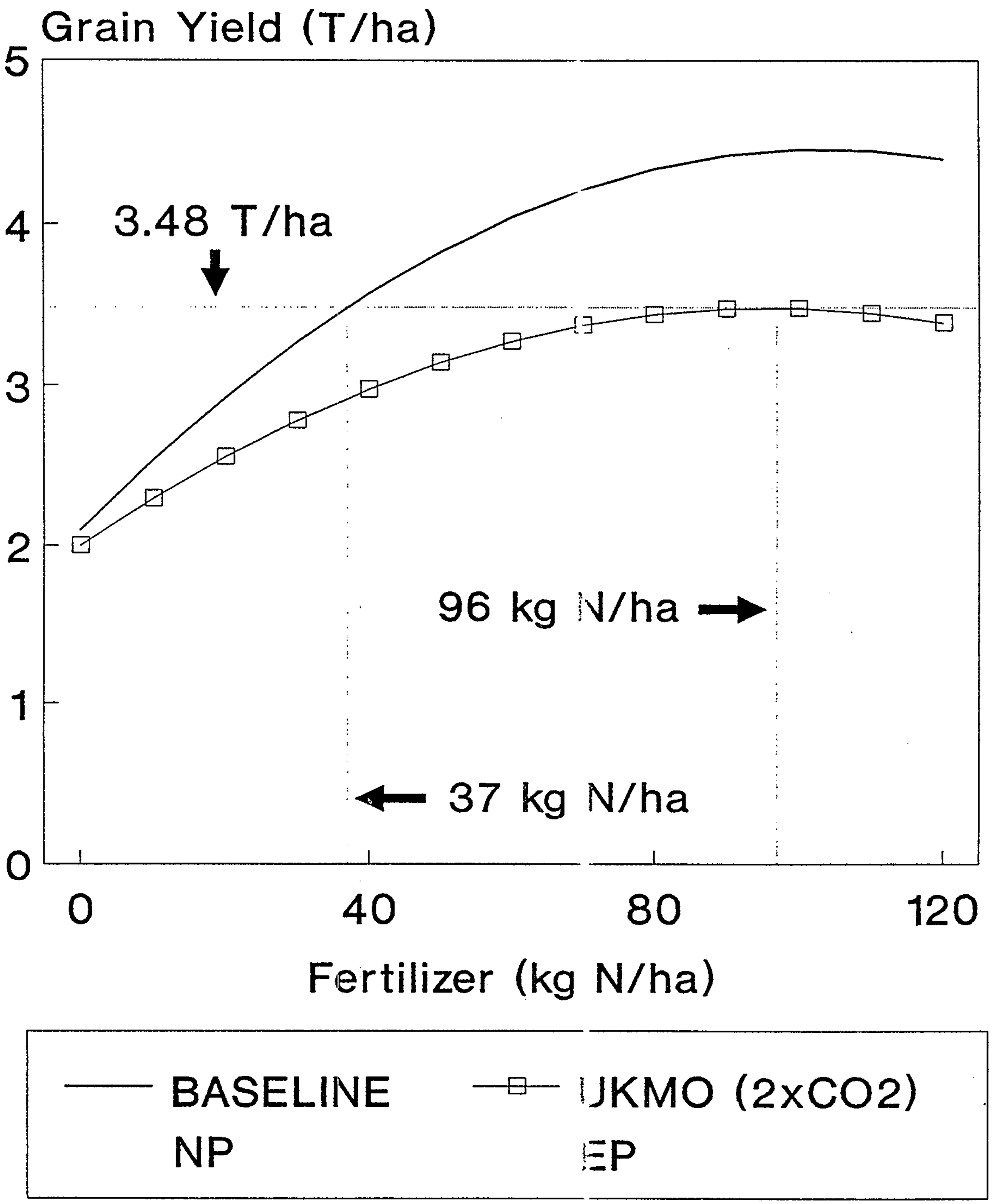


Fig. 15


Grain Yield (T/ha)
5
4
3
2
1
0
3.48 T/ha
96 kg N/ha
37 kg N/ha
0
40
80
120
Fertilizer (kg N/ha)
BASELINE
NP
UKMO (2xCO2)
EP

SECTION 4: EUROPE

POSSIBLE EFFECTS OF INCREASING $C0_2$ CONCENTRATION ON WHEAT AND MAIZE CROPS IN NORTH AND SOUTHEAST FRANCE

R. Delécolle, D. Ripoche
Station de Bioclimatologie INRA, France

F. Ruget, G. Gosse
Station de Bioclimatologie INRA, France

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The authors are grateful to Claude Varlet-Grancher and Pierre Pluchard (both from INRA) for providing wheat data.

SUMMARY

This study evaluated the potential effects of climate change due to increased trace gas concentrations in the atmosphere on wheat and maize yields in France. Sensitivity studies showed that yields generally decreased with increasing temperature, probably due to a shorter crop-growing season. When the direct effects of CO_2 on the crop were included, yield decreases were somewhat counteracted.

Under both temperate and mediterranean climates in France, winter cereal yields did not decrease under future climate conditions (provided that irrigation supply was not limiting under dry conditions). Under temperate climate, maize yields increased, while under mediterranean conditions, the reduction of phase duration induced a drastic yield decrease, even under optimal irrigation. Adaptation simulations (change in planting date) produced slightly higher yields. If these results are realized with global warming, maize may be farmed in France more extensively in the future.

INTRODUCTION

This study was part of an international endeavor to assess the possible effects of global climate change on world food production in the coming century. Any study of this type must account for the climate modifications induced by increasing trace gas concentrations in the atmosphere, which are simulated by general circulation models (GCMs), and the direct effects of increasing carbon dioxide concentration on plant physiology. These studies are particularly interesting in northern and middle Europe, where cropping systems will likely shift, within a few decades, from high-input production to more extensive practices, due to an increasing concern for pollution costs and over-production. It is therefore necessary to estimate whether climate change will create extra costs (irrigation, pesticides), or if increasing CO_2 will promote crop production at steady costs. In this study, we used the CERES plant process models to estimate the response of wheat and maize crops in France and to address the effects of climate change on yield and water demand.

Agricultural Regions and Systems

The research was conducted in two different agricultural areas in France (Figure 1). These regions were chosen because they represent two extremes of French agroclimatologic conditions. The northern plain is characterized by intensive cropping practices, semi-oceanic climate, and little water stress. The soils are deep silts with high field capacities. The most frequently grown crops are wheat and sugarbeet, with several secondary crops such as peas, potatoes, and beans. Maize was introduced in the northernmost areas 15 years ago.

The southeast has diverse crops. Fruits and vegetables, maize, sunflower, and sorghum are grown in irrigated areas; wheat (soft and durum) and barley, are usually rainfed except on very shallow soils. The climate is mediterranean, with drought periods during the summer, characterized by a large interannual variability. Soil types are highly variable and generally shallow with low field capacities. In river valleys, however, alluvial deposits and water tables insure better water supplies.

METHODS

Climate

For northern France, we used a timeseries of climate data from 1951 to 1980 (1984 for wheat) that was available from Versailles-INRA (lat. 49°N). This weather station, albeit located in the southern part of the study area, provides data that are representative of the area. For the South, the Avignon-INRA weather station (lat. 44.9°N) provided data from 1968 to 1984.

Crop Models and Management Variables

Wheat and maize were the sample crops for this study. These crops provide a physiological comparison between C3 and C4 crop responses to the direct effects of increased CO_2, and a comparison between winter and spring crops for testing the influence of indirect climatic effects on season length and water requirements. Both crops were tested at each site.

The choice of genotypes was guided by the availability of calibration data. For wheat, we chose one genotype per location to account for the specific conditions and farmers' practices at each site. We chose the genotype Arminda (winter type, long cycle) for northern France, and the genotype Fidel (half-spring, medium-length cycle) for the South. For maize, we used only one genotype, Dea, which can be grown in both climates, with special regard to its insensitivity to photoperiod. It is often used as a control in productivity tests.

Crop models. The CERES-Wheat (Godwin et al. 1989) and CERES-Maize (Ritchie et al. 1989) models provided by the DSSAT package were used to simulate wheat and maize crops. Modified versions accounted for higher-than-ambient CO_2 concentration changes. Photosynthesis enhancement factors for various CO_2 concentrations came from Allen et al. (1987).

Soils. For northern France, we used a standard "Deep Silt Loam" soil (IBSNAT 1989) tp represent the soils found in this area. For the Southeast, we created a specific soil file from the soil properties that exist in a typical alluvial area near Avignon—although farmers would grow mostly vegetables and other high-return crops on this soil.

Irrigation. For all of the simulations, the initial soil water was set to 100% capacity for each layer. This is a realistic assumption for both locations *under present climatic conditions*. When irrigation was applied, the "automatic" option was chosen to provide the crop with a non-limiting situation.

Calibration of the Crop Models

Wheat. The CERES-Wheat genetic coefficients for both wheat genotypes were estimated from a dataset from the Mons-en-Chaussée-INRA experiment station (49.8°N). The data were representative of the wheat area in the North. We used a sowing date experiment with three years of data and with eight independent treatments. Experimental data were split into two sets—one for calibration and the other for validation. The calibration was carried out in two phases. First, each parameter was calibrated directly from observed results (phase durations, biometric ratios, growth rates) to obtain rough parameter values. Second, these values were used in model runs and arbitrarily adjusted to attain a pseudo-best fit of observed data (Table 1). The validation procedure showed acceptable results for Fidel, but underestimated yields for Arminda by 13%, due to underestimation of final kernel weights.

Durations from sowing to anthesis were simulated adequately most of the time, but simulated anthesis-to-maturity periods were generally too short in comparison to reality. These results were attained with values of G_1 coefficients which are different from what is suggested in DSSAT's CERES-Wheat guide for European wheats (Godwin et al. 1989). All growth coefficients are highly correlated, thus leading to potentially large instabilities in estimated values—a crucial point for study in the future. Figure 2 displays the sensitivity of simulated yields to values of P1D, G1, and G2.

Maize. Two sets of data were used to study maize. The results from a planting-density trial in Mons-en-Chaussée were used for the calibration of genetic parameters and initial values (sowing depth). The results from another density trial in Grignon (near Versailles) allowed us to test the consistency of estimated parameters. P1 and sowing depth have been adjusted to attain satisfactory anthesis dates and maximum leaf area indices, and P2 was set to zero because Dea has been shown to be a non-photoperiodic genotype.

The calibration of parameters linked to grain number and grain filling was problematic. In France, maize kernels rarely reach "physiological maturity" (P5). Also, the potential grain number was dramatically increased to insure an adequate simulation of the final number. Finally, the grain-filling rate (G3) was set to far below the potential value. Therefore, the set of parameters obtained (Table 2) is different from the values indicated for our latitude (Ritchie et al. 1989).

Climate Change Scenarios

Climate change ratios from three GCMs have been applied to both weather series. Three equilibrium GCMs were used: GISS (Goddard Institute for Space Studies; Hansen et al. 1983); GFDL (Geophysical Fluid Dynamics Laboratory Model; Manabe and Wetherald 1987); and UKMO (United Kingdom Meteorological Office Model; Wilson and Mitchell 1987). Transient climate scenarios were also created with the GISS transient model (Hansen et al. 1988). Figure 3 shows the monthly averages of changes in required weather variables for the three doubled CO_2 and transient (2010s, 2030s, 2050s) scenarios.

Temperature. For both regions, temperatures simulated by GISS and GFDL lie 3-4°C above the present mean values, whereas UKMO predicts more drastic changes—more than 10°C during the summer in Avignon, and more than 6°C during the winter in Versailles.

Precipitation. According to all scenarios, precipitation increases during the winter in Avignon and throughout the year in Versailles. UKMO simulates a dramatic precipitation decrease during the summer in the South. Individual monthly values for precipitation change are very chaotic in the Southeast for the GISS and UKMO simulations, and in the North for GFDL.

Solar radiation. For UKMO and GISS, the simulations of solar radiation suggest an increase of about 10% over the year for both sites. GFDL simulations are very close to baseline values.

RESULTS WITHOUT ADAPTATION

Wheat

The following results correspond to current management practices: sowing on November 1 and plant population of 250 plants m^{-2} for both sites.

Yield and season length. To synthesize the effects of global change on crop behavior (yield, days to maturity), Figures 4-9 show scenarios arranged by the corresponding yearly mean increase in temperature. We simulated both irrigated and rainfed production at each location. For the North (Versailles), the effect of irrigation is negligible, so irrigated and rainfed treatments are represented by one set of points in Figures 4a and 4b. The effects of climate change alone tended to decrease yields up to almost 30% (GFDL), probably due to the shortened season length of up to one month (Figure 4b). When CO_2 physiological effects were added, this effect was counteracted; the yield changes were almost nonexistent (at least for the transient and equilibrium GISS scenarios).

Figures 5a and 5b show the results for irrigated and rainfed wheat in Avignon. The irrigated results were similar to those obtained from Versailles. Rainfed wheat was less adversely affected by climate change, with the exception of the UKMO climate change scenario. When the direct effects of CO_2 were included, all scenarios produced increased yields except UKMO. Table 3 summarizes results of water consumption by the crops as a percent variation from the baseline for Versailles (irrigated) and for Avignon (irrigated and rainfed).

Water consumption. The simulation results show the difference between the effects of climate change alone, due to a shortening of the crop season, and the effects of climate change and increased CO_2, due to increasing stomatal resistance. In both cases, the major reduction in evapotranspiration (ET) (Table 3) was mostly attributable to climate effects (up to about two thirds), with a magnitude that varies according to scenario. See also the sensitivity analysis (Appendix A). In the North, transient scenarios induced a small reduction in ET, whereas equilibrium scenarios had a greater influence (up to a 22% reduction). For irrigated wheat in the South, the overall effect on evapotranspiration could range from -10% to -20%. Rainfed crop ET showed less dramatic reductions.

Maize

The following results correspond to sowings on May 1 in Versailles and April 15 in Avignon. The plant population was 9 plants m^{-2} in both cases.

Yield and season length. Figures 6a and 6b summarize the results for yield and season length for maize in Versailles, with the same representation as for wheat. Irrigation did not modify season length, which showed a significant decline when the mean temperature roses, especially in the extreme case of UKMO. Surprisingly, the yield response to climate change alone shows a marked optimum for conditions in 2010. This could be interpreted as a consequence of the shift in development phases, which positioned the grain-filling period more favorably in terms of available solar radiation. Even if season length was reduced, the yield was not substantially decreased below the baseline level even in the least favorable conditions (equilibrium scenarios). This trend was confirmed by sensitivity analysis results (Appendix B). Adding the CO_2 physiological effect increased yields up to 15-20% above the baseline.

Figure 7 shows the results from irrigated and rainfed maize at Versailles. Irrigation had only a slight influence on the yields. (Irrigated baseline was 8.52 t ha^{-1} compared with 8.43 t ha^{-1} under rainfed conditions.) Although changing the climate reduced the length of the development phases, it also increased the yields in the rainfed case (Figure 8a), probably due to the same phenomenon that occurred in Versailles (better timing of development to radiation availability). Adding direct CO_2 effects led to a large increase in grain dry-matter production. Rainfed baseline yields were very low (simulated 2.3 t ha^{-1}). Yet if the simulation results are reliable, a high CO_2-high temperature environment would lead to high yields under rainfed conditions (simulated 5.9 t ha^{-1} for UKMO). With irrigation, maize yields showed a decline from 10 to 30% with climate change alone, and adding CO_2 effects did not consistently modify the results (Figure 9). The worst yields in this case were still higher than the best rainfed simulations.

Water consumption. Table 4 summarizes simulated ET for maize. In Versailles, decreases in water use largely depended on the assumed scenario. When direct CO_2 effects were added, a 20% to 30% decrease in water consumption occurred in the equilibrium and 2050 scenarios for irrigated and rainfed crops. These results were generally similar to results for irrigated crops in Avignon.

RESULTS WITH ADAPTATION

Possible adaptations to future climate conditions were tested with a range of sowing dates to adjust the timing of crop phenological events for photothermal time and radiation availability.

Wheat

For wheat, three sowing dates were tested for both locations: two of them earlier (September 1 and October 1) than the regular date (November 1) and one later (December 1). A four-point response curve for grain yield appears in Figure 10. Figure 10 also illustrates the grain dry-matter response to the sowing date, representing (in percent of $1xCO_2$ baseline value for November 1 sowing) the transient scenarios including direct CO_2 effects. For Versailles, the sowing date ded not help to counteract the effect of season length in the most pessimistic case (2050). Whatever the scenario, the yield difference between the first and last sowing was about the largest that can be expected in an agronomic experiment at potential production level. In Avignon, even earlier sowing dates improved the situation in the near future projections (compare September 1, October 1, November 1, 2010s, and 2030s), but the initial soil water conditions would probably hinder this solution.

Maize

Figure 11 illustrates the effects of two more sowing dates, 15 days earlier and 15 days later than the regular date. For the North, it appears that an earlier sowing date would not modify the yield changes, but delaying the planting date clearly reduced the benefit of climatic change. Earlier sowing dates present a problem for spring crops that are limited by soil temperature. Additional studies on the possible warming of upper soil layers under changing weather conditions are needed to study this adaptation.

In the South, postponing the planting dates would counterbalance the negative influence of climate change, at least in the near future. This effect may be due to a better synchrony between phasic development and available energy, as was suggested for Versailles. For the 2050 scenario, further study of an earlier sowing (April 1) is necessary, assuming again that more information on soil temperature will be available.

DISCUSSION

The overall trends that can be deduced from this study are: (1) Season lengths will be shortened by climate change; (2) Yields will decrease in proportion to the magnitude of warming, but may be partially mitigated by direct CO_2 effects (up to an increase of 5°C in temperature); and (3) Water use will decrease.

Two major questions remain: (1) Do the multiplicative coefficients used to represent high-CO_2 photosynthetic response account for long-term plant behavior especially with possible acclimation? and (2) How realistic is the simulation of the water budget in the crop models?

The calibration problems we encountered preclude straightforward interpretation of absolute values, but the relative or differential results probably deserve more credit. Assuming that complete water repletion of all soil layers at sowing may strongly temper the following statements, it may be concluded that: (1) Under both temperate and mediterranean climates in France, winter cereal yields will not be decreased by future conditions (provided that irrigation supply is not limiting under dry conditions); and (2) Under temperate climate, maize could take advantage of development-phase shrinkage and improve its radiation-use efficiency. The traditional assumption that C3 crops would take precedence over C4 crops because they use CO_2 more efficiently would become questionable in this case. Inversely, under mediterranean conditions, the reduction of the phase duration may induce a drastic decrease in yields, even under optimal irrigation. Could maize become a potential crop for extensive farming in the two regions, as the simulations would suggest? The answer depends in part on the ability of CERES-Maize to account for the effect of water stress on ear fertility and the potential grain number.

Finally, the diversity of French climates and soils prohibits generalizing these results for the entire country. The two sites chosen for this study represent extremes for intensive crops in France; more continental situations should be studied to investigate the behavior of crops in the eastern agricultural plains regions under future climate.

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FIGURES CAPTIONS

Figure 1. Location of test sites (Versailles and Avignon) and calibration station (Mons-en-Chaussée) used for France.

Figure 2. Sensitivity analysis of wheat yield to parameters P1D, G1 and G2. Mean values (solid line) and confidence intervals (dotted lines) are computed for all available years in each weather series.

Figure 3. Changes in weather variables as simulated by GCMs (a,b: temperature; c,d: rainfall; e,f: radiation).

Figure 4. Yield variation (in percent of 1xCO_2 baseline) and season length for wheat in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 5. Yield variation (in percent of 1xCO_2 baseline) and season length for wheat in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 6. Yield variation (in percent of 1xCO_2 baseline) and season length for rainfed maize in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 7. Yield variation (in percent of 1xCO_2 baseline) for irrigated maize in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 8. Yield variation (in percent of 1xCO_2 baseline) and season length for irrigated maize in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 9. Yield variation (in percent of 1xCO_2 baseline) for irrigated maize in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

Figure 10. Wheat-yield response to sowing date (in percent of 1xCO_2 baseline) for GISS transient scenarios in Versailles and Avignon.

Figure 11. Maize-yield response to sowing date (in percent of 1xCO_2 baseline) for GISS transient scenarios in Versailles and Avignon.

Table 1. Values of genetic coefficients used for wheat.

Genotype	P1V	P1D	P5	G1	G2	G3
Fidel	4.5	3.0	4.5	4.5	1.5	2.5
	(0.5)	(3.5)	(2.5)	(4.0)	(3.0)	(2.0)
Arminda	6.0	4.5	4.5	4.6	1.2	1.7
	(6.0)	(3.5)	(4.0)	(4.0)	(3.0)	(2.0)

P1V Vernalization coefficient
P1D Photoperiodism coefficient
P5 Grain filling duration coefficient
G1 Kernel number coefficient
G2 Kernel weight coefficient
G3 Spike number coefficient
(Values recommended in DSSAT are shown between brackets)

Table 2. Values of genetic coefficients used for maize.

Genotype	P1	P2	P5	G1	G2
Dea	180	0.0	640	800	7
	(130)	(0.2)	(680)	(780)	(8)

P1 Juvenile phase coefficient
P2 Photoperiodism coefficient
P5 Grain-filling duration coefficient
G1 Kernel number coefficient
G2 Kernel weight coefficient
(Values recommended in DSSAT are shown between brackets)

Table 3. Simulated total evapotranspiration for wheat (in percent base $1xCO_2$).

Scenario	Climate Change Alone	Climate Change and CO_2 Physiol. Effects
	Versailles (irrigated)	
BASE	0	-6
GISS	-5	-12
GFDL	-16	-22
UKMO	-16	-16
2010	4	1
2030	3	-1
2050	-1	-7
	Avignon (irrigated)	
BASE	0	-8
GISS	-12	-8
GFDL	-12	-18
UKMO	-10	-16
2010	-6	-8
2030	-5	-10
2050	-10	-16
	Avignon (rainfed)	
BASE	0	-4
GISS	-7	-11
GFDL	-9	-13
UKMO	-7	-10

Table 4. Simulated total evapotranspiration for maize (in percent of base $1xCO_2$).

Scenario	Climate Change Alone	Climate Change and CO_2 Physiol. Effects
	Versailles (rainfed)	
BASE	0	-16
GISS	-11	-24
GFDL	-16	-29
UKMO	-11	-25
2010	0	-5
2030	-4	-12
2050	-6	-19
	Versailles (irrigated)	
BASE	0	-17
GISS	-10	-25
GFDL	-16	-29
UKMO	-11	-26
	Avignon (irrigated)	
BASE	0	-16
GISS	-8	-23
GFDL	-9	-23
UKMO	-7	-20
2010	-6	-11
2030	-8	-16
2050	-9	-21

Appendix A. Sensitivity analysis of CERES-Wheat to climate and CO_2 changes.

	Changes		VERSAILLES			AVIGNON		
CO_2	Precip.	Temp.	Yield	Seas.L.	ET	Yield	Seas. L.	ET
(ppm)	(%)	(°C)	(t ha^{-1})	(days)	(mm)			
330	0	+0	6.4	252	483	6.32	216	421
		+2	5.9	241	460	6.3	205	396
		+4	5.3	231	437	5.8	194	375
	+20	+0	6.5	252	491	6.8	216	440
		+2	6.0	241	466	6.6	205	410
		+4	5.3	231	442	5.9	194	387
	-20	+0	6.3	252	470	5.5	216	394
		+2	5.9	241	449	5.8	205	375
		+4	5.2	231	429	5.5	194	357
555	0	+0	7.7	252	454	7.9	216	403
		+2	7.0	241	431	7.7	205	376
		+4	6.2	231	410	6.9	194	357
	+20	+0	7.7	252	458	8.2	216	418
		+2	7.0	241	435	7.9	205	387
		+4	6.2	231	412	7.0	194	366
	-20	+0	7.6	252	445	7.1	216	380
		+2	6.9	241	424	7.3	205	361
		+4	6.2	231	405	6.7	194	343

Appendix B. Sensitivity of CERES-Maize to climate and CO_2 changes.

	Changes		VERSAILLES			AVIGNON		
CO_2	Precip.	Temp.	Yield	Seas. L.	ET	Yield	Seas. L.	ET
(ppm)	(%)	(°C)	(t ha^{-1})	(days)	(mm)			
330	0	+0	8.4	159	442	10.9	109	458
		+2	9.3	128	416	9.5	97	428
		+4	8.6	108	384	8.5	89	408
	+20	+0	8.5	159	450	10.9	109	461
		+2	9.3	128	423	9.5	97	432
		+4	8.6	108	389	8.5	89	411
	-20	+0	9.4	159	432	10.8	108	453
		+2	9.1	128	405	9.5	97	424
		+4	8.5	108	376	8.5	89	405
555	0	+0	10.0	159	369	11.6	109	385
		+2	9.9	128	349	10.2	97	361
		+4	9.1	108	323	9.1	89	345
	+20	+0	9.0	159	375	11.6	109	389
		+2	9.9	128	354	10.1	97	363
		+4	9.1	108	328	9.0	89	346
	-20	+0	9.0	159	361	11.5	108	381
		+2	9.9	128	342	10.2	97	356
		+4	9.1	108	318	9.1	89	341

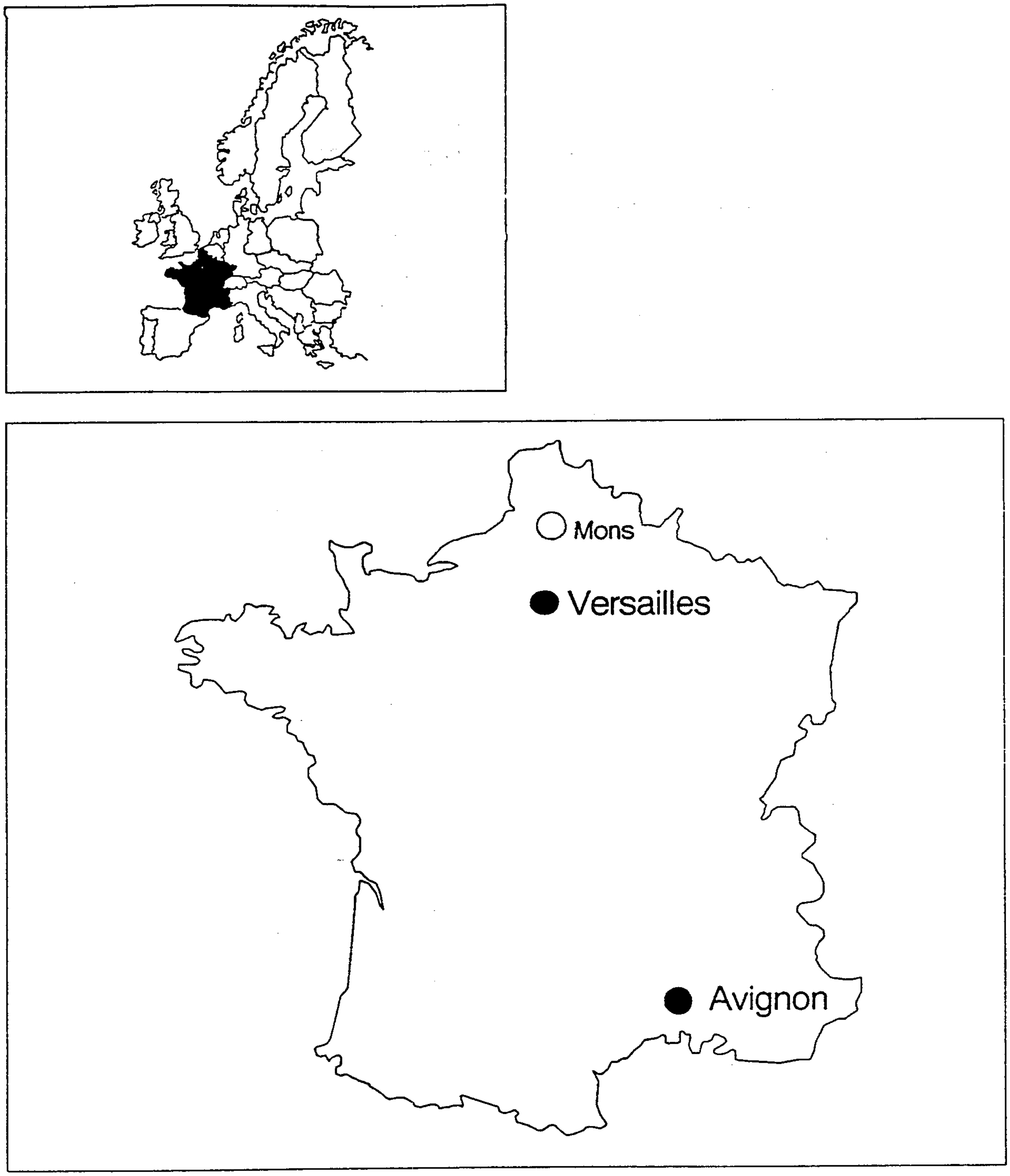

Figure 1. Location of test sites (Versailles and Avignon) and calibration station (Mons-en-Chaussée) used for France.

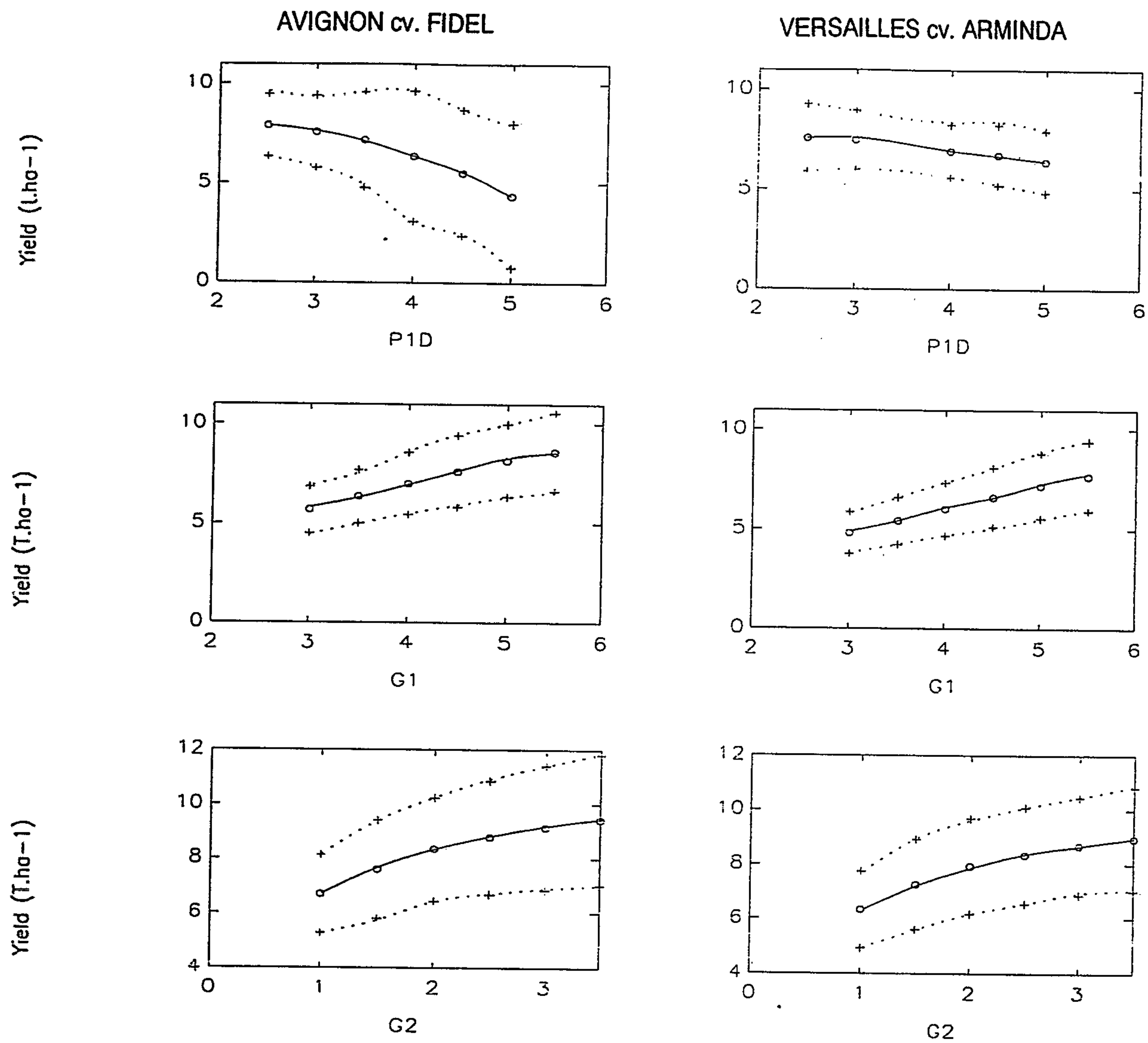

Figure 2. **Sensitivity analysis of wheat yield to parameters P1D, G1 and G2. Mean values (solid line) and confidence intervals (dotted lines) are computed for all available years in each weather series.**

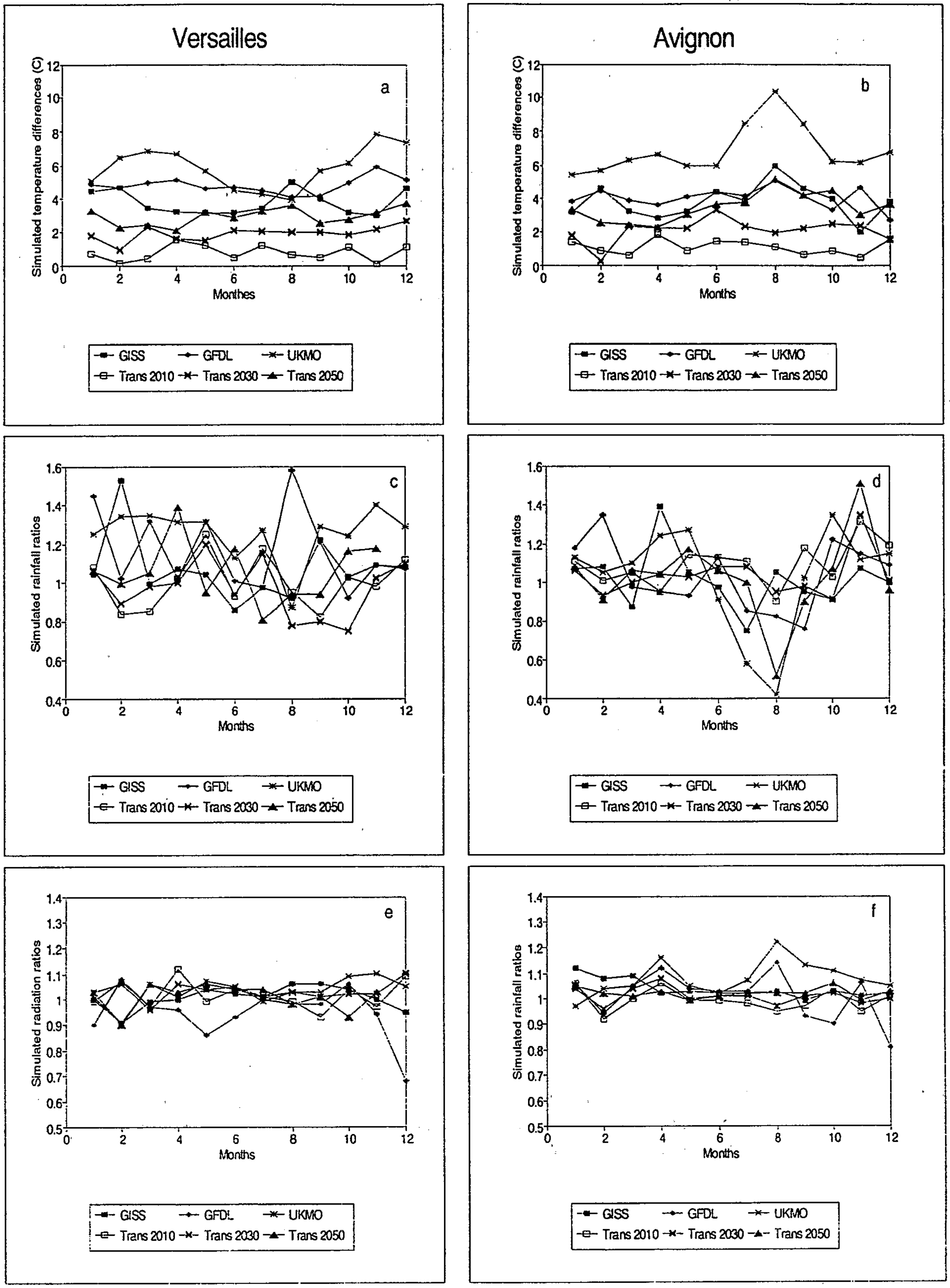

Figure 3. **Changes in weather variables as simulated by GCMs (a,b: temperature; c,d: rainfall; e,f: radiation).**

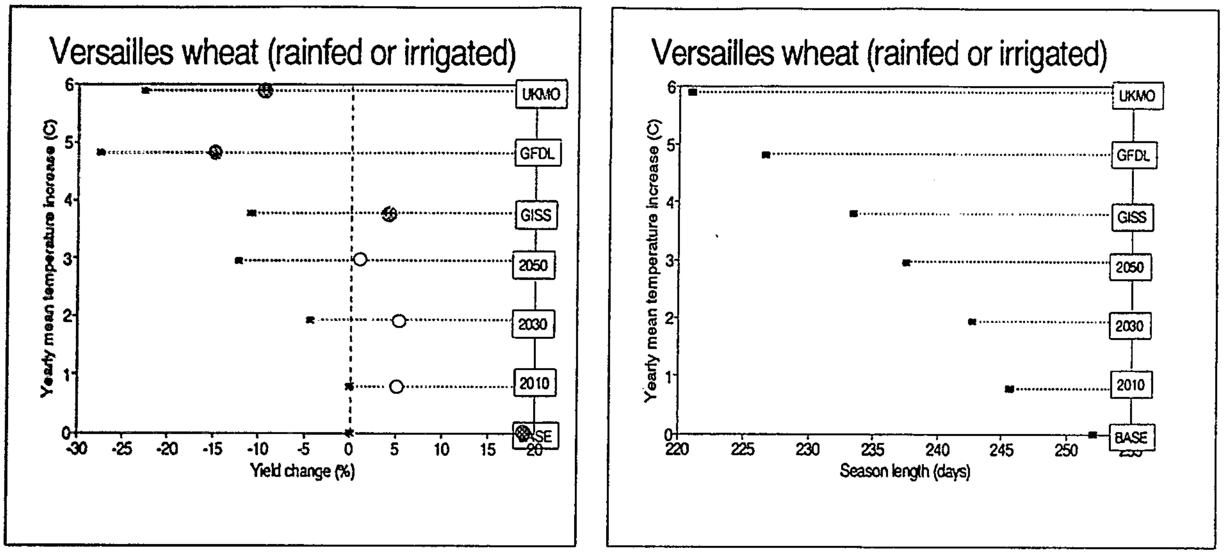

Figure 4. Yield variation (in percent of $1xCO_2$ baseline) and season length for wheat in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

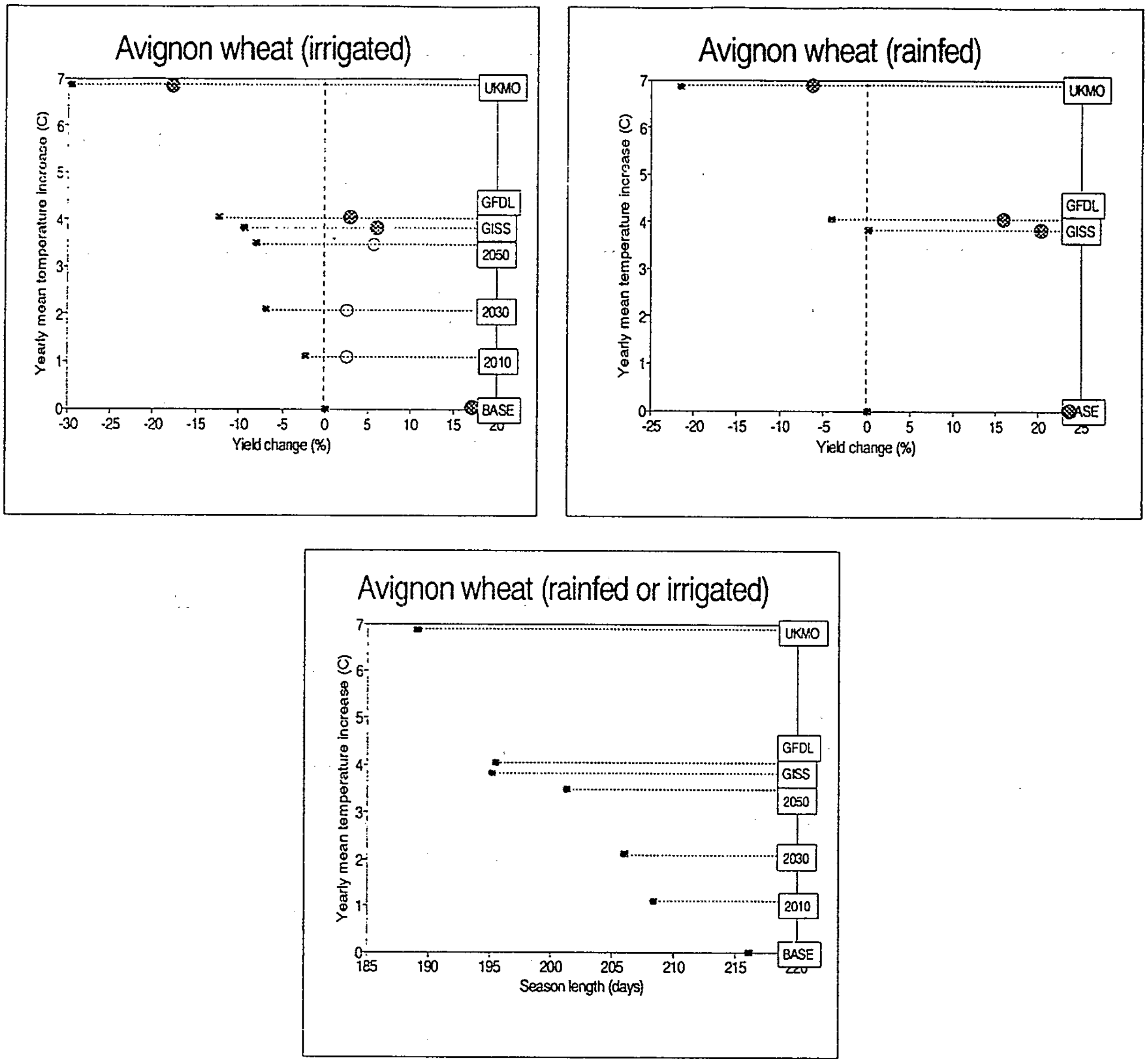

Figure 5. Yield variation (in percent of $1xCO_2$ baseline) and season length for wheat in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

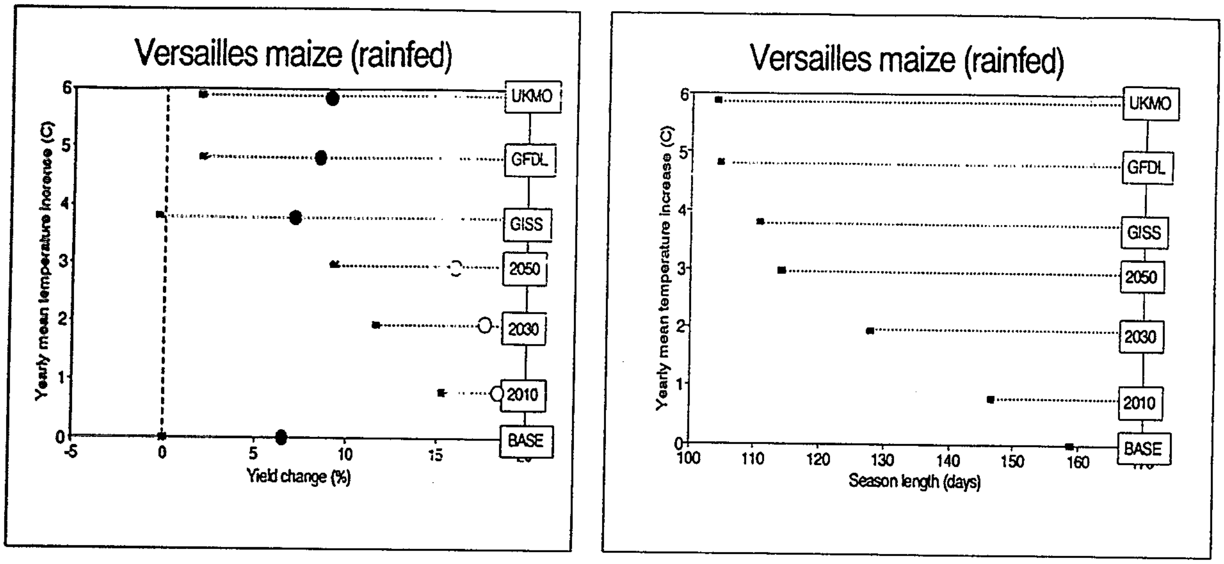

Figure 6. Yield variation (in percent of $1xCO_2$ baseline) and season length for rainfed maize in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

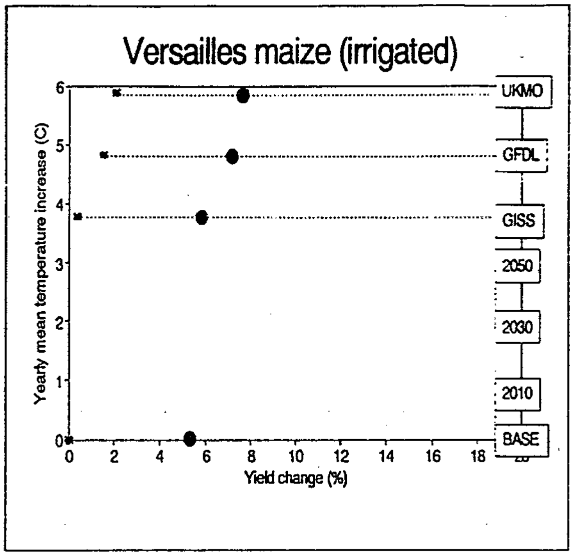

Figure 7. Yield variation (in percent of $1xCO_2$ baseline) for irrigated maize in Versailles (squares = climate change alone; circles = climate change with physiological CO_2 effects).

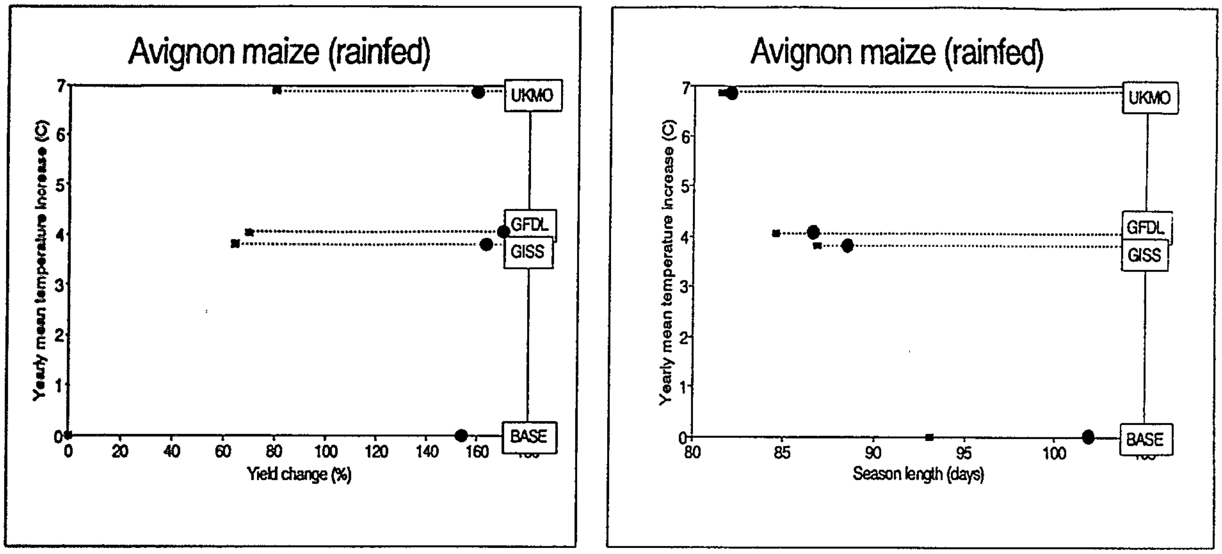

Figure 8. Yield variation (in percent of $1xCO_2$ baseline) and season length for irrigated maize in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

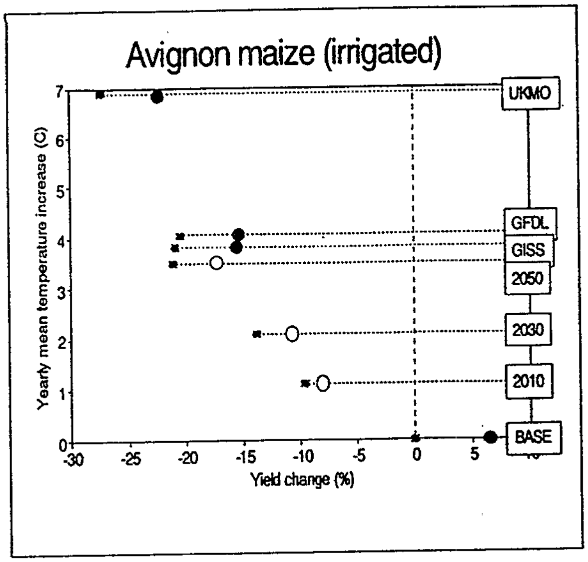

Figure 9. Yield variation (in percent of 1xCO_2 baseline) for irrigated maize in Avignon (squares = climate change alone; circles = climate change with physiological CO_2 effects).

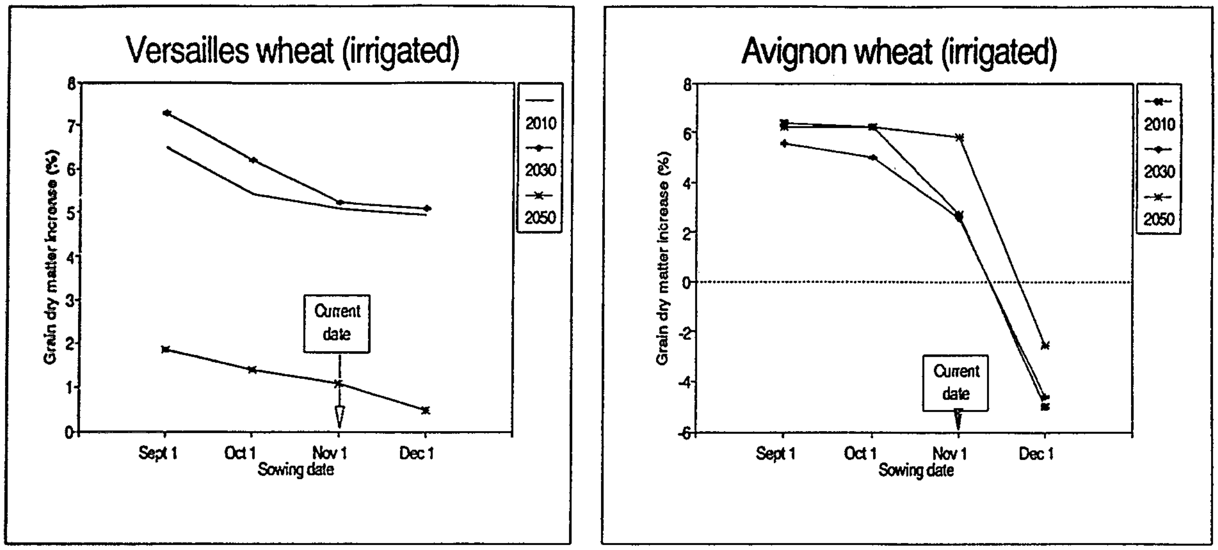

Figure 10. **Wheat-yield response to sowing date (in percent of 1xCO_2 baseline) for GISS transient scenarios in Versailles and Avignon.**

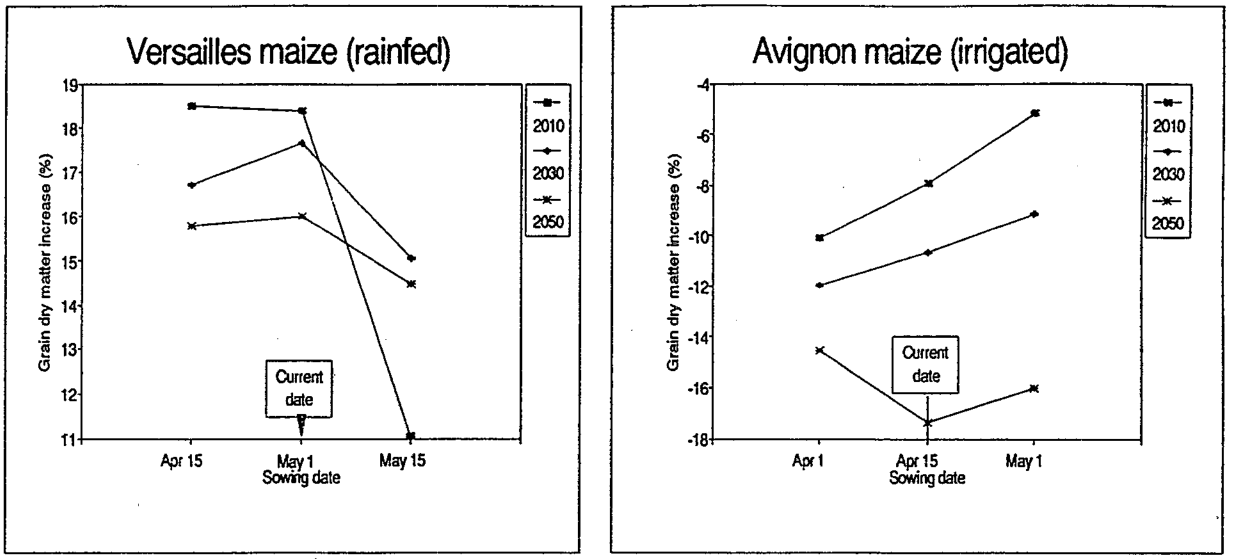

Figure 11. **Maize-yield response to sowing date (in percent of $1xCO_2$ baseline) for GISS transient scenarios in Versailles and Avignon.**

POTENTIAL EFFECTS OF GLOBAL WARMING AND CARBON DIOXIDE ON WHEAT PRODUCTION IN THE FORMER SOVIET UNION

Gennadiy V. Menzhulin and Larisa A. Koval

Department of Climatic Changes
State Hydrological Institute, Russia

Alexander L. Badenko

Laboratory of Plant Biophysics
Agrophysical Institute, Russia

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SUMMARY

This study combines the CERES-Wheat crop growth model and climate change scenarios to estimate the possible impacts of climate change on wheat production (the main food crop of the country) in 19 sites in Russia and the former Soviet Republics. This is the first crop modeling study in the former Soviet Union (FSU) that uses future climate change scenarios generated by General Circulation Models (GCMs). The results will make a significant contribution to the understanding of possible yield changes under future climate.

1. The sensitivity of the crop model to arbitrary incremental temperature and precipitation changes was estimated in two regions. A 2°C increase in temperature decreased yields by an average of approximately 20%, and a temperature increase of 4°C resulted in yield decreases of more than 30%. These yield decreases probably result from a shortening of the wheat season under a higher temperature. Changes in the precipitation by ±20% had a smaller impact on simulated wheat yields than changes in temperature.

2. GCM climate change alone resulted in considerable regional differences in simulated changes in wheat yields compared to baseline yields. The simulation study considered the beneficial physiological effects of CO_2 on wheat yields. Under the GISS scenario, spring and winter wheat yield increases exceeding 50% were obtained in the northwestern, central, and eastern regions of Kazakhastan. These regions are presently fairly arid, but with the increase in precipitation in the climate change scenarios they are predicted to become very favorable to wheat production. In contrast, under the GFDL scenario, wheat yields were not favored in these regions. In general, the climate change scenarios used were more favorable for winter than for spring wheat growth and production.

4. The GCMs forecast significant changes in temperature. These changes would result in the contraction of the crop growing season and the cold period of the year, and could be of great importance for agriculture in Russia and the republics of the FSU. In some regions these changes would raise the possibility of new cropping techniques, especially the ability to grow a second crop during the calendar year. The potential decrease in duration of the cold period is particularly significant in the case of vegetable crops which currently have a short growing season.

5. The results of the simulated yield changes for each site were aggregated to estimate the possible impact of climate change on national wheat yield. Under the GISS scenario and considering the direct physiological effects of CO_2 on crop growth and water use, winter and spring wheat yields increased by 41% and 21% respectively. The GFDL and UKMO scenarios were significantly less favorable for the simulated wheat production. The largest yield decreases— -19% —were simulated under the UKMO scenario.

6. Changes in sowing date and irrigation were studied as possible adaptation strategies to climate change in two regions. While small changes in the sowing date did not appear to have a large impact on yields, irrigation had a dramatic effect on spring wheat yields.

INTRODUCTION

Background

Russia and the former Soviet Republics have the world's largest area of arable land. Agriculture has been predominant throughout all periods of the country's history, and there is important ongoing research on the impacts of climate on crop yields (Golzberg 1967; Mishchenko 1984; Shashko 1985). Scientists in Russia and the former Soviet Republics have developed several empirical statistical models for forecasting crop yields in different regions of the country. Publications of the Agrometeorological Forecast Department of the Moscow Hydrometeorological Centre (Ulanova 1984) illustrate the developments in this field. Recently, scientists have developed prognostic models with a physical and physiological basis. For example, the St. Petersburg Agrophysical Institute has developed a special Supporting Agrotechnological Decisions System for the study of prognostic crop models (The Modeling...., 1982).

In the last fifteen years, a number of important studies have been done in the former Soviet Union related to the possible impacts of climate change on agricultural systems and crop production (Zhukovskiy and Belchenko 1988, Zhukovskiy et al. 1992, Sirotenko et al. 1984). These studies did not include the physiological (direct) effects of increased CO_2 on crop yield.

Menzhulin (1976 a,b, 1984), Koval and Savvateyev (1982), and Menzhulin and Nikolayev (1987) have developed crop models that consider both the climate impacts and the statistical analysis of annual variation, and can be combined with different climate and technological scenarios to evaluate the CO_2 physiological effects on yield. These crop models have been used to study the impact of climate on wheat yield in Russia and the former Soviet Republics, North America, and Europe (Menzhulin and Savvateyev 1980, 1981; Menzhulin et al. 1987 a,b; Anthropogenic... 1987; and Prospects... 1990; Rosenzweig et al. 1993).

Historically, Russian scientists and their colleagues have not used climate change scenarios generated by the General Circulation Models (GCMs) to study the possible impact of climate change on agriculture. The climate change scenarios were paleoclimatic analogues of global warming: up to 1°C (year 2000) used the Holocene Optimum; up to 2°C (year 2025) used the Eemian Interglaciar; and up to 4°C (year 2050) used the Pliocene Optimum. The carbon dioxide concentrations corresponding to these three periods would be 380 ppm, 420 ppm, and 560 ppm, respectively.

Crop Production

Today, agriculture presents a complex set of challenges in the former Soviet Union. Agricultural and economic policies and the monopoly of the agricultural industry by the State have led agriculture to its current crisis. These past policies have resulted in a country that cannot provide for itself with adequate agricultural production. The low effectiveness of Soviet agriculture is evident by the following statistics. In 1991, more than 22 million people were involved in the agricultural sector of the former USSR, which is more than in any country in the Organization for Economic Co-operation and Development (OECD) comprised of the countries of Europe, North America, Australia, New Zealand, and Japan. Yet agricultural production in the former Soviet Union is five times smaller than that of the OECD as a whole. The efficiency of Soviet agriculture is ten times lower than that of the USA, the Netherlands, Canada, and Belgium.

The general agricultural crisis is particularly manifested in grain production. Average yields of winter and spring wheat, the main components of national grain production, increased slightly before the 1970s, but leveled off during the last two decades. Although Russia holds a leading position in the total amount of wheat production, it ranks 35th in yield level among the 45 wheat-producing countries.

Objectives

The actual crisis in Soviet agriculture is sufficient cause for alarm, but the alarm is greater if the problem has to be solved during a period of possible climate change. This is the first crop-modeling study in the FSU that uses future climate change scenarios generated by GCMs. The results will make a significant contribution to the understanding of possible yield changes under future climate.

An analysis of Soviet agricultural production (Appendix 1) suggests that the best crop for the simulation study is wheat. Wheat (winter and spring) is the main food crop in Russia and the other republics. Its mean annual production is 100 million t. Other crops such as sugarbeet, potato, and barley are also major components of national agricultural production, and subsequent studies of the impacts of climate change on their production would be valuable. The production of wheat in Russia and the Soviet Republics has been described and analyzed in more detail than that of any other crop, providing empirical information for the validation of the simulation model.

Simulations of wheat yields and production changes require meteorological, soil, and crop management information about the zone of production. We chose 113 administrative regions (oblasts) in the main grain-producing area of the country (Figure 1 and Appendix 4) that include 65 regions of Russia, 25 regions of Ukraine, 6 regions of Belarus, 13 regions of Kazakhastan, the Baltic Republics, and Moldova. The Republics of the Caucasus and Middle Asia, and the regions of East Siberia and Russian Far East were not included because their wheat production does not significantly contribute to the total national wheat production.

METHODS

Crop Model

The simulation model used was the CERES-Wheat v2.10 model (Ritchie and Otter 1985) developed by IBSNAT (International Benchmark Sites Agrotechnology Transfer). The model has been calibrated and validated over a wide range of geographical locations, and thus the results of the simulation are comparable to previous and current studies in other regions of the world.

GCM Climate Change Scenarios

We used the scenarios of future climate generated by three equilibrium GCMs: the Goddard Institute for Space Studies (GISS) (Hansen et al. 1983), the Geophysical Fluid Dynamics Laboratory of Princeton University (GFDL) (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987). The climate scenarios provided by these GCMs correspond to the global warming resulting from an increase of the greenhouse gas content in the atmosphere equivalent to the doubling of CO_2 concentration. It is projected that CO_2 would account for 83.3% (550 ppm) of the equivalent concentration (660 ppm) and that other trace gases (methane, nitrogen oxides, etc.) would account for 16.7%.

The local climate scenarios were developed from the GCM output (temperature, precipitation, and solar radiation) that is associated with a particular grid network for each GCM. We developed the local climate change scenarios by two methods.

Simplified method. Local scenarios for each site were created by the direct extrapolation (attribution) of the changes in climate variables at the nearest gridpoint. This method has been used in previous climate change impact studies (Smith and Tirpak 1989), and therefore the results of simulation under such scenarios can be compared to other studies. We created scenarios for 19 selected sites with this method (Appendix 2).

Multi-point interpolation. We developed this more complex method to create climate change scenarios that simulate local climate more accurately (Appendix 3). This method used the GCM output of changes in temperature, precipitation, and solar radiation occurring in several of the nearest gridpoints to each site. This method was applied to generate scenarios in all of the 113 selected regions. With this complete set of scenarios we estimated the national changes in spring and winter wheat production.

Transient scenarios

In addition to the equilibrium GCM scenarios, we used scenarios generated by the GISS transient model for the decades of the 2010s, 2030s, and 2050s (Hansen et al. 1988). We calculated the local changes of climate variables in 113 selected regions (as described above) and applied them to the crop model.

INPUT INFORMATION

Climate Data

Ten years (1970-79) of daily maximum and minimum temperatures and precipitation data were obtained from the Union Research Institute of Meteorological Information (World Data Center "B" in Obninsk, Moscow Region) at 51 locations. When necessary, extrapolation of data based on geographical proximity and environmental and climatic conditions was done to create data for the entire set of 113 selected locations included in this study.

Daily solar radiation values were generated using long-term monthly radiation normals (obtained from the Solar Radiation Data Bank in the Geophysical Observatory (St. Petersburg) and the solar radiation generator included in the CERES-Wheat v2.10 model. Appendix 2 shows the stations selected to create scenarios for the 19 representative sites discussed in this report.

Soil Data

Soil data were obtained from the largest soil information archive at the Dokuchayev Soil Scientific Museum, with the help of the Soil Departments at the St. Petersburg and Moscow Universities. All the information in these archives is uniformly systematized (Ivanova and Rozov 1967, Glazovskaya 1966). The large territory included in this study and the wide variety of soils within each region required careful study for the selection of the representative soils and the determination of the input parameters for the simulation (Aderikhin 1964; Kovda and Lobova 1964; Liverovskiy 1965; Dobrovolskiy 1968; Glazovskaya and Friedland 1980; and Kovda 1973). We selected 26 soil types in the wheat-producing region. For a complete representation of grain production in each region, it was necessary to include more than one soil in each region (Table 1).

Initial Soil Conditions

Initial soil moisture in the profile, acidity, and the content of nitrates and ammonium must be defined for the simulation model. Unfortunately, there is not enough reliable annual information on initial soil moisture and nitrogen content for each region. Therefore, we used the following standard values. For arid regions, the soil water content at the end of the previous season was assumed to be equal to the lower limit (LOL) of water availability to the plant. In the regions where precipitation is always sufficient to fill the soil water store to the drained upper limit (DUL), the initial value was taken as equal to DUL just before sowing (Ritchie et al. 1989). Although there is nitrogen stress in some areas, we assumed that the nitrogen was not limiting.

Management Variables

For spring wheat, the simulated planting date occurs when the average temperature is about 5°C. For winter wheat, the simulated planting date occurs in autumn, about 60 days before the mean temperature reaches 0°C.

Calibration

The CERES-Wheat model has been calibrated and validated extensively with a number of wheat cultivars (Ritchie and Otter 1985). In this study, however, we used specific cultivars that were representative of production in Russia and the other republics, and that were not previously included in the CERES model. Therefore, we had to determine the genetic coefficients and calibrate the model for the cultivars used in the FSU. (The Manual... 1982).

According to specifications developed by the National Seed Inspection, all varieties of wheat cultivars recommended for use in national grain production are divided into eight adaptation groups: East European Forest; East European Forest-Steppe; East European Southern Steppe; Volga Steppe; West-Siberian Forest Steppe; East Siberian Forest Steppe; East Siberian Forest; and Middle Asian Rainfed.

The genetic coefficients were determined based on experimental data provided by the Agrophysical Research Institute. We calibrated the model with Russian cultivars so that the simulated values correspond effectively to the experimental observations on duration and phenophases, weight and number of grains in the ear, growth of phytomass and leaf area and yield.

Table 1 shows the adaptation group number (1 to 8) and the wheat cultivars selected for the 19 regions. The actual wheat production in any region of the FSU involves more than one cultivar. The number of cultivars used and their relative contribution to the total regional production is subject to yearly changes and the introduction of new cultivars. We used a set of nonvariable genetic parameters that represents only one cultivar and therefore we do not completely represent current practices. This assumption could introduce possible error into the results that could be significant because we have simulated only ten years of wheat production.

Validation

The model was validated for the eight adaptation groups by comparing observed experimental values of yields from the National Bureau of Agricultural Statistics to simulated values.

RESULTS AND DISCUSSION

Sensitivity Analysis

We estimated the sensitivity of the CERES-Wheat model to step changes in temperature and precipitation. The mean daily temperature was increased by 2°C and 4°C, and the precipitation was changed by +20% and by -20%. All possible combinations were evaluated. The physiological effects of increased CO_2 were also considered in each scenario. The sensitivity study was simulated for two important wheat producing regions, Zhitomir and North Bashkiria (for both spring and winter wheat).

Table 2 shows the results of simulations conducted with climate change alone and with climate change and physiological effects of CO_2. The results show large decreases in simulated yields due to changes in temperature. In the case of climate change alone, a 2°C increase in temperature decreased yields by approximately 20%; a temperature increase of 4°C resulted in yield decreases of more than 30% (the largest decrease was 45% for winter wheat in North Bashkiria). The physiological effects of CO_2 partially compensated for the adverse impact of temperature increases in simulated yields. For example, for spring wheat in North Bashkiria, a 4°C increase produced a 40% decrease in yield for temperature change alone (330 ppm) and a 17% decrease for temperature change with physiological effects of CO_2 (550 ppm). The impact of changes in precipitation on winter and spring wheat yields was noticeably smaller than the impact of changes in temperature.

The simulated yield increases due to the beneficial direct effects of CO_2 were close in magnitude to the yield decreases produced by a +2°C temperature increase. In all cases, when considering the physiological CO_2 effects, the simulated yields of winter and spring wheats increased more than 20% compared to the baseline yields with a maximum of 35% in the case of winter wheat in North Bashkiria.

In the CERES-Wheat model, the phenological stages are influenced by temperature, and our results show that the length of the growing season was not affected by changes in precipitation. In addition, the physiological CO_2 effects did not have any influence on the length of the growing period in this case. A temperature increase of 2°C resulted in a decrease in the length of the spring wheat growth period by 8 days in both Zhitomir and North Bashkiria. With temperature increases of 4°C, the decrease was 14 and 15 days for spring wheat and 10 and 18 days for winter wheat in Zhitomir and North Bashkiria respectively.

The most significant evapotranspiration (ET) change (-18%) was for spring wheat in Zhitomir under the warmest and driest scenario (temperature +4°C and precipitation -20%). ET was not significantly affected by the simulated physiological effects of CO_2. Under the baseline climate, ET was reduced only 6% due to the physiological CO_2 effects. It is important to note that this estimate is dramatically smaller than estimates from experimental data (Rose 1989).

Description of the GCM Climate Scenarios

Tables 3, 4, and 5 show the seasonal and annual changes in temperature, precipitation, and solar radiation under the three GCM scenarios for the selected sites. The temperature changes (Table 3) simulated by the GISS and GFDL scenarios are comparable in all sites and average 4 - 5°C higher than current temperatures. The changes under the UKMO scenario are almost twice as large as those simulated by the other two scenarios. In most cases, the differences between scenario and baseline temperatures are more noticeable in the cold season.

The average annual and seasonal precipitation under the climate change scenarios is significantly greater than the baseline precipitation in most cases (Table 4). In general, the largest amounts of precipitation are projected by the GISS and UKMO scenarios.

Table 5 shows changes in solar radiation under the three scenarios. There is a general tendency for increased solar radiation under the GFDL and UKMO scenarios. Under the GISS scenario, solar radiation decreases slightly in most sites.

Wheat Crop Changes

The simulated changes in yield, season length, and evapotranspiration under GCM climate change scenarios are given in Tables 6, 7, and 8 for the 19 representative sites of the grain production area of Russia, the Ukraine, Belarus, and Kazakhstan.

Yield. Climate change alone resulted in considerable regional differences in simulated changes in wheat yield under the GCM scenarios. The maximum increases in yield were projected under the GISS scenario. The following results are for climate change including the physiological effects of CO_2.

Under the GISS scenario, increases in spring wheat yields exceeding 50% were obtained in the northwestern, central, and eastern regions of Kazakhastan (Aktyubinsk, Zelinograd, Karaganda). In the same regions, the changes in winter wheat yields were also characteristically high. These regions are fairly arid, but with the increase in precipitation under the climate change scenarios, were very favorable to wheat production. The GFDL scenario was not as favorable for wheat production in the regions listed above. Under this scenario, the decreases in yields were characteristic of the sites in Kazakhstan, as in most of the other sites.

A systematized interpretation of the meaning of climate change for wheat production is complicated because of the considerable differences in yield changes estimated under the three GCM scenarios. Yet we can conclude that, on average, the climate change scenarios used were more favorable for winter than for spring wheat yields.

Length of the growing season. To analyze the possible impacts of global climate change on agriculture in the FSU, it is important to consider the changes in the lengths of the growing period and the warm seasons under the climate scenarios (Table 7). All three GCM scenarios resulted in a shortening of the growing season for both winter and spring wheat at all sites. Under the UKMO scenario, which is characterized by the highest temperature increases, the growing season in the Baltic regions for winter wheat decreased by more than two months. For spring wheat the decrease was about one month. The shortening of the simulated growing season for winter and spring wheats occurred in all regions of the FSU.

The GCMs forecast significant changes in the temperature regime, which would result in the contraction of the crop-growing season and of the cold period of the year, and could be of great importance for agriculture in Russia and the republics of the former Soviet Union. In some regions these changes would raise the possibility of new cropping techniques, especially the growth of a second crop during the calendar year. The decrease in the duration of the cold period is especially significant in the case of vegetable crops, which have currently have a short growing season in many regions.

Evapotranspiration. The evapotranspiration changes under the GCM scenarios were generally insignificant (Table 8). In most cases, the total crop ET compared to baseline data. We believe that the CERES-Wheat model needs to be improved in order to simulate the crop water regime accurately. In the simulation of evapotranspiration of the wheat crop, it is necessary to account for the interactions among leaf temperature, moisture level, and the physiological effects of CO_2 that increase stomatal resistance (Rose 1989).

Projections of National Wheat Yields

The national production changes for equilibrium and transient scenarios were estimated using the 16-point interpolation scheme for all 113 sites, not the nearest gridpoint extrapolation method.

Aggregation of the GCM-scenario results. The possible impact of climate change on wheat production in Russia, the Ukraine, Belarus, and Kazakhstan can be estimated from the simulated changes in yield under the climate change scenarios. Table 9 shows estimates in yield changes calculated from the results of 113 subregions of the grain production zone. Under the GISS scenarios and considering the physiological effects of CO_2, winter wheat production increased by 41% and spring wheat production increased by 21%. The GFDL and UKMO scenarios were significantly less favorable for the simulated wheat production. Under the UKMO scenario and considering the physiological effects of CO_2, the simulated wheat production decreased by 19%.

Aggregation of the transient scenario results. Wheat yield changes were also simulated under the GISS transient scenarios. The first two transient scenarios correspond to the intermediate levels of climate change, which are simulated for the decades of the 2010s and 2030s, with a corresponding increase in greenhouse gas concentration in the atmosphere equivalent to 405ppm and 430ppm of CO_2. The third GISS transient scenario can be used as another alternative scenario of climatic change for the decade of the 2050s.

Winter and spring wheat yields were simulated under the three GISS transient scenarios for the 113 selected regions. Table 9 shows the results of the aggregation of the yield changes. The results suggest that the production of both winter and spring wheat would gradually increase due to climate change.

ADAPTATION

A realistic approach to the problem of climate change impacts on agriculture requires studying possible measures to avoid unfavorable consequences. A detailed investigation of this question was beyond the scope of this study, but we analyzed some possible adaptation responses, such as changes in the sowing date and in irrigation on spring wheat yields at Zhitomir and Saratov regions (Table 10). The adaptation responses were analyzed under the UKMO scenario because it is the most unfavorable scenario. This small adaptation study shows approaches and methods that can be and should be applied to a more detailed study of adaptation responses to unfavorable climate changes in agriculture in Russia and in the former Soviet Republics.

The most significant result of the analysis was that changes in the sowing date (both later and earlier) by 15 days and even by 30 days did not noticeably affect crop yields. Under the UKMO scenario, there is a considerable precipitation increase in the winter and spring seasons at these two sites (Table 4). However, these precipitation changes did not fully compensate for the moisture limitation of wheat in the summer season due to a temperature increase. In addition, in the Saratov region, the UKMO scenario predicts a 24% decrease in the summer precipitation, which is already limited. Irrigation could have a large impact on spring wheat yields in these two regions, especially in Saratov.

SOURCES OF UNCERTAINTY

Models

The use of the simulation crop model (CERES-Wheat) and the climate change scenarios (GISS, GFDL, and UKMO) introduce uncertainties. In principle, we could quantify the uncertainty associated with the use of GCMs in the agricultural zones, applying the methods proposed in Global Comparison of Selected GCM: Control Runs and Observed Data (Kalkstein 1991).

Input Parameters

Here we include uncertainties derived from the limited availability of current information on input parameters of the models. As discussed above, the possible error in the calculations of the climate scenarios could be smaller when we use the procedure for daily climate data generation described in Appendix 3. The standard procedure used to develop climate scenarios for important agricultural sites that are situated far from the GCM gridpoints could be incorrect. With the multipoint interpolation system we can simulate more accurately the current climate than when we use the GCM output from the nearest gridpoint. Therefore, additional uncertainty may be generated when using the conventional system to create local scenarios.

Another potential error is associated with the large size and climatic diversity of some of the study regions that would require data from more than one station to represent their climate more accurately.

Technological Adjustments

There are unavoidable uncertainties in estimating the future changes of agricultural technology and management in response to climatic change. These are significant factors limiting the reliability of the results. Climate change can alter the geography of the current regions and influence soil processes, and will eventually create demand for newly developed technologies.

Variability

Another major factor that limits the reliabiity of these results is the direct extrapolation to the future of the current variation of daily temperatures and precipitation. In order to obtain more reliable estimates of future changes in wheat yields, it would be necessary to consider potential differences in climate variability.

FUTURE RESEARCH NEEDS

The present study is a contribution to the understanding of the possible impacts of climate change on the FSU's agricultural systems. However, future research is still needed. With improved models and a more accurate set of input parameters, some of the uncertainties could be eliminated.

An adaptation study with a larger scope—one that would consider the complex agrotechnological decisions that might decrease the negative consequences of climate change on wheat production—is essential for continued progress in this field. In addition, further research should consider the impact of climate change on the production of other major crops. Finally, the frequency of extreme climate events, especially the occurrence of drought periods, needs to be investigated.

The impact of drought variability on agriculture was addressed during the preparation of the Intergovernmental Panel on Climate Change (IPCC) Working Group II report. However, methods for estimating such variability were not clearly established within the framework of the IPCC or other projects. It will require considerable work to compile and analyze GCM output and to prepare appropriate input data, but such an effort is justified by the importance of potential impacts of future climate variability in the FSU and other agriculturally important regions of the world.

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APPENDIX 1. Production (x 100,000 t)/Area (x 100,000 ha) of the principal food crops.

Crops	Years 1940	1950	1960	1970	1987
W.Wheat	145/143	114/125	182/121	427/185	462/153
S.Wheat	172/260	197/260	461/483	576/467	371/314
Sugar Beet	180/12	208/13	577/30	789/34	904/34
Potatoes	759/77	886/85	844/91	968/81	760/62
Barley	121/105	64/81	160/110	383/213	584/306
Maize	51/36	66/48	98/51	94/34	323/46
Vegetables	137/15	93/13	166/15	212/15	292/17
Oats	168/202	130/162	120/128	142/92	219/118
Rye	210/231	180/236	182/162	130/100	181/97
Beans	15/24	12/20	27/33	76/51	100/64
Sunflower	26/35	18/36	40/	61/48	61/42
Millet	44/60	17/38	32/38	21/27	39/28
Buckwheat	13/21	13/30	6/14	11/19	13/16

APPENDIX 2. Meteorological and solar radiation stations used for the 19 representative sites.

No.	Region	Site (Lat/Long)	Meteorological Station (Lat/Long)	Distance+ (km)	Solar Station (Lat/Long)
1	W Russia	Bryansk 52.9/33.4	Smolensk 54.7/32.0	290	Br.forest 53.1/34.5
2	C Chernozem of Russia	Kursk 51.7/36.0	Kursk 51.7/36.0	0	Ostrogozhsk 50.9/39.0
3	Central Russia	Yaroslavl 57.6/38.9	Kostroma 57.8/41.0	125	Vologda 59.2/40.0
4	Middle Volga	Saratov 51.6/46.6	Saratov 51.3/46.0	75	Saratov 51.3/46.0
5	South Volga	Astrakhan 46.6/48.0	Astrakhan 48.2/46.2	270	Or. Promysel 45.9/47.5
6	Southern Russia	Rostov-Don 47.4/40.8	Rostov-Don 47.0/40.0	100	Rostov-Don 47.0/40.0
7	East Euro Russia	N Bashkiria 55.0/55.6	Ufa 54.9/55.9	35	Ufa 54.9/55.9
8	Western Ukraine	L'vov 49.5/23.6	L'vov 49.5/23.6	0	L'vov 49.5/23.6
9	Northwestern Ukraine	Zhitomir 50.0/28.4	Vinnitsa 49.3/28.3	80	Kiev 50.6/30.3
10	Eastern Ukraine	Kharkov 49.5/36.3	Kharkov 50.1/36.3	75	Kharkov 50.1/36.3
11	Southern Ukraine	Kherson 46.7/33.5	Askania-Nova 46.3/33.5	45	Kherson 46.4/32.4
12	Moldova	Kishinev 47.0/28.9	Kishininev 47.0/28.9	0	Kishinev 47.0/28.4
13	Western Belarus	Brest 52.0/24.2	Brest 52.2/23.9	40	Vasilyevichi 52.2/30.0
14	Central Belarus	Minsk 53.3/26.0	Minsk 54.0/27.3	165	Minsk 54.0/27.3
15	Baltic	Lithuania 55.0/23.0	Kaunas 54.5/24.0	125	Zarasay 55.7/26.3
16	NW Kazakhstan	Aktyubinsk 49.9/57.9	Aktyubinsk 50.2/57.1	95	Orenburg 51.4/55.1
17	N Kazakhstan	N Kazakhstan 54.6/68.3	Petropavlovsk 54.5/69.1	90	Petropavlovsk 54.5/69.1
18	C Kazakhstan	Zelinograd 51.6/70.1	Zelinograd 51.5/68.2	210	Atbasar 51.1/71.2
19	E Kazakhstan	Karaganda 50.0/72.4	Karaganda 49.1/73.1	125	Karkaralinsk 49.5/75.5

+ Distance from the agricultural region to the meteorological station

APPENDIX 3. Method for calculating local climate change scenarios.

The procedure for developing the local climate change scenarios using the nearest GCM gridpoint and the local climate data set may not always be the best representation of the local future climate. In certain cases there may be discrepancies between the observed climate variables and the simulated baseline climate for a site. Problems may arise when the climate variables are nonuniformly distributed on the region, and when two grain-producing sites are closely situated or within the same GCM gridbox. This is a particular problem in the creation of the scenarios in the 113 grain-producing regions selected for this study, because the gridpoint resolution of the GCMs used (GISS, GFDL, and UKMO) is lower than ideal. The distance between gridpoints in the latitudinal direction for any of the GCMs used is two times the size of the average region selected for the study; Furthermore, when we want to develop a map of the spatial distribution of the changes of climatic variables and the productivity in the agricultural territory.

These problems arise because of the large agricultural region used in this study. To obtain potential representative estimates of changes of national agricultural production under the climate change scenarios it is important to study the responses of crops yields in relatively small regions. In addition, it would be best to represent the simulation results as territorial distributions of output parameters in the forms of maps with isolines.

We developed a method called Multipoint Interpolation for developing local climate scenarios based on a modification of the standard method. The method is based on the interpolation of climate variables from several gridpoints for each GCM to each of the centers of the wheat-producing regions (113). For reasons of symmetry, the 16 nearest surrounding gridpoints were used in this modified procedure. To calculate the values of the three climate variables (temperature, precipitation, and solar radiation) for each agricultural site we used the formula:

$$X(\text{in the site}) = \text{Sum}[p(i) * X(i)]; \quad i=1,2,\ldots 16$$

where X(i) are the climatic variables in each of the 16 gridpoints, and p(i) are their relative weights.

To estimate the relative weight values (p(i)), we assumed that the weight of each of the 16 gridpoints that surround the agricultural site for each variable must be proportional to the value of the correlation coefficient between its magnitudes in the gridpoint and of the site. The coefficient of correlation for temperature (K(T,i)), precipitation (K(P,i)), and solar radiation (K(S,i)) have been plotted as a function of distance by the formulas:

$$\begin{aligned} K(T,i) &= \exp[-r(i)/R(T)] \\ K(P,i) &= \exp[-r(i)/R(P)] \qquad i= 1,2,\ldots 16 \\ K(S,i) &= \exp[-r(i)/R(S)] \end{aligned}$$

where R(T), R(P), and R(S) are so-called radii of correlation, (e.g., the distances for which correlation has decreased e = 2.7183). The final formulas for weights after normalization can be represented as follows:

$$\begin{aligned} p(T,i) &= K(T,i)/\text{Sum}[K(T,i)]; \\ p(P,i) &= K(P,i)/\text{Sum}[K(P,i)]; \\ p(S,i) &= K(S,i)/\text{Sum}[K(S,i)]. \end{aligned}$$

To carry out the calculations in accordance with this procedure, the values of these three parameters must be known: radii of temperature, precipitation, and solar radiation correlation. In this particular study we considered these values to be:

R(T) = 1500 km; R(P) = 600 km; R(S) = 700 km.

The use of this procedure establishes a better correlation between the local climate and the climate scenarios generated by the GCMs. But in spite of the use of this more accurate technique of interpolation, there is still a degree of uncertainty associated with the local climatic scenarios. Specifically, there is also uncertainty associated with the extrapolation of present spatial meteorological fields into the future. For more accurate use of this multipoint interpolation procedure, it is necessary to have information on the changes of correlation radii R(T), R(P), and R(S) during climate change.

APPENDIX 4. A complete list of sites in the FSU used in the simulation study. The numbers below each site indicate its latitude/longitude. An asterisk (*) indicates the sites selected as examples for this report. In these sites the climate change scenarios were created by the simplified method.

1.	Vinnitsa 48.7/28.6	2.	Volyn 50.8/24.4
3.	Dniepropetrovsk 48.4/34.7	4.	Donetsk 47.9/37.5
*5.	Zhitomir 50.0/28.4	6.	Zaporozhye 47.3/35.7
7.	Kiev 50.1/31.0	8.	Kirovograd 48.3/32.2
9.	Lugansk 49.0/38.8	10.	Nikolaev 47.2/32.0
11.	Odessa 46.6/30.4	12.	Poltava 49.6/33.8
13.	Rovno 50.4/26.0	14.	Sumy 51.0/33.9
*15.	Kharkov 49.5/36.3	*16.	Kherson 46.7/33.5
17.	Cherkassy 49.0/31.3	18.	Chernigov 51.1/32.0
*19.	Moldova 47.1/28.6	20.	Belgorod 50.7/37.7
*21.	Bryansk 52.9/33.4	22.	Voronezh 51.1/40.0
*23.	Kursk 51.7/36.0	24.	Lipetsk 52.6/38.8
25.	Oryol 52.8/36.2	26.	Tambov 52.6/41.5
*27.	Brest 52.0/24.2	28.	Vitebsk 55.2/28.3
29.	Gomel 52.0/29.4	30.	Grodno 53.0/24.2
*31.	Minsk 53.3/26.0	32.	Mogilyev 53.6/30.4
33.	Vladimir 56.0/40.9	34.	Nizhniy Novgorod 55.9/44.2
35.	Ivanovo 57.2/41.4	36.	Kaluga 54.3/35.0
37.	Kostroma 58.2/43.2	38.	Mary 56.4/47.8
39.	Mordovia 54.4/44.3	40.	Ryazan 54.2/40.7

41. Tula
53.9/37.4

42. Udmurtia
56.6/52.2

43. Chuvashia
55.4/47.0

*44. Yaroslavl
57.6/38.9

45. Moscow
55.4/38.1

*46. Astrakhan
46.6/48.0

47. Volgograd
49.9/44.1

48. Kalmykia
45.9/44.4

49. Krasnodar
45.2/39.2

*50. Rostov
47.4/40.8

51. Stavropol
44.8/43.2

52. Samara
53.0/50.6

53. West Orenburg
51.8/54.3

54. East Orenburg
51.3/59.6

55. Penza
53.1/44.7

*56. Saratov
51.6/46.6

57. Tataria
55.3/51.0

58. Ulyanovsk
53.9/48.0

*59. North Bashkiria
55.0/55.6

60. South Bashkiria
52.9/57.3

61. Kurgan
55.4/65.0

62. Perm
57.5/55.9

63. South Yekaterinburg
57.2/61.9

64. Region "A" of Mid.Ural
57.8/59.9

65. Region "B" of Mid.Ural
54.8/58.9

66. North Chelyabinsk
55.0/60.5

67. South Chelyabinsk
53.1/60.2

68. South Urals Region
53.2/59.1

*69. North Aktyubinsk
49.9/57.9

70. North Guryev
57.5/53.4

*71. Karaganda
50.0/72.4

72. Kokchetav
53.4/70.3

73. Kustanaiy
52.4/63.5

74. Pavlodar
52.3/76.0

*75. North Kazakhstan
54.6/68.3

76. North Semipalatinsk
50.3/79.6

77. C'trl Semipalatinsk
48.7/80.0

*78. Zelinograd
51.6/70.1

79. North Ural
50.2/52.9

80. South Ural
49.3/49.4

81. Tver
57.1/34.5

82. Smolensk
54.6/32.3

83. St. Petersburg
59.2/29.0

84. Pskov
57.1/28.5

85. Novgorod
58.2/32.0

86. Vologda
59.5/40.4

87. Latvia
56.2/23.8

*88. Lithuania
55.0/23.0

89. Estonia
58.2/25.5

90. Karelia
61.9/32.4

91. Kaliningrad
54.2/20.6

92. North Tomsk
59.5/80.0

93. South Tomsk
58.0/83.9

94. NE Novosibirsk
55.6/82.1

95. South-West Novosibirsk
55.0/77.9

96. North-West Kemerovo
56.0/86.0

97. South-East Kemerovo
54.1/87.0

98. North-West Altai
52.1/79.8

99. North-East Altai
53.6/84.4

100. South-East Altai
51.9/83.0

101. North Omsk
57.2/73.4

102. South Omsk
55.1/73.0

103. North Tyumen
58.9/68.6

104. South Tyumen
56.9/68.4

105. V'yatka
57.9/49.8

106. East Kazakhstan
50.7/82.3

*107. Lvov
49.5/23.6

108. Ivano-Frankovsk
48.4/24.0

109. Carpathians
47.7/22.3

110. Chernovtsy
48.0/26.1

111. Ternopol
49.0/25.1

112. Khmelnitsky
49.1/26.0

113. Crimea
45.4/34.0

Table 1. Soil types and wheat cultivars used in the simulation.

SITE	SOIL TYPE	WHEAT CULTIVAR (Spring, Winter)
Bryansk	Gray Wooded	Palmira, Bezostaya-1
Kursk	Chernozem: Leached, Modal	Albidum-43, Mironovskaya-808
Yaroslavl	Dernopodzolic	Palmira, Bezostaya-1
Saratov	Chernozem: Steppe, Modal, Southern; Deep Chestnut	Albidum-43, Mironovskaya-808
Astrakhan	Light Chestnut, Brown Steppe, Desert	Albidum-43, Mironovskaya-808
Rostov-Don	Deep Chestnut Chernozem: Southern, Deep	Lutescens-62, Krymskaya
N. Bashkiria	Chernozem: Modal, Leached	Albidum-43, Mironovskaya-808
Lvov	Leached Chernozem, Dernopodzolic	Ostka, Lutescens-17
Zhitomir	Modal Chernozem Dernopodzolic	Ostka, Lutescens-17
Kharkov	Modal Chernozem	Albidum-43, Mironovskaya-808
Kherson	Chernozem: Deep, Steppe, Southern	Lutescens-62, Krymskaya
Kishinev	Gray Wooded, Modal Chernozem	Lutescens-62, Krymskaya
Brest	Podzolic, Ferruginous, Humic	Palmira, Bezostaya-1
Minsk	Dernopodzolic Podzolic	Palmira, Bezostaya-1
Lithuania	Glee Wooded	Palmira, Bezostaya-1
Aktyubinsk	Deep Chestnut, Brown Steppe Desert	Albidum-43, Mironovskaya-808
N. Kazakhstan	Brown Meadow Steppe	Albidum-43, - NO -
Zelinograd	Chernozem: Steppe, Southern; Deep Chestnut	Albidum-43, - NO -
Karaganda	Chestnut: Light, Deep	Albidum-43, Mironovskaya-808

Table 2. Sensitivity analysis of CERES-Wheat to climate and CO_2 changes in Zhitomir and N. Bashkiria.

CO_2 level (ppm)	Precip. (%)	Temp. (°C)	Changes from baseline					
			Yield (%)	Season L.(days)	ET (mm)	Yield (%)	Season L.(days)	ET (mm)
330	0%	0	0	0	0	0	0	0
		2	-16	-8	-4	-23	-10	-3
		4	-33	-14	-9	-38	-18	-6
	20%	0	5	0	3	8	0	4
		2	-12	-8	0	-13	-10	2
		4	-27	-14	-4	-27	-18	0
	-20%	0	-8	0	-6	-18	0	-8
		2	-26	-8	-11	-36	-10	-12
		4	-44	-14	-18	-52	-18	-13
555	0%	0	26	0	-6	27	0	-6
		2	8	-8	-9	0	-10	-7
		4	-9	-14	-11	-17	-18	-9
	20%	0	30	0	-4	36	0	-2
		2	12	-8	-6	14	-10	-3
		4	-4	-14	-8	-3	-18	-5
	-20%	0	20	0	-9	16	0	-10
		2	0	-8	-13	-13	-10	-14
		4	-19	-14	-18	-34	-18	-10
			N. Bashkiria Spring Wheat			N. Bashkiria Winter Wheat		
330	0%	0	0	0	0	0	0	0
		2	-22	-8	-4	-25	-10	-3
		4	-40	-15	-9	-45	-18	-5
	20%	0	2	0	4	13	0	5
		2	-18	-8	-2	-12	-10	2
		4	-36	-15	-4	-34	-18	1
	-20%	0	-4	0	-8	-20	0	-7
		2	-26	-8	-12	-40	-10	-10
		4	-44	-15	-16	-56	-18	-11
555	0%	0	21	0	-6	35	0	-5
		2	1	-8	-6	10	-10	-5
		4	-17	-15	-10	-15	-18	-7
	20%	0	27	0	-4	48	0	1
		2	3	-8	-4	22	-10	-1
		4	-14	-15	-6	-3	-18	-3
	-20%	0	13	0	-10	17	0	-9
		2	-2	-8	-12	-9	-10	-11
		4	-21	-15	-16	-32	-18	-13

Table 3. Temperature change (°C) predicted by GISS, GFDL, and UKMO climate change scenarios.

Site		Spring	Summer	Autumn	Winter	Annual
Bryansk	GISS	4.3	1.0	4.3	6.3	4.0
	GFDL	4.6	4.8	4.7	4.2	4.6
	UKMO	11.0	8.6	7.5	8.5	8.9
Kursk	GISS	4.6	1.4	4.6	6.6	4.3
	GFDL	4.6	4.1	4.2	4.1	4.2
	UKMO	11.0	8.6	7.5	8.5	8.9
Yaroslavl	GISS	4.4	0.7	4.4	6.8	4.1
	GFDL	5.3	4.1	4.8	4.6	4.7
	UKMO	9.6	5.8	6.5	9.9	7.9
Saratov	GISS	4.7	3.0	5.0	6.9	4.9
	GFDL	4.5	3.6	3.7	4.1	4.0
	UKMO	10.1	8.3	7.1	8.4	8.9
Astrakhan	GISS	3.6	4.3	4.8	4.6	4.3
	GFDL	4.0	3.6	3.6	4.2	3.8
	UKMO	10.2	8.1	7.3	8.2	8.7
Rostov-on-Don	GISS	4.6	1.4	4.6	6.6	4.3
	GFDL	4.0	3.8	4.0	3.9	3.9
	UKMO	9.0	8.9	7.5	9.5	8.7
N. Bashkiria	GISS	5.0	3.9	4.6	6.4	5.0
	GFDL	4.4	3.8	4.3	4.2	4.2
	UKMO	9.8	8.5	7.0	8.0	8.3
Lvov	GISS	3.7	2.3	4.2	5.8	4.0
	GFDL	4.6	5.2	4.8	4.6	4.8
	UKMO	10.4	8.2	7.7	8.7	8.8
Zhitomir	GISS	4.3	1.0	4.3	6.3	4.0
	GFDL	4.6	4.8	4.7	4.2	4.6
	UKMO	11.4	7.1	7.1	8.7	8.6
Kharkov	GISS	4.6	1.4	4.6	6.6	4.3
	GFDL	4.6	4.1	4.2	4.1	4.2
	UKMO	10.6	8.5	7.2	9.7	8.0
Kherson	GISS	4.8	3.5	4.7	4.7	4.4
	GFDL	4.1	4.5	4.3	3.9	4.2
	UKMO	10.6	8.5	7.2	9.7	8.0
Kishinev	GISS	4.8	3.5	4.7	4.7	4.4
	GFDL	4.1	4.5	4.3	3.9	4.2
	UKMO	10.6	8.5	7.2	9.7	8.0

Brest	GISS	3.7	2.3	4.2	5.8	4.0
	GFDL	4.6	5.2	4.8	4.6	4.8
	UKMO	11.4	7.1	7.1	8.7	8.6
Minsk	GISS	4.3	1.0	4.3	6.3	4.0
	GFDL	4.6	5.2	4.8	4.6	4.8
	UKMO	11.4	7.1	7.1	8.7	8.6
Lithuania	GISS	4.0	1.6	3.5	5.3	3.6
	GFDL	5.3	4.7	5.0	5.3	5.1
	UKMO	11.5	6.2	6.0	9.5	8.3
Aktyubinsk	GISS	5.0	3.9	4.6	6.4	5.0
	GFDL	4.8	4.0	5.8	5.0	4.9
	UKMO	10.1	9.1	7.0	9.0	8.8
N. Kazakhstan	GISS	5.0	4.1	4.1	7.5	5.2
	GFDL	5.2	4.0	6.1	6.0	5.3
	UKMO	10.5	8.3	7.7	6.9	8.3
Zelinograd	GISS	5.0	4.1	4.1	7.5	5.2
	GFDL	5.3	4.1	6.4	6.0	5.4
	UKMO	10.5	8.3	7.7	6.9	8.3
Karaganda	GISS	5.0	4.1	4.1	7.5	5.2
	GFDL	5.4	4.5	5.9	6.1	5.5
	UKMO	10.5	8.3	7.7	6.9	8.3

Table 4. Precipitation change (%) predicted by GISS, GFDL, and UKMO climate change scenarios.

Site		Spring	Summer	Autumn	Winter	Annual
Bryansk	GISS	+24	+35	+33	+16	+27
	GFDL	+36	-3	+8	+6	+12
	UKMO	+71	-24	+25	+34	+27
Kursk	GISS	+28	+37	+18	+38	+30
	GFDL	+15	+20	-3	+18	+12
	UKMO	+72	-24	+25	+34	+27
Yaroslavl	GISS	+34	+74	+35	+36	+45
	GFDL	+8	+2	+23	+5	+9
	UKMO	+79	-12	+33	+47	+37
Saratov	GISS	+16	+38	-6	+41	+22
	GFDL	+28	+57	+6	+26	+29
	UKMO	+70	-24	+18	+30	+23
Astrakhan	GISS	+22	-98	-8	+19	+33
	GFDL	+10	+31	-5	+19	+13
	UKMO	+68	-20	+14	+22	+21
Rostov-on-Don	GISS	+30	+37	+18	+38	+30
	GFDL	+3	+8	-27	+38	+5
	UKMO	+44	-32	+21	+37	+17
N. Bashkiria	GISS	+40	+45	-22	+31	+24
	GFDL	+18	+18	+44	+39	+29
	UKMO	+77	-31	+21	+28	+23
Lvov	GISS	+27	+9	+6	+14	+14
	GFDL	+25	-16	+2	-6	+2
	UKMO	+49	-16	+19	+26	+19
Zhitomir	GISS	+24	+35	+33	+16	+27
	GFDL	+36	-3	-3	+6	+12
	UKMO	+60	+6	+6	+47	+38
Kharkov	GISS	+28	+37	+18	+37	+30
	GFDL	+15	+20	-3	+18	+12
	UKMO	+52	-35	+28	+23	+ 16
Kherson	GISS	+15	-11	+6	+5	+4
	GFDL	-1	+9	+15	+29	+12
	UKMO	+52	-35	+28	+23	+16
Kishinev	GISS	+15	-11	+6	+5	+4
	GFDL	-1	+9	+15	+29	+12
	UKMO	+52	-35	+28	+23	+16

Site		Spring	Summer	Autumn	Winter	Annual
Brest	GISS	+27	+9	+6	+14	+14
	GFDL	+25	-16	+2	-6	+2
	UKMO	+70	+6	+33	+47	+38
Minsk	GISS	+24	+35	+33	+16	+27
	GFDL	+25	-16	+2	-6	+2
	UKMO	+70	+6	+33	+47	+38
Lithuania	GISS	+29	+49	+28	+14	+32
	GFDL	+2	-9	+24	+23	+10
	UKMO	+84	+11	+29	+50	+42
Aktyubinsk	GISS	+40	+45	-22	+31	+24
	GFDL	+12	+7	+94	+46	+40
	UKMO	+59	-22	+24	+32	+23
N. Kazakhstan	GISS	+51	+99	+52	+78	+70
	GFDL	+33	+37	+38	+76	+46
	UKMO	+84	-26	+2	+30	+22
Zelinograd	GISS	+51	+99	+52	+78	+70
	GFDL	+16	+11	+33	+22	+20
	UKMO	+84	-26	+2	+30	+22
Karaganda	GISS	+51	+99	+52	+78	+70
	GFDL	+47	+24	-4	+23	+22
	UKMO	+84	-26	+2	+30	+22

Table 5. Solar rdiation change (%) predicted by GISS, GFDL, and UKMO climate change scenarios.

Site		Spring	Summer	Autumn	Winter	Annual
Bryansk	GISS	0	-3	-6	-16	-6
	GFDL	+10	+6	+6	+83	+26
	UKMO	+22	+9	+10	+4	+11
Kursk	GISS	-1	-3	-4	-20	-7
	GFDL	+14	-2	-9	+62	+20
	UKMO	+22	+9	+10	+4	-11
Yaroslavl	GISS	-5	-11	-9	-18	-8
	GFDL	+47	+1	-2	+37	+20
	UKMO	+8	+5	+6	-1	+4
Saratov	GISS	-3	-2	0	-20	-6
	GFDL	+11	-3	+2	+24	+8
	UKMO	+31	+15	+15	+6	+16
Astrakhan	GISS	+1	0	+5	+1	+2
	GFDL	-2	-1	+6	+25	+7
	UKMO	+29	+16	+14	+3	+17
Rostov-on-Don	GISS	-1	-3	-4	-20	-7
	GFDL	+1	0	+11	+14	+4
	UKMO	+18	+9	+6	0	+7
N. Bashkiria	GISS	-4	-1	0	-20	-6
	GFDL	+10	-1	+9	+10	+15
	UKMO	+29	+1	+11	+10	+15
Lvov	GISS	-2	+1	-4	-12	-4
	GFDL	+2	+7	+7	+51	+17
	UKMO	+26	+6	+12	+7	+12
Zhitomir	GISS	0	-3	-6	-16	-6
	GFDL	+10	+6	+6	+83	+26
	UKMO	+23	0	+6	+1	+8
Kharkov	GISS	-1	-3	-4	-20	-7
	GFDL	+14	-2	+9	+62	+20
	UKMO	+21	+4	+5	-6	+6
Kherson	GISS	0	0	+7	+1	+2
	GFDL	-1	0	+4	+16	+5
	UKMO	+21	+4	+5	-6	+6
Kishinev	GISS	0	0	+7	+1	+2
	GFDL	-1	0	+4	+16	+5
	UKMO	+21	+4	+5	-6	+6

Site		Spring	Summer	Autumn	Winter	Annual
Brest	GISS	-2	+1	-4	-12	-4
	GFDL	-2	+7	+7	+51	+17
	UKMO	+23	0	+6	+1	+8
Minsk	GISS	0	-3	-6	-16	-6
	GFDL	+2	+7	+7	+51	+17
	UKMO	+23	0	+6	+1	+8
Lithuania	GISS	-2	-2	-4	-1	-4
	GFDL	+9	+3	-1	+37	+12
	UKMO	+14	-3	+14	-2	+6
Aktyubinsk	GISS	-5	-1	0	-20	-6
	GFDL	+21	+2	+12	+7	+10
	UKMO	+13	+8	+3	-2	+5
N.Kazakhstan	GISS	-5	0	-2	-21	-7
	GFDL	+6	0	+12	+1	+5
	UKMO	+1	+14	+15	+1	+10
Zelinograd	GISS	-5	0	-2	-21	-7
	GFDL	+10	-1	+6	+21	+9
	UKMO	+11	+14	+15	+1	+10
Karaganda	GISS	-5	+0	-2	-21	-7
	GFDL	+10	-1	+9	+35	+12
	UKMO	+11	+14	+15	+1	+10

Table 6. Simulated change in wheat yield under projected GCM climate scenarios for selected sites. The physiological effects of 555 ppm CO_2 were considered in each climate change scenario.

	Base Yields ($t\ ha^{-1}$)		Simulated yield changes under GCM scenarios %					
			GISS		GFDL		UKMO	
Site	Spr	Win	Spr	Win	Spr	Win	Spr	Win
Bryansk	5.0	6.2	+12	+23	-31	0	+34	-12
Kursk	3.0	6.0	+25	+23	+ 1	+ 9	-31	-16
Yaroslavl	3.5	5.7	+18	-28	+ 1	-34	- 1	0
Saratov	2.1	3.2	+ 4	+45	+ 6	+45	-48	-44
Astrakhan	0.7	1.0	+ 9	+13	+51	+28	- 7	+32
Rostov-Don	3.2	3.7	+12	+51	- 9	+30	-30	+30
N. Bashkiria	2.8	4.6	- 5	+25	- 3	+11	-38	-53
Lvov	6.7	5.8	+ 6	+18	-20	- 8	-19	-16
Zhitomir	5.4	4.0	+16	+13	-18	- 4	-33	-33
Kharkov	2.9	5.2	+ 4	+34	-11	+12	-44	-17
Kherson	1.9	2.1	+30	+52	- 3	+25	+ 1	+91
Kishinev	2.8	2.4	+31	+95	+ 3	+71	+11	+130
Brest	4.2	3.9	+ 5	+22	-25	+ 6	-35	-33
Minsk	4.0	4.6	+10	+23	-32	+ 2	-32	0
Lithuania	4.3	4.7	+17	+42	-26	-38	-27	+47
Aktyubinsk	1.6	1.3	+61	+68	+16	+12	-36	- 1
N. Kazakhstan	4.6	-	- 5	-	- 1	-	-38	-
Zelinograd	2.4	-	+55	-	-12	-	-28	-
Karaganda	2.0	1.7	+59	+102	+ 6	+ 5	-18	+ 9

Base yields are simulated considering a CO_2 concentrationof 330 ppm.

Table 7. Simulated changes in wheat season length for GCM climate change scenarios at selected sites. The physiological effects of 555 ppm CO_2 were considered in each climate change scenario.

	Season Length Changes (days)					
	GISS		GFDL		UKMO	
Site	Spr	Win	Spr	Win	Spr	Win
Bryansk	-8	-23	-19	-25	-27	-55
Kursk	-9	-22	-11	-20	-24	-49
Yaroslavl	-1	-72	-6	-20	0	-16
Saratov	-8	-20	-6	-15	-16	-35
Astrakhan	-9	-14	-7	-15	-14	-39
Rostov-Don	-8	-20	-8	-19	-13	-34
N.Bashkiria	-13	-20	-11	-16	-22	-37
Lvov	-10	-25	-19	-25	-23	-52
Zhitomir	-8	-23	-15	-20	-26	-44
Kharkov	-8	-24	-10	-20	-21	-44
Kherson	-12	-22	-10	-18	-19	-50
Kishinev	-11	-22	-11	-18	-19	-48
Brest	-10	-20	-18	-23	-26	-52
Minsk	-8	-18	-20	-23	-25	-50
Lithuania	-8	-33	-18	-38	-25	-70
Aktyubinsk	-8	-16	-8	-16	-13	-32
N.Kazakhstan	-14	-	-14	-	-22	-
Zeli-grad	-10	-	-11	-	-18	-
Karaganda	-9	-16	-12	-19	-17	+32

Table 8. Simulated changes in wheat evapotranspiration for projected GCM climate scenarios at selected sites. The physiological effects of 555 ppm CO_2 were considered in each climate change scenario.

Change in ET (mm)

	GISS		GFDL		UKMO	
Site	Spr	Win	Spr	Win	Spr	Win
Bryansk	-9	-6	-12	+4	-14	0
Kursk	-5	-3	-4	+4	-10	+2
Yaroslavl	-2	-30	-10	+8	+20	+27
Saratov	0	+1	-1	+7	-10	+8
Astrakhan	-4	0	-4	+2	-5	0
Rostov-Don	-2	-2	-10	-3	-10	+1
N.Bashkiria	-4	-1	-8	-1	-13	+4
Lvov	-7	-5	-13	-1	-9	-7
Zhitomir	-8	-8	-9	+6	-8	0
Kharkov	-7	-4	-6	0	-11	+3
Kherson	-4	-3	-8	-3	0	-4
Kishinev	-8	-2	-10	-2	-2	-1
Brest	-10	-12	-15	-9	-11	-24
Minsk	-8	-10	-12	-3	-9	-3
Lithuania	-4	-2	-16	-12	-4	-6
Aktyubinsk	+7	+8	-4	+9	-6	+11
N.Kazakhstan	+2	-	-5	-	-13	-
Zeli-grad	+15	-	-12	-	-10	-
Karaganda	+15	+22	-2	+12	-6	+18

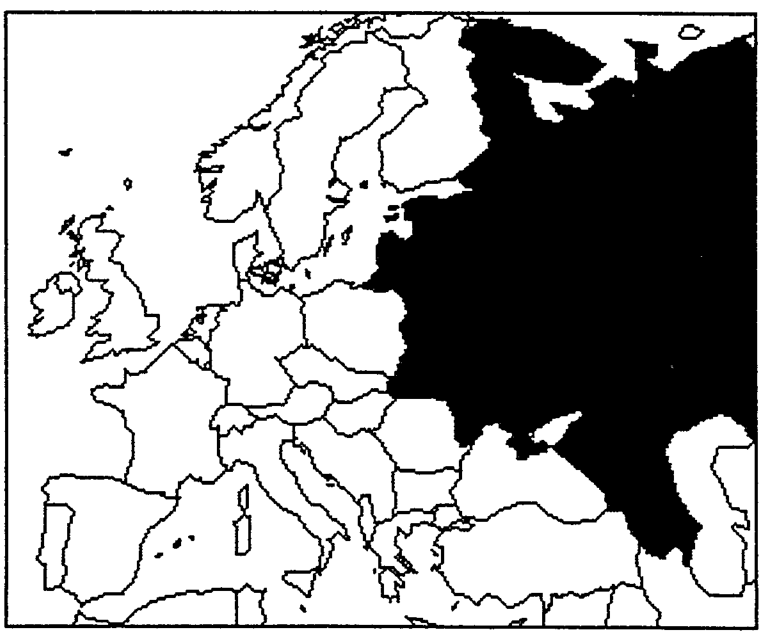
Table 9. Aggregated national wheat yield change (%) for GCM equilibrium and the GISS transient climate change scenarios.

Scenario	Carbon Dioxide (ppm)	Yield changes (%)	
		Spring Wheat	Winter Wheat
GISS-Trans-2010	405	+8	+16
GISS-Trans-2030	460	+12	+24
GISS-Trans-2050	530	+18	+38
GISS	555	+21	+41
GFDL	555	-4	+12
UKMO	555	-18	+9

Table 10. Simulated wheat yield response to changes in sowing date and irrigation under the UKMO climate change scenario. The physiological effects of 555 ppm CO_2 were considered in the simulation.

Site	Management	Sowing date	% Change from Baseline yield
Zhitomir	Rainfed	15 days late	-1
	Rainfed	30 days late	-3
	Irrigated	15 days late	+50
	Irrigated	30 days late	+40
Saratov	Rainfed	15 days early	+1
	Rainfed	30 days early	-1
	Irrigated	15 days early	+70
	Irrigated	30 days early	+100


N_BASHKIRIA
YAROSLAVL
LITHUANIA
N_KAZAKHSTAN
MINSK
BRYANSK
BREST
KURSK
SARATOV
ZELINOGRAD
ZHITOMIR
N_AKTYUBINSK
KARAGANDA
LVOV
KHARKOV
ODESSA
ROSTOV_NA_DON
KHERSON
ASTRAKHAN



SECTION 5: AFRICA

IMPACT OF CLIMATE CHANGE ON SIMULATED WHEAT AND MAIZE YIELDS IN EGYPT

H.M. Eid

Soils & Water Resources Institute,
ARC, Ministry of Agriculture, Egypt

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SUMMARY

The potential impact of climate change on maize and wheat production in Egypt was evaluated by simulating crop production under different climatic scenarios and by analyzing crop sensitivity to temperature increases in the two major agricultural regions of Egypt. Increases of 2°C and 4°C reduced wheat and maize yields in the Delta and Middle Egypt regions. Under GCM climate change scenarios, yields decreased in comparison to current climate conditions, even when the beneficial effects of CO_2 were taken into account. The UKMO scenario produced the largest yield decreases. According to this simulation study, the impact of climate change on national wheat and maize production would be severe. Future adaptation strategies to climate change may involve the development of new, more heat-tolerant cultivars.

INTRODUCTION

Major crops in Egypt include wheat (used as a staple food crop), maize (used primarily as coarse grain for animal feed), clover, cotton, rice, sugar cane, fava bean, and soybean. The national wheat and maize production do not meet the current demand for these crops, and each year additional amounts have to be imported—up to 60% of total consumption in the case of wheat. The rapid growth of the country's population, the economic stress of reliance on food imports, and the limited area for agriculture (most of the country is a desert) require Egyptians to find new ways to increase agricultural productivity. If climate change as projected by atmospheric scientists (IPCC 1990) adversely affects crop production, Egypt would have to increase its reliance on costly food imports.

The purpose of this study was to investigate the potential effects of climate change on wheat and maize yields and irrigation demands in Egypt. Wheat and maize are irrigated under the flood irrigation system, using water from the Nile River. Two important agricultural regions were selected for the study (Figure 1). The Sakha region, at the north of the Nile delta, is represented by the site Sakha (Khafr El-Sheik governorate) (31.07°N; 30.57°E). This region of the delta is the most fertile area in Egypt and produces about 60% of the national wheat and 75% of the total maize crop (Table 1). The Giza region, near Cairo, is represented by the site Giza (30.03°N; 31.13°E).

METHODS

Climate Data and Climate Change Scenarios

Daily maximum and minimum temperatures, precipitation, and solar radiation data were obtained for Sakha from 1975 to 1989 and for Giza from 1960 to 1989 (Table 2).

The climate change scenarios used in this simulation study were created using three equilibrium General Circulation Models (GCMs) combined with the observed daily climate data for each site (Table 2). Three GCMs were used: Goddard Institute for Space Studies, (Hansen *et al.* 1983), Geophysical Fluid Dynamics Laboratory, (Manabe and Wetherald 1987), and United Kingdom Meteorological Office, (Wilson and Mitchell 1987). Table 3 shows the projected seasonal and annual GCM climate changes for these sites. In Giza, the GISS and UKMO climate change scenarios presented consistent, unexplained errors in the years 1968 (GISS scenario) and 1974 and 1989 (UKMO scenario). These years were not included in the study.

The study also includes: (a) a sensitivity study to arbitrary changes in temperature (+2°C and +4°C); and (b) a transient scenario study, using the GISS transient run A for the years 2010, 2030, and 2050 (Hansen *et al.* 1988). Atmospheric CO_2 concentrations of 405 ppm, 460 ppm, and 530 ppm were used for the years 2010, 2030, and 2050, respectively.

Crop Models

Crop yields and demand for irrigation water were estimated with the CERES-Wheat (Ritchie and Otter 1985) and CERES-Maize (Jones and Kiniry 1986) models using the version developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT 1989). The IBSNAT crop models can simulate the physiological effects of CO_2, i.e., increase in rate of photosynthesis and change in evapotranspiration due to increases in stomatal resistance (Acock and Allen 1985). Simulations for the GCM scenarios and sensitivity analyses included climate change alone and climate change with the physiological effects of CO_2 at both sites.

Management Variables for the Crop Models

Typical soils at Giza and Sakha are montmorillonitic, thermic, slightly calcareous, and deep (Abdel Wahed 1983). The texture, albedo, and water-related specific characteristics of these soils are adequately represented by the generic soil (Medium Silty Clay) provided for the study (Jones *et al.* 1990).

Wheat and maize are grown using flood irrigation (Gad-El Rab *et al.* 1988; Eid 1977) . For the simulations, the automatic irrigation option was chosen to provide the crops with nonlimiting water; the models do not include an option that simulates flooding. Maize and wheat are fertilized in the regions in this study, and therefore the simulations did not consider nitrogen stress.

Crop Model Validation

The CERES-Wheat and CERES-Maize models were validated by comparing observed data on biomass, yields, and maturity dates to simulated values (Table 4). The results of the validation experiment indicate that the CERES crop models can be used at the selected sites in Egypt. The observed data on grain yield and season length were very close to the corresponding simulated values. The observed total biomass was slightly smaller than the simulated one. According to these results, the models were considered validated for the conditions of the study.

RESULTS AND DISCUSSION

Crop Sensitivity to Temperature and CO_2 Increases

Table 5 shows simulated grain yield, season length, evapotranspiration (ET), and irrigation demand in response to arbitrary changes in temperature. The physiological effects of CO_2 were considered in each scenario (shown as 555 ppm in the tables). Increases in temperature resulted in lower grain yields for both crops at the two sites; yield reductions showed a linear relation to temperature increases. Yield decreases were larger for maize, a summer crop, than for wheat, a winter crop. The temperature-induced reductions in maize and wheat may be due to a shortening of the grain-filling periods. Although not simulated in CERES-Maize, high temperatures as projected by the GCM scenarios may also cause pollinization failure. When the direct effects of CO_2 were considered, simulated grain yields increased in all scenarios compared with the results in the scenarios of climate change alone. These increases, however, did not compensate for the yield decreases under the higher temperature scenarios compared to base yields.

Total crop evapotranspiration and irrigation demand increased with temperature increases in the case of maize, but decreased in the case of wheat, due to the shortening of the crop growing season. When the physiological effects of CO_2 were considered, ET and irrigation water demand were reduced for both crops compared to the case of climate change alone. These reductions are the consequence of the CO_2-induced decreases in the transpiration rate per unit leaf area (Acock and Allen 1985) and the shortening of the crop growing season included in the crop models.

Yields under GCM Climate Change Scenarios

All climate change scenarios considered resulted in simulated decreases in maize and wheat yields at both sites (Table 6 and Figures 2 and 3). The largest decreases in yield for both wheat and maize were under the UKMO scenario in Giza. The physiological effects of CO_2 caused simulated maize yields to increase slightly and wheat yields to increase substantially compared to yields under the climate change scenario alone. The relative responses of wheat and maize are due to the greater CO_2 photosynthetic response in C3 crops (wheat, barley, soybean, cotton, rice, and many others) than in C4 crops (maize, sugarcane, and sorghum) (Cure 1985).

Considering the simulated negative impacts of climate change on simulated wheat and maize yields in the Delta and Middle Egypt regions, it is possible to conclude that climate change may bring about substantial reductions in the national grain production.

Transient Scenarios

The crop responses to the transient GISS scenarios are shown in Table 7. Simulated grain yield decreases were not linear with time; the largest reductions correspond to the 2030s.

Adaptation Strategies for Wheat and Maize to Climate Change

Changes of maize and wheat cultivars were considered as possible adaptation strategies to climate change (Table 6). Nevertheless, for the two locations, all cultivars tested had similar losses in yield under the climate change scenarios in comparison to baseline yields. It will be important for Egypt to develop new cultivars that are more adapted to higher temperatures. Since the crop models can be used to identify appropriate crops, varieties, and management strategies to maximize benefits and minimize risks associated with future climatic change, further simulation studies would be valuable in assessing the risks associated with given production strategies.

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Table 1. Wheat and maize production in Egypt.

	Area (ha)	Production (t)	Yield (t ha^{-1})
WHEAT			
Giza Region (1984)	26,111	107,055	4.15
Sakha Region (1984)	39,395	162,110	4.12
Egypt total (avg. 1980-1988)	572,000	2,166,000	3.79
MAIZE			
Giza Region (1984)	54,269	309,290	5.66
Sakha Region (1984)	36,264	204,557	6.64
Egypt total (avg. 1980-1988)	754,000	3,386,000	4.49

Table 2. Observed average temperature, total precipitation, and solar radiation during the crop growing season at Giza and Sakha.

Maize at Giza	
Temperature	25.6 °C
Precipitation	0.0 mm
Solar radiation	549 MJ m^{-2}
Maize at Sakha	
Temperature	23.9°C
Precipitation	2.0 mm
Solar radiation	546 MJ m^{-2}
Wheat at Giza	
Temperature	16.5°C
Precipitation	17.0 mm
Solar radiation	408 MJ m^{-2}
Wheat at Sakha	
Temperature	15.4°C
Precipitation	42.0 mm
Solar radiation	399 MJ m^{-2}

Table 3. Seasonal and annual changes in temperature, precipitation, and solar radiation under GCM climate change scenarios at Giza and Sakha.

GCM CLIMATE CHANGES AT SAKHA AND GIZA

Temperature Change (°C)

	GISS	GFDL	UKMO
Spring	5.1	4.5	4.7
Summer	3.2	4.4	4.1
Autumn	4.4	4.1	4.5
Winter	4.0	3.7	4.5
Annual	4.2	4.2	4.4

Precipitation Change (%)

	GISS	GFDL	UKMO
Spring	-7.1	-19.2	-12.5
Summer	350.0	0.0	-37.0
Autumn	27.3	-20.0	1.2
Winter	5.9	-10.0	-8.9
Annual	55.7	-15.3	-13.8

Solar Radiation Change (%)

	GISS	GFDL	UKMO
Spring	-0.3	2.0	6.2
Summer	-4.2	-0.6	6.1
Autumn	-1.2	0.6	1.3
Winter	0.0	0.8	8.7
Annual	1.7	0.6	5.5

Table 4. Simulated and observed wheat and maize yields, biomass, and season length at Giza and Sakha.

		Yield (t ha^{-1})		Biomass (t ha^{-1})		S. length (days)	
Cultivar	Year	Sim	Obs	Sim	Obs	Sim	Obs
				Maize (Sakha)			
Giza-2	1985	9.95	9.90	23.47	26.73	120	121
H.204	1985	10.70	10.54	24.77	28.45	122	121
Cairo-1	1958	9.77	9.61	24.75	25.94	122	121
Pio.514	1985	9.92	9.83	24.11	26.53	122	121
				Maize (Giza)			
D.C.202	1984	9.20	8.93	31.59	24.44	128	124
				Wheat (Sakha)			
Sakha 8	1983	4.30	4.35	18.72	14.41	153	156
				Wheat (Giza)			
Giza-156	1975	6.22	6.14	14.77	18.27	132	133
Mexipak65	1975	6.24	6.27	15.10	16.73	132	133

Maize experiments: Sakha Clayey soil; planting June 1; row spacing 70 cm; 5.7 plants m^{-2}; initial soil water (depth, water content) (5,.246) (10,.246) (15,.208) (15,.208) (15,.208) (15,.318) (15,.318) (15,.318); irrigation dates and amounts (julian day, mm) (169,158) (192,37) (199,39) (204,35) (210,41) (216,39) (222,36) (228,37) (234,37) (240,35) (246,36) (253,37) (260,39) (267,37) (274,38) (282,36) (290.35) = 751 for H.204; N-fertilization dates and amounts (julian day, kg ha$^{-1)}$ (169,69) (190,133).

Wheat experiments: Sakha Clayey soil; planting December 24; row spacing 10 cm; 350 plants^{-2}; irrigation dates and amounts (julian day, mm) (385,146) (29,35) (42,34) (73,35) (84,34) (95,37) (103,34) (111,36) (119,34) (126,40) (132,36) (137,35) (142,38) (147,37); N-Fertilization dates and amounts (julian day, kg ha^{-1}) (18,63) (46,63).

Table 5. Sensitivity analysis of yield, season length (SL), total evapotranspiration (ET), and irrigation water (Irrig.) simulated with CERES-Wheat and CERES-Maize.

		WHEAT (SAKHA)				WHEAT (GIZA)			
CO_2 level (ppm)	Temp Increase (°C)	Yield ($t\ ha^{-1}$)	SL (days)	ET (mm)	Irrig. (mm)	Yield ($t\ ha^{-1}$)	SL (days)	ET (mm)	Irrig. (mm)
330	0	3.80	141	552	475	5.60	118	288	250
	2	3.30	133	547	456	4.40	106	246	209
	4	3.20	125	511	430	3.20	96	206	174
555	0	4.40	141	517	432	6.00	118	260	220
	2	3.89	133	498	418	4.80	106	219	183
	4	3.46	125	498	404	3.58	96	181	151

		MAIZE (SAKHA)				MAIZE (GIZA)			
CO_2 level (ppm)	Temp. Incr. (°C)	Yield (T/Ha)	SL (days)	ET (mm)	Irrig. (mm)	Yield (T/Ha)	SL (days)	ET (mm)	Irrig. (mm)
330	0	10.25	115	569	524	9.80	120	583	543
	2	8.73	107	565	527	8.70	114	608	567
	4	7.54	104	609	566	7.50	114	665	624
555	0	10.33	115	480	433	10.40	120	500	462
	2	9.11	107	481	438	9.20	114	525	482
	4	7.96	104	521	475	8.00	114	577	534

* The cultivar used at Sakha was "Giza-2" and at Giza, "D.C. 202." Similar results were obtained with cultivars "H-204," "Cairo 1," and "Pioneer 514."

** The cultivar used at Sakha was "Sakha-8" and at Giza, "Giza-156." Similar results were obtained with the cultivar "Mexipak-65" at Giza.

Table 6. Simulated maize and wheat yields under baseline climate and GCM climate change scenarios at Sakha and Giza.

Site	Cultivar	BASE	GISS	GISS	GFDL	GFDL	UKMO	UKMO
		330	330	555	330	555	330	555
		Simulated maize yield (t ha^{-1})						
Sakha	Giza-2	10.25	7.96	8.41	7.56	7.98	8.38	8.46
	H.204	10.60	8.16	8.62	7.85	8.28	8.63	8.71
	Cairo-1	7.61	7.61	8.04	7.24	7.65	8.01	8.07
	Pio. 514	10.15	7.79	8.23	7.44	7.86	8.21	8.28
Giza	D.C.202	9.83	6.96	7.35	7.73	8.16	3.20	3.38
		Simulated wheat yield (t ha^{-1})						
Sakha	Sakha-8	4.16	3.03	3.20	3.21	3.41	3.27	3.46
Giza	Giza 156	5.57	3.22	3.59	3.44	3.82	1.32	1.49
	Mexipak65	5.42	3.17	3.52	3.38	3.74	1.30	1.46

330: Effects of climate alone on crop yield
555: Physiological effects of CO_2 on crop yield

Table 7. Simulated wheat and maize yields under the GISS transient scenarios. The physiological effects of CO_2 on crop yield were included.

Crop	Site	Scenario	Yield (t ha^{-1})
MAIZE	Sakha*	BASE	10.25
		2010	8.76
		2030	7.93
		2050	8.15
	Giza**	BASE	9.80
		2010	8.99
		2030	8.29
		2050	7.74
WHEAT	Sakha*	BASE	4.40
		2010	4.79
		2030	4.47
		2050	3.89
	Giza**	BASE	5.60
		2010	5.48
		2030	4.31
		2050	3.58

* Maize cultivar shown at Sakha "Giza-2". Similar results were obtained with "H-204," "Cairo-1," and "Pioneer-514." Wheat cultivar simulated at Sakha "Sakha 8."

** Maize cultivar simulated at Giza "D.C.202." Wheat cultivar simulated at Giza "Giza-156"; similar results were obtained with "Mexipak-65."

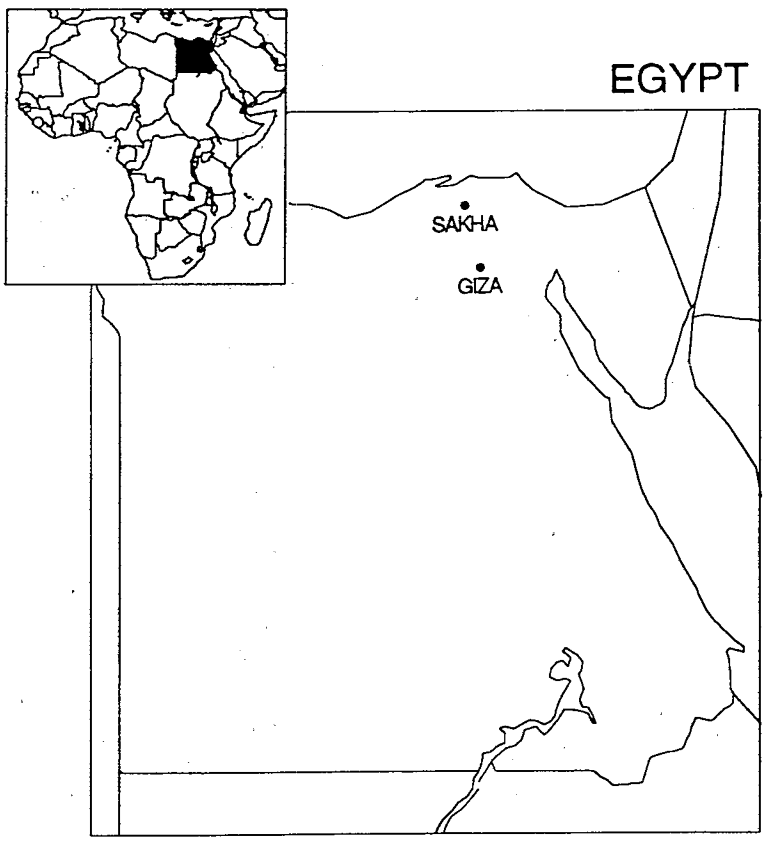

Figure 1. Map of Egypt and location of the crop modeling sites.

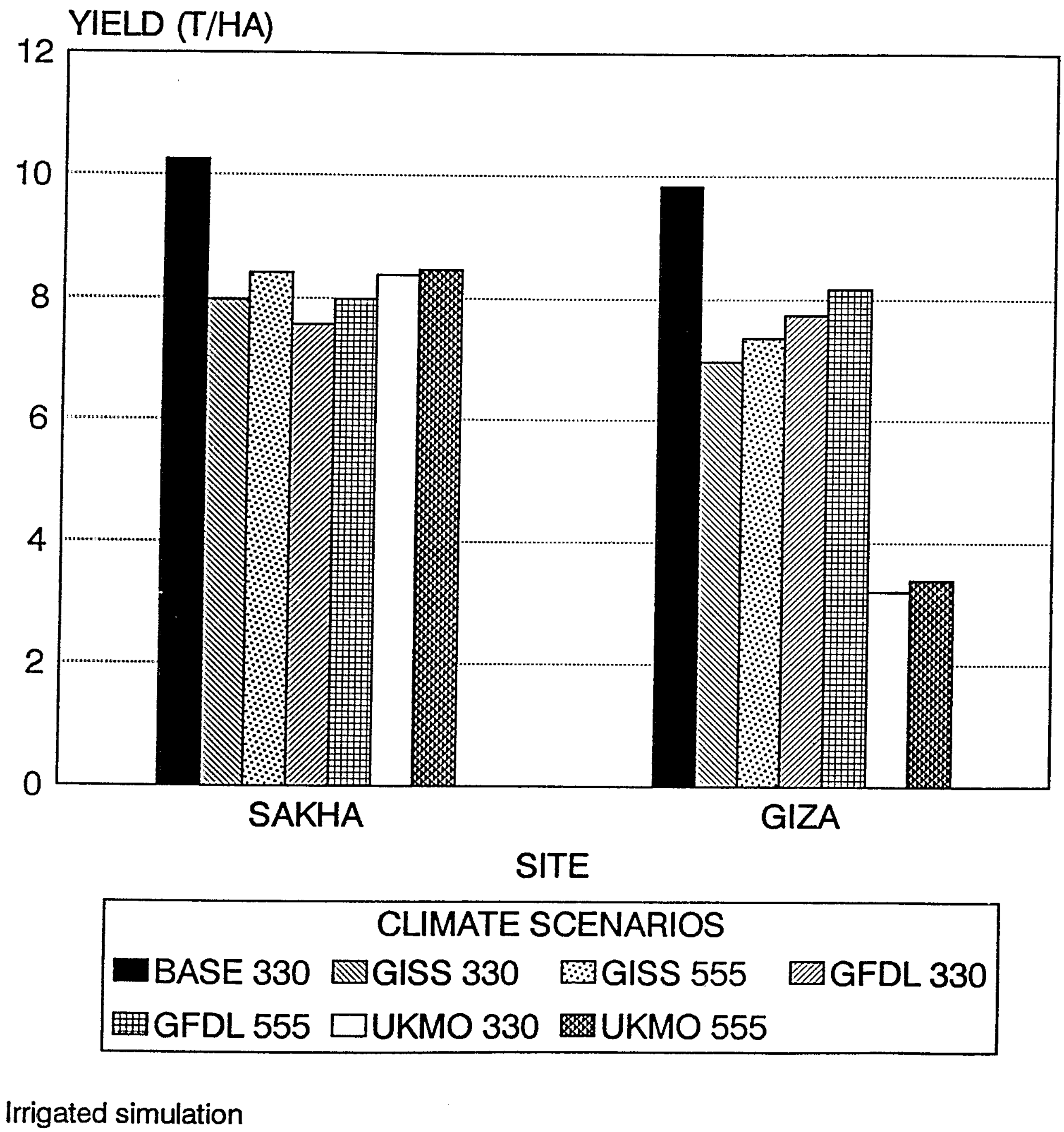

Figure 2. Simulated maize yield under GCM $2xCO_2$ climate change scenarios.

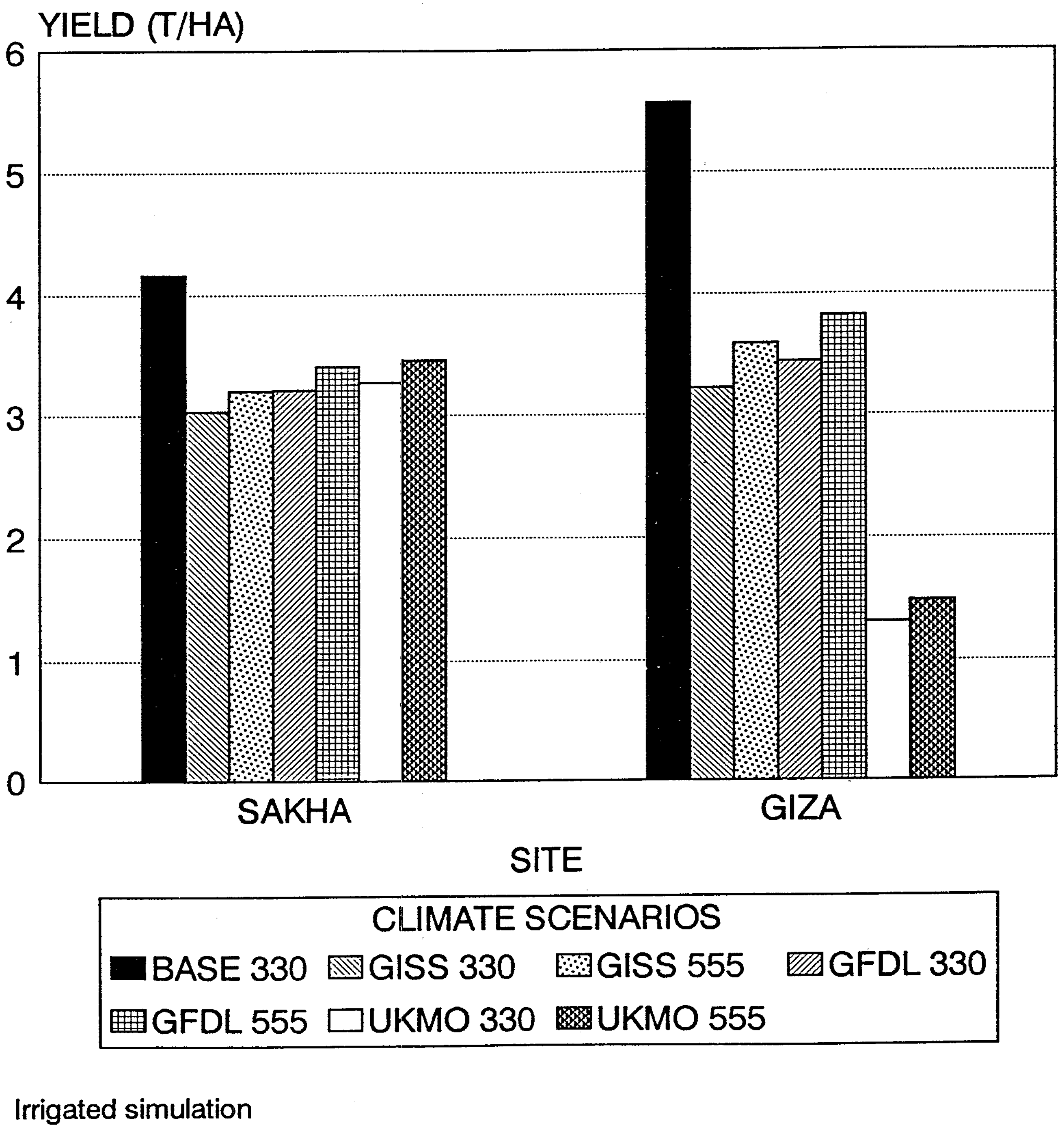

Figure 3. Simulated wheat yield under GCM $2xCO_2$ climate change scenarios.

IMPLICATIONS OF CLIMATE CHANGE FOR MAIZE YIELDS IN ZIMBABWE

Paul Muchena

Plant Protection Research Institute, Zimbabwe

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SUMMARY

The potential impact of climate change on maize production in Zimbabwe was evaluated by simulating crop production under climate scenarios generated by General Circulation Models (GCMs). The baseline climate data for each site was also modified by increasing daily air temperatures by 2°C and 4°C for a sensitivity analysis. Maize yields decreased under the GCM climate change scenarios, even when the direct beneficial effects of CO_2 were included in the simulation. Temperature increases of 2°C and 4°C reduced maize yields at all sites.

If these results are realized, the impact on national maize production in Zimbabwe would be severe. Many farmers would not find maize economical to produce. Adaptation results suggest that major changes in the farming system might ameliorate some losses, but the costs of additional fertilizer, seed supplies, and irrigation could be high.

INTRODUCTION

Description of the Agricultural Regions

Zimbabwe is situated in southern Africa between the latitude of 15° and 23°S and the longitude of 25° and 33°E, and occupies a land area of 390,759 square kilometers. Although Zimbabwe lies within the tropics, only one-fifth of the country's area experiences typical tropical climate. The rest of the country includes areas of altitude between 600 and 1,200 meters above sea level (three-fifths of the total area) and areas above 1,200 meters (one-fifth of the total area). Agricultural land constitutes 85% of the land resources in the country. The land is divided into five natural agroecological regions on the basis of rainfall and temperature (Figure 1).

Farming Sectors, Management Systems and Crops in Zimbabwe

The agricultural land is used by large- and small-scale commercial sectors, and by communal and resettlement sectors. The large-scale commercial sector includes private and state enterprises (39% of the total agricultural land). Private enterprises (about 4,500 large-scale farmers) hold title deeds to the land. The large-scale cropping system is intensive and mechanized, using modern production technologies over large areas of monoculture. Summer crops are irrigated when necessary, and winter crops are always irrigated. The small-scale commercial sector consists of small private farms in which the farmers hold title deeds to their farms (4% of the total agricultural land).

The communal sector comprises about 900,000 farming families (4.5 million people; 49% of the total agricultural land). Individual farmers hold family rights to limited areas for cultivation (2.5 ha/family). Monoculture of maize, the staple crop, generally dominates the system. The cropping system is similar to the small-scale sector, although the farms are smaller and the production capacity is comparatively less. About 40,000 families have been resettled on about 8% of the total agricultural land. As in the case of the communal sector, the resettlement sector has socioeconomic constraints due to poor planning and management.

Maize is the primary food crop food in Zimbabwe and occupies about half of the total agricultural crop land. It is grown by all of the farming sectors, although the productivity varies largely among them (mean yields of 3.2 t ha^{-1} and 1.1 t ha^{-1} in the commercial and communal sectors, respectively). Eighty percent of the area sown with maize is communal. Other important crops are small grain cereals (sorghum, finger millet, and pearl millet); oil-seed crops (soybeans, groundnut, and sunflowers); and important cash crops (tobacco, cotton, coffee, tea, and horticultural crops). The small grains use about 20% of the total crop land and are generally grown by communal farmers.

Food Trade and Vulnerabilities

Crop production in Zimbabwe usually exceeds demand, especially in years when rainfall is not limiting. However, when rainfall is below average, production in the marginal regions is often not enough to meet local demand, and the population can experience food deficits.

Objectives

During the last 10 years, the frequency of drought has increased in Zimbabwe, causing crop yields to be below average. If climate change brings about warmer and dryer conditions in the region, crop production may be seriously damaged. For an adequate impact study, it is important to select sites representing the different agroecological regions of Zimbabwe. For this study, these three sites were selected: Banket, Gweru, and Chisumbanje. The sites represent high, low, and marginal productivity regions, respectively. They were also chosen because the long-term, daily weather data sets (solar radiation, maximum and minimum air temperatures, and precipitation) were available to run the crop simulation model.

The specific objectives of the study are to evaluate: (1) potential climate changes that might occur from doubled CO_2; (2) the possible impact of climate change on maize yields; and (3) the sensitivity of maize yields to temperature increases (+2°C or +4°C).

METHODS

Baseline Climate Data

Figure 2 shows the daily observed climate data (precipitation, solar radiation, maximum and minimum air temperatures) for Banket (1968 to 1988), Gweru (1960 to 1987), and Chisumbanje (1962 to 1988). Chisumbanje has the warmest average annual temperature. The seasonal precipitation regime is similar at all sites (wet in the summer and dry in the winter), but there are large differences in the total precipitation among the sites. Chisumbanje is the driest site with average annual precipitation of about 560 mm.

Climate Change Scenarios

Using the GCMs, the observed climate data were modified to create climate change scenarios for each site. The GCMs used were developed by the Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1983), the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office (UKMO) ((Wilson and Mitchell 1987). Daily observed climate values were modified with the monthly outputs of the GCMs for the particular gridbox where the site is located.

The climate change scenarios created for each site show major changes from the current climate (Table 1). Temperature increases are very similar in the three sites. The GFDL scenario produces the lowest temperature increase (3.6°C), while the UKMO scenario produces the largest (5°C). Precipitation changes vary among the sites: the GFDL scenario is the driest. Considering the temperature increases projected by the GCMs and their possible effects on evapotranspiration, the climate change scenarios could imply water shortages, especially in the sites that currently have low precipitation, such as Chisumbanje.

The baseline climate data for each site was also modified by uniformly increasing the values of the daily air temperatures by +2°C and +4°C.

Crop Model, Inputs and Simulations

The maize simulation model used was the CERES-Maize model (Jones and Kiniry 1986). The model simulates crop responses to changes in climate, management variables, soils, and different levels of CO_2 in the atmosphere. The software used to run the programs was developed by the Decision Support System for Agrotechnology Transfer (DSSAT) and includes database management, crop models, and application programs (Jones *et al.* 1990).

Management variables. Maize in Zimbabwe is mainly rainfed and partially fertilized. For the simulations, maize was not irrigated and nitrogen was applied four and eight weeks after planting (60 kg ha^{-1} each time). Additional simulations to evaluate potential adaptive strategies considered possible changes in management variables. For the irrigation simulation, the water demand was calculated assuming 100% efficiency of the automatic irrigation system; a 1-meter irrigation management depth; automatic irrigation when the available soil water is 50% or less of capacity; and the soil water for each layer is re-initialized to 100% capacity at the start of each growing season. The plant population was higher in the irrigated simulations (7 plants m^{-2}) than in the rainfed simulations (5 plants m^{-2}).

Soils. Zimbabwe's soils are predominantly derived from granite and are often sandy and light-textured, with low agricultural potential due to low nutrient content (especially nitrogen and phosphorus). Nevertheless, in all regions, there is a significant portion of soils with a heavier clay content that is more suitable for crop growth. The representative soils in Banket and Gweru are medium sandy loam soil and in the smaller region of Chisumbanje are medium silt loam (as described in Jones *et al.* 1990).

Physiological CO_2 effects. Since the scenario climate change has higher levels of CO_2 than the current climate, the CERES-Maize model includes an option to simulate the physiological effects of CO_2 on photosynthesis and water-use efficiency that results in higher yields (Acock and Allen 1985).

Simulations. For all climate scenarios included in this study (GCMs, sensitivity, GISS transient, and UKMO scenarios for adaptation), maize growth was simulated under the conditions of climate change alone and under the conditions of climate change with the physiological effects of CO_2 on crop growth and yield.

Validation of the Crop Model

The CERES-maize model was validated at Banket and Gweru using local experimental and climate data. The experimental data included soil fertility before planting, cultivar, planting date, phenological growth-stage components and growth analysis, harvesting date, and final yield components. Experimental crop data and climate were used for the 1987-88 season in Banket, and for the 1985-86 and 1986-87 seasons in Gweru. In Banket, the observed yield was 13.6% lower than the simulated yield, and the observed season length was 1.6% shorter than the simulated season length. In Gweru, the mean observed yield was 2% lower than the simulated yield and the observed season length was 1% longer than the simulated season length. The results indicate that CERES-Maize is adequate to simulate maize growth under the conditions of this study, especially to evaluate changes in phenology and relative changes in crop yields.

RESULTS

Sensitivity Analysis

A temperature increase of 2°C over the baseline climate reduced maize yields by 8% to 14% and by 24% to 27% when the baseline temperature was increased 4°C (Table 2). The largest yield decreases were in Chisumbanje, suggesting that, at this site, maize is already close to the upper temperature limit for growth. The increase in temperature reduced maize yields because the growing season was shortened and the crop had less time for grain-filling and biomass accumulation. When the direct effects of CO_2 were added, maize yields increased slightly, but not enough to compensate for the adverse effects of the temperature increase.

Maize Yields under GCM Climate Change Scenarios

In Banket, simulated maize yields under the GISS, GFDL, and UKMO scenarios were reduced by 21%, 14%, and 28%, respectively. In Gweru, the reductions were 28%, 26%, and 50%, and in Chisumbanje, they were 27%, 25%, and 39% (Figure 3). These yield reductions were a consequence of the shortening of the growing season induced by higher temperatures. The physiological effects of CO_2 caused maize yields to increase at all sites, due to the higher photosynthetic rate of the crop with the elevated CO_2. In Chisumbanje, the probability of obtaining an acceptable yield (e.g., 2.5 t ha^{-1}) decreased with an increase of +2°C and under the UKMO scenario (Figure 4).

Adaptation to Climate Change

We tested possible adaptation strategies to climate change at Gweru because, under the UKMO scenario, it projects the largest yield decreases. Two high-cost adaptation strategies were tested: (1) increased fertilization (double the amount of nitrogen) and (2) a combination of increased fertilization and irrigation (simulated under the automatic irrigation option of the CERES model) (Figure 5). Increased fertilization alone had a small, positive effect on the yield under the UKMO scenario. However, even if increased fertilization was combined with irrigation (nonlimiting water), the combined positive effect was not enough to fully compensate for the yield losses under the UKMO scenario.

CONCLUSIONS

The results show that even when the physiological effects of CO_2 were included, modeled maize yields decreased significantly at all sites, as a result of climate change. The effect of climate change on maize production may force some farmers to switch to other crops with higher thermal requirements and drought tolerance, such as sorghum, pearl millet, and finger millet. Although the results suggest that farmers may be able to offset some of the yield losses by adaptation, this solution may not be a very realistic one. This is because the costs of additional fertilizer, seed supplies, and irrigation may be high in a country with very limited financial resources.

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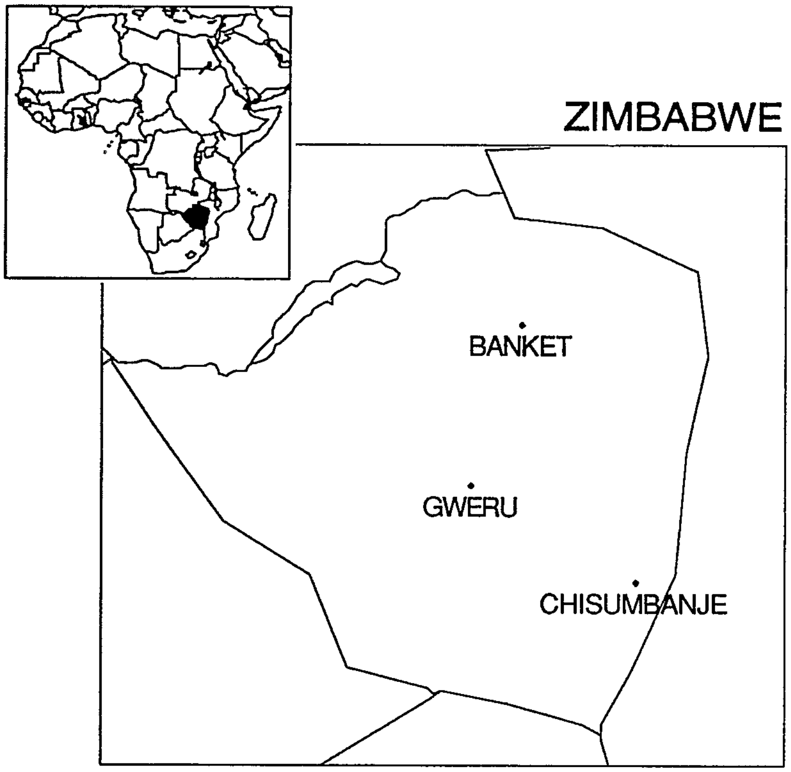
Table 1. Annual temperature differences and precipitation ratios under GCM scenarios at selected sites in Zimbabwe.

	Temperature Changes		
	GISS	GFDL	UKMO
BANKET	4.5	3.7	4.8
GWERU	4.6	3.7	5.0
CHISUMBANJE	4.5	3.6	3.9

	Precipitation Ratios		
	GISS	GFDL	UKMO
BANKET	1.18	1.04	1.10
GWERU	1.22	0.93	1.59
CHISUMBANJE	1.24	1.05	1.09

Table 2. Sensitivity analysis of CERES-Maize to temperature and CO_2 changes in Zimbabwe.

		Simulated Yield (T/Ha)			Simulated Season Length (days)		
CO_2 level (ppm)	Temp. (°C)	Banket	Gweru	Chisumb.	Banket	Gweru	Chisumb.
330	0	4.93	3.72	2.86	120	135	97
	2	4.40	3.41	2.47	107	115	90
	4	3.68	2.83	2.09	96	101	87
555	0	5.25	4.41	3.09	120	135	95
	2	4.70	3.99	2.63	107	115	88
	4	3.95	3.29	2.22	96	101	85


ZIMBABWE
BANKET
GWERU
CHISUMBANJE

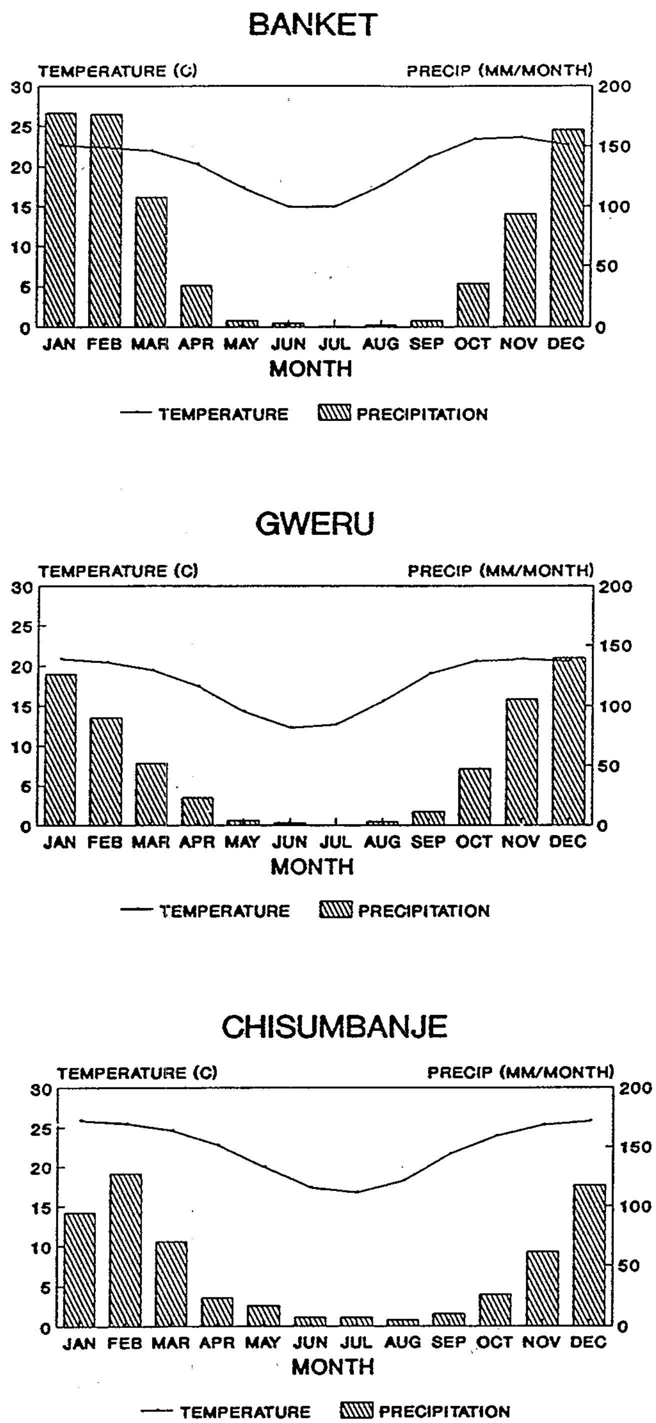


Figure 2. Baseline climate for Banket, Gweru, and Chisumbanje.

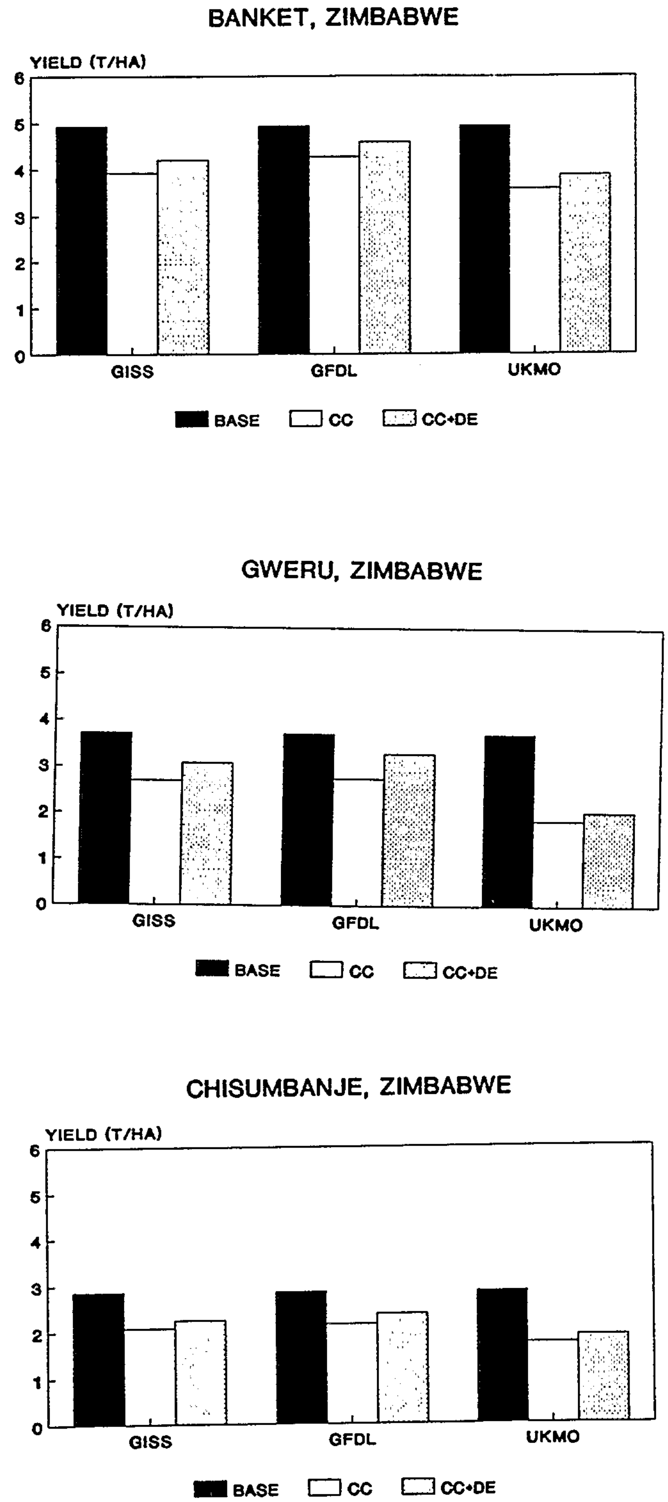


Figure 3. Simulated maize yields under base climate and GCM climate change scenarios. CC indicates simulations under climate change alone; CC+DE indicates simulations under climate change including the direct effects of CO_2 on maize yield.

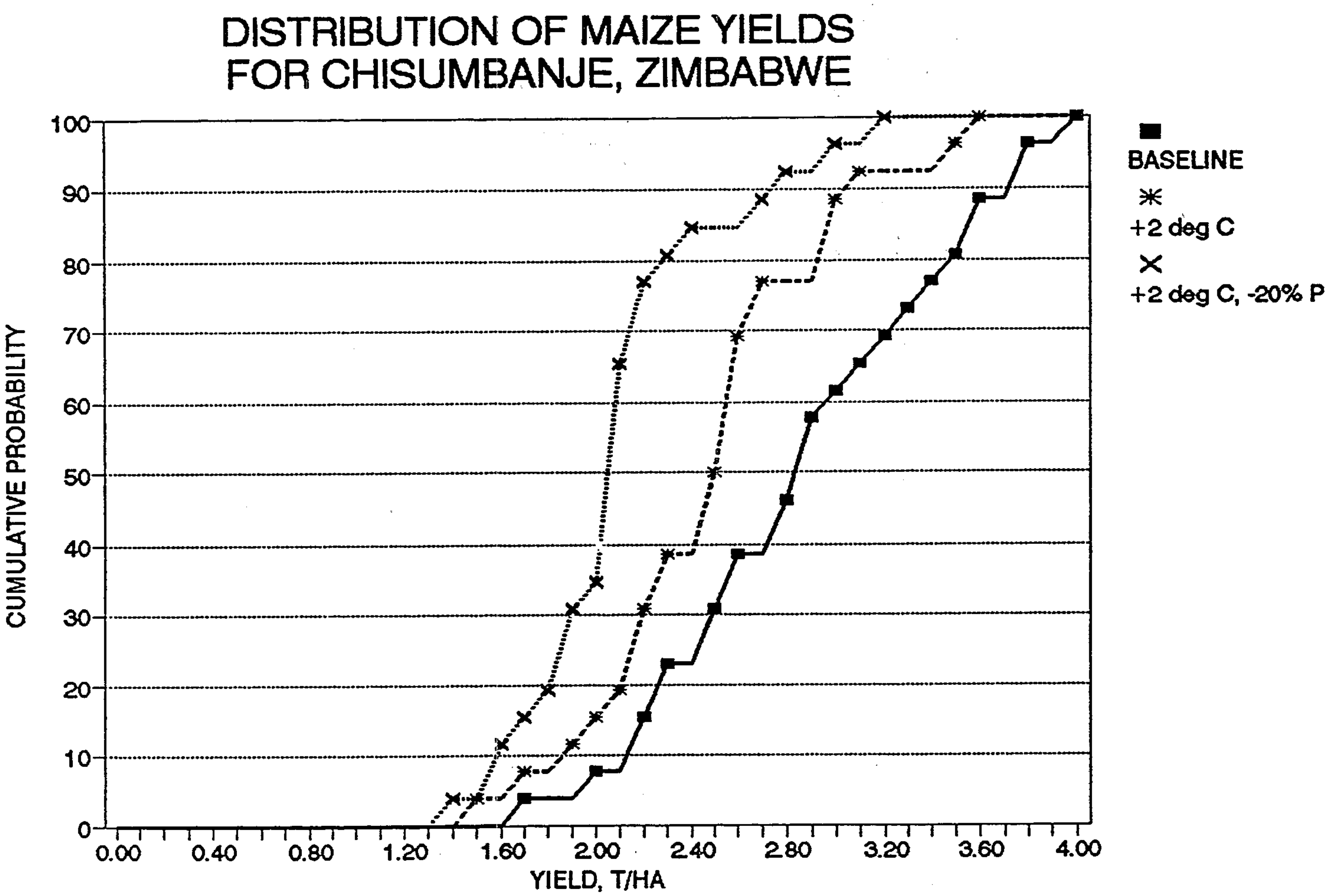


Figure 4. Cumulative probability of maize yields under baseline, +2°C and -20% precipitation, and the UKMO GCM scenario at Chisumbanje. Acceptable yield equals 2.5 T/ha.

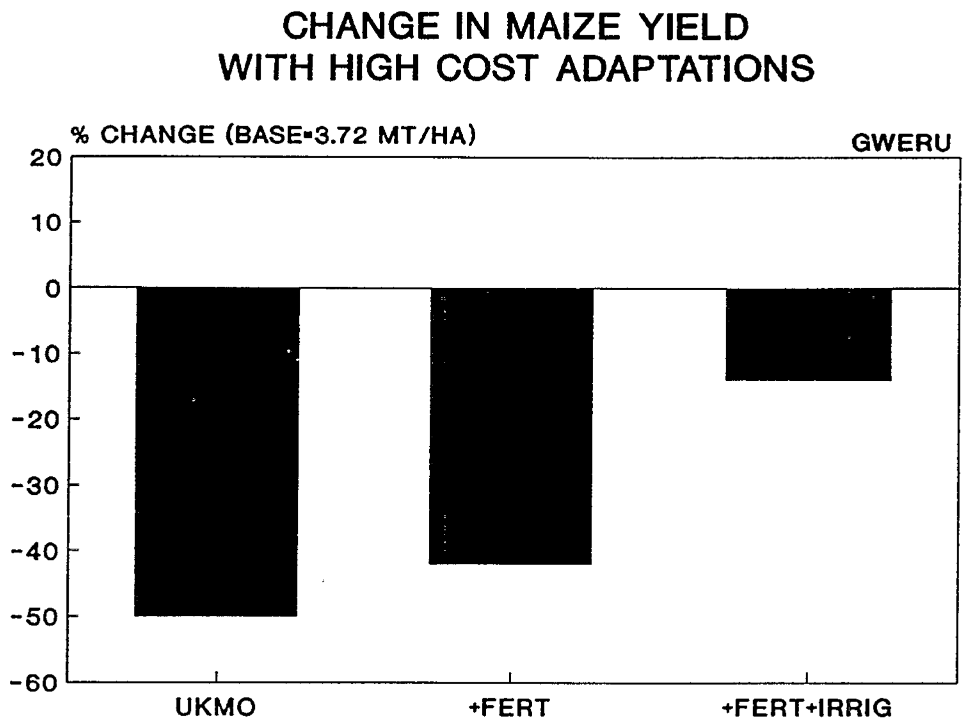


Figure 5. Maize yield changes from baseline under the UKMO scenario considering possible adaptation strategies at Gweru. The direct effects of CO_2 on yield were included in the simulation. +FERT indicates simulations with double the amount of nitrogen fertilizer (120 kg/ha applied at 4 and 8 weeks after planting). +FERT +IRRIG indicates simulations with double the amount of nitrogen fertilizer combined with full irrigation.

SECTION 6: ASIA

IMPLICATIONS OF GLOBAL CLIMATE CHANGE FOR AGRICULTURE IN PAKISTAN: IMPACTS ON SIMULATED WHEAT PRODUCTION

Ata Qureshi
Climate Institute
Washington, DC, USA

and

Ana Iglesias
Inst. Nacional de Investigaciones Agrarias (INIA)
Madrid, Spain

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SUMMARY

This study used global climate models (GCMs) and dynamic crop growth models to estimate the potential agricultural effects of climate change in Pakistan. Under present climate conditions, wheat is currently under stress due to high temperatures and arid conditions. Projected climate change caused simulated wheat yields to decrease dramatically in the major regions of agricultural production, even under fully irrigated conditions. Decreases in modeled grain yields were caused primarily by temperature increases that shortened the duration of the life cycle of the crop, particularly the grain-filling period, exerting a strong negative pressure on yields. These decreases were somewhat counteracted by the beneficial physiological CO_2 effects on crop growth, as simulated in this study. Some adaptation strategies were tested that partially offset the negative impacts of climate change on wheat yields.

INTRODUCTION

Background

Pakistan is located between the Tropic of Cancer (23°N) and latitude 38°N and longitudes 61°E and 77°E (Figure 1). The total area of the country is 803,943 km^2. The main river, the Indus, flows across the regions of the Northwestern frontier (NWFP), Punjab, and Sind; the Baluchistan region is traversed by the Zhob river. The Punjab region (in the great Indogangetic plain) accounts for the major part of agricultural production (Wescoat and Leichenko 1990). Pakistan's climate is generally hot and arid, except some locations have a distinct southwest monsoon rainy season.

Agriculture is a main contributor to the Pakistani economy. Agricultural systems in Pakistan (arable crops, rangelands, forestry, and fisheries) employ 52% of the labor force and account for 32% of the Gross National Product (GNP). Crop production accounts for about 70% of agricultural revenues and contributes to export earnings. Cotton textile output is the most important industry. Food processing is also a major industry, and wheat is the staple food crop in Pakistan. The principal crops grown in Pakistan are cotton, rice, wheat, sugarcane, fruits, and vegetables. Cotton and rice are the main export agricultural commodities. Wheat is of very high economic value and represents a large proportion of the food in the region. Therefore, wheat was selected for this climat change simulation study. Wheat production occurs over a large area of Pakistan and under very different climatic and management conditions. Temperature, precipitation, and soil moisture, as well as frequency of heat waves and droughts, are significant factors in crop productivity.

Crop production in Pakistan is heavily dependent on the irrigation systems that have been installed over the past four decades. Pakistan boasts the largest system of integrated irrigation in the world, covering 75% (195,000 km^2) of the cultivated land (Wescoat and Leichenko 1990). Irrigated cropland accounts for about 90% of Pakistan's agricultural production. The irrigated areas in the Indus basin and plains (154,000 km^2) account for the bulk of the national harvest. Another 10 million hectares are cultivated under rainfed conditions, also known as the "barani" method of crop production. Irrigation management practices in Pakistan vary, but in most cases the system involved is "partial irrigation", whereby water is provided only to ensure limited production. The potential need for increased irrigation is a concern for some areas of the region under present circumstances. Overapplication and inadequate drainage has aggravated waterlogging in other areas. In 1985, Pakistan suffered critical water shortages, leading to inadequate irrigation water supplies for the main crop growing season and causing power blackouts (Wescoat and Leichenko 1992).

In addition to irrigation, crop production in Pakistan is also increasingly dependent on chemicals, such as fertilizers and biocides. The environmental damage resulting from this dependence is one of Pakistan's most severe problems. The inadequate attention to water drainage has resulted in soils that suffer from waterlogging and salinization, reducing soil fertility on about 100,000 km^2 of land. At least 400 km^2 of irrigated land is lost to agriculture each year. In addition, more than 12,000 km^2 of agricultural lands suffer from soil erosion.

Uncertain water supplies, soil problems, and floods along the entire Indogangetic plain also cause crop production losses. Natural disasters such as earthquakes and landslides also account for destruction of crops and damage to the country's agricultural infrastructure. In the first half of the 1980s, floods caused $3 billion of damage to crops, buildings, roads, and other installations. Sedimentation from upper watersheds could completely fill several reservoirs in the not-too-distant future.

At present, Pakistan is self-sufficient in grain production and is a net grain exporter. The decline of the agricultural resource base could change the net balance. In addition, as the current 2.9% population growth rate continues, the amount of cultivated land per rural habitant is expected to decrease from 0.32 ha/person (1983) to a projected 0.14 ha/person in the year 2010. The 1990 population was 122.7 million, and the projected population for 2025 is 267.1 million (Wescoat and Leichenko 1990).

Climate change could have a critical impact in a country that already has limitations on agricultural and natural resources (Myers 1989; Qureshi 1989). The enhanced greenhouse effect, due to an increased atmospheric concentration of CO_2 and other trace gases, is projected to lead to higher global surface temperatures and changed hydrological cycles (IPCC 1990). Evidence of the potential impacts of climate change in the Indian subcontinent has been mostly limited to studies in northern India, where a temperature increase of 0.5°C is estimated to reduce wheat yields by about 10%; similar increases in central India would probably lead to larger percentage reductions from a lower base yield (IPCC 1990; Gadgil *et al.* 1988). Few studies have projected potential agricultural impacts in Pakistan.

Description of the Regions and Sites

To assess the potential impacts of climate change, four sites were selected to represent the broad differences in the agroecological zones of Pakistan (Figure 1).

- The upper Indus plain in the Punjab region varies from 150-300 meters in altitude and is a fertile agricultural area that accounts for about two-thirds of the total national wheat production (Table 1). The site of **Jhelum** represents wheat production in the northern plateau of Punjab's agroecological region. A large portion of the production is dryland, but irrigation is also important.
- The lower Indus plain corresponds to the Sind province, is lower in altitude than the Punjab, and declines to sea level at the coast. There are large tracts of deserts and marshes to the southeast, but there are also agricultural areas that account for about 20% of the national wheat production. The site of **Khanpur** represents wheat production in the region, which is conducted mainly under irrigated conditions.
- The northern area of Pakistan is mountainous, and wheat production is limited. It is represented by the site of **Gilgit** in this study.
- The central west area of Pakistan is represented by the site of **D.I. Khan,** which is also sandy and mountainous. The wheat production is dryland.
- The region of Baluchistan falls in the great plateau (914-1220 meters in altitude). Relatively small amounts of wheat are produced in this region, which is unimportant from an international trade perspective. Therefore, a site from this region was not included in this study.

Since Jhelum and Khanpur together account for nearly 90% of the country's wheat production, some of the discussion that follows will pertain to these two sites only.

Aims of the Study

This study analyzed the results of the simulation of wheat production, crop water use, and irrigation demand at four contrasting locations under current climate and under climate change scenarios generated with GCMs. The study also included a sensitivity analysis of arbitrary temperature and precipitation changes. The physiological effects of elevated CO_2 on wheat yields were simulated in all climate change scenarios.

METHODS

Observed Climate

Climate data for the four sites were obtained from the Pakistan Meteorology Department and include monthly temperatures and precipitation. Daily climate variables were generated from monthly temperature and precipitation data using the weather generator supplied by IBSNAT (IBSNAT 1989). Daily solar radiation values were generated from observed monthly sunshine values using the WGEN program (Richardson and Wright 1984).

Pakistan experiences extreme temperature fluctuations both seasonally and daily, and its climate is generally arid. The three seasons are: November to February (cool and dry), March to May (hot and dry), and June to October (hot and humid). The latter is the southwest monsoon season. In the Indus valley, the climate becomes progressively more arid from north to south. In Sind, temperatures sometimes rise to 50°C in the summer, and precipitation can drop to below 100 mm per year.

Figure 2 shows the observed climate for the selected sites. The temperature regime shows strong seasonality at all four of the sites, with the summers being very hot. Khanpur has the warmest average annual temperatures. Gilgit is the coolest of the sites. There are large differences in the amounts of precipitation. Jhelum, in the southwest monsoon region, has the highest precipitation and Khanpur has the lowest, with less than 10 mm during 10 months of the year. Gilgit is also very dry, but is slightly wetter than Khanpur, with maximum precipitation during the spring. D.I. Khan has a similar precipitation pattern to Jhelum, but it has less rainfall.

Climate Change Scenarios

GCM Climate Change Scenarios. The GCMs compute climatic variables for different longitude and latitude gridboxes; the predicted variables do not reflect variations within the gridbox. Mean annual changes in climate variables from doubled CO_2 simulations of three GCMs—Goddard Institute for Space Studies (GISS, Hansen *et al* 1983), Geophysical Fluid Dynamics Laboratory (GFDL, Manabe and Wetherald 1987), and United Kingdom Meteorological Office (UKMO, Wilson and Mitchell 1987)—were applied to the generated daily climate to create climate change scenarios for each site. GCMs were used to create climate change scenarios because they produce climate variables which are internally consistent; thus they allow for comparisons between or among regions. The method used the differences between $1xCO_2$ and $2xCO_2$ monthly GCM temperatures, and the ratio between $2xCO_2$ and $1xCO_2$ monthly precipitation and solar radiation amounts ($1xCO_2$ refers to current climate conditions and $2xCO_2$ refers to the climate that would occur with an equivalent radiative forcing of doubled CO_2 in the atmosphere).

The annual averages of the climate change scenarios show some major differences when compared with the observed climate (Table 2). The temperature increases are similar at the four sites. The GISS and GFDL scenarios produce comparable temperature increases (3°C to 5°C) while the UKMO scenario produces more drastic changes (5°C to 7°C). The precipitation changes are more variable among the sites. In general, the GCMs predict increases in global precipitation associated with warming because warmer air can hold more water vapor. Khanpur, the more humid site under current conditions, shows the largest increase in precipitation (UKMO scenario). In Gilgit, all scenarios show very small precipitation increases. In Jhelum

(Punjab region), the GISS and GFDL scenarios show very small increases in precipitation amounts, while the UKMO scenario shows decreases. The climate change scenarios in D.I. Khan are comparable to those in Jhelum.

Because the water supply in the Indus basin depends entirely upon climate conditions within the basin, any decrease in precipitation could affect the quantity of irrigation water available for the crops. Wescoat and Leichenko (1992) used a river-basin model to show that flows in the Indus delta are sensitive to changes in precipitation. When the GISS (+3.2°C, +30% precipitation) and the GFDL (+3.6°C, +20% precipitation) climate changes were put into their model, water flow increased almost 30%. However, a 2°C temperature increase combined with a 20% decrease in precipitation decreased flows into the delta by close to 50%, which would result in economic and ecological devastation.

Sensitivity Scenarios. An alternative approach to analyze the possible impacts of different climate on crop yield is to specify incremental changes to temperature and precipitation and to apply these changes uniformly to the baseline climate. We used combinations of temperature increases of 0°C, +2°C, and +4°C and precipitation changes of -20%, 0%, and +20%. The scenario, +2°C with a precipitation decrease of -20%, is interesting because it assumes a possible temperature increase combined with a large decrease in monsoon rain, which is not simulated under the GCM climate scenarios.

Wheat Growth Simulation

CERES-Wheat Model. Potential changes in wheat physiological responses (yield, season length, ET, and irrigation demand) were estimated with the CERES-Wheat model (Ritchie and Otter 1985) under different climate scenarios. The CERES crop model has been validated with experimental data from many locations that encompass a wide range of environments (Ritchie and Otter 1985). The model simulates physiological crop responses (water balance, phenology, and growth throughout the season) on a daily basis to the major factors of climate (daily solar radiation, maximum and minimum temperature, and precipitation), soils (albedo and a variety of measures relating to water in the profile), and management (cultivar, planting date, plant population, row spacing, and sowing depth). The choice of the CERES-Wheat model allowed us to compare the simulation results with other studies in different regions of the world, and therefore, view Pakistan's results from a global perspective.

Simulation of the Direct CO_2 Effects. Higher levels of atmospheric CO_2 have been found to increase photosynthesis and water-use efficiency, resulting in yield increases in experimental settings (Acock and Allen 1985). Because the climate change scenario has higher levels of CO_2 than the current climate GCM simulations (330 ppm), the CERES-Wheat model includes an option to simulate the physiological effects of CO_2 on photosynthesis and water-use efficiency (Peart *et al.* 1989) that result an increase in yield. A level of 555 ppm CO_2 was used in the crop models. The physiological effects of CO_2 were considered in all scenarios and at all sites.

Management Variables. The cultivar selected for the study in the four sites was Mexipak (Table 3) because it accurately represents the most common cultivars in the area. Mexipak is a classic wheat variety introduced in Pakistan during the Green Revolution. Mexipak (or a cultivar with similar characteristics) is a variety that performs well almost anywhere in Pakistan, especially in the irrigated areas that produce the bulk of the national wheat production. Mexipak has been calibrated and validated for many different climate conditions. The "genetic coefficients" of Mexipak were taken from the DSSAT data base (IBSNAT 1989). Season length and yield were compared with experimental data from the Barani Agricultural Research Institute for the site of Jhelum. A number of new wheat varieties are currently grown in Pakistan: Chakwal-86, Rewal-87, and Pak-81.

The management variables used for the CERES-Wheat model were determined for each location according to information on current practices. Wheat in Pakistan is grown under partial or deficit irrigation, in which farmers provide water to the crop but do not seek to optimize yield per hectare. This subirrigation phenomenon is difficult to simulate exactly with the CERES model, since the input irrigation has to be prescheduled before starting the simulation. Therefore, we simulated wheat production under dryland and irrigated conditions to provide a range of possible scenarios and to analyze the production changes. We simulated irrigation under the "automatic option" to provide the crop with a hypothetical, nonlimiting situation. The amount of irrigation water used and consequent yields obtained are overestimates, but this approach permits us to compare the relative changes in each site and in each scenario. For the irrigation simulation, the water demand was calculated assuming: 100% efficiency of the automatic irrigation system; a 1-meter irrigation management depth; automatic irrigation when the available soil water is 50% or less of capacity; and the soil water for each layer is reinitialized to 100% capacity at the start of each growing season.

To account for the supplementary type of irrigation practiced in D.I. Khan and Khanpur, these sites are best represented by irrigated simulations. In Jhelum, simulation of both irrigated and dryland production is appropriate. Here, most wheat is grown under irrigation, but certain marginal areas are dryland. In Gilgit, wheat production is marginal and basically dryland. For dryland multi-year simulations, it is desirable to establish the initial soil-moisture levels at planting because soil moisture is a major factor in determining final yields. Unfortunately, we had no data available on initial soil-moisture conditions, so we tested the sensitivity of simulated wheat yields to initial conditions. In all areas of wheat production in Pakistan, the level of fertilization are relatively low. In Jhelum and Khanpur the soils are deeper with higher fertility and better management practices than at the other two sites.

Simulations. The CERES-Wheat model was run for 29 years of baseline climate and the GISS, GFDL, and UKMO climate change scenarios under dryland and irrigated conditions. It was also run for the scenarios created by superimposing arbitrary temperature and precipitation changes on the baseline climate (sensitivity scenarios). Simulations for all scenarios included climate change alone and climate change with the physiological effects of CO_2 at all sites. The mean and standard deviation of the yield, evapotranspiration, water applied for irrigation, and crop-maturity date are simulated in the study.

Limitations of the Study

Climate Change Scenarios. While GCMs are useful for climate change studies, current climate models oversimplify many aspects of the climate system, especially ocean dynamics, cloud physics, and land-surface hydrology. GCMs do not accurately simulate the current climate at regional scales, and they were not designed for predictive regional studies. Therefore, the climate change scenarios created from GCM output must not be viewed as predictions, but as examples of possible future climates for the regions under study. GCM output analyzed by the U.S. Environmental Protection Agency indicated that the GCMs perform least well in the Indus Valley and in four other regions of the world. Given the seriousness of these deficiencies, a detailed examination of the GCM output was undertaken in Pakistan. Different gridboxes of the GISS, GFDL, and UKMO GCMs were compared with historic temperatures and precipitation levels of sites in the region, and recommendations were made for the use of climate scenarios in the area (Wescoat and Leichenko 1990). Mean annual changes of each variable were used in this study, instead of the usual monthly changes. The justification for the use of the climate change scenarios generated by GCMs is to have comparability among agricultural production in different countries, and among river basins and climate change impacts projects.

As configured, the climate change scenarios do not alter the patterns of events in the base climate. Therefore, they do not simulate changes in the underlying variability (e.g., extended periods of high temperature, droughts, etc.) that can be vital for crops. Dryland yields may be considerably different depending on whether a change in precipitation results from a change in mean, frequency, or intensity. However, the scenarios created for this study do result in an increased frequency of temperatures above certain thresholds.

Also, the weather generator used in this study does not simulate observed daily weather with complete accuracy.

Crop Models. For this study, we assumed that nutrients are nonlimiting, pests are controlled, and that there are no catastrophic weather events. These assumptions tend to overestimate the simulated yields. We also assumed that technology and climatic tolerance of cultivars do not change under the conditions of climate change, although this is not a realistic assumption (see discussion on adaptation). The physiological effects of CO_2 in the crop model may be overestimated because experimental results from controlled environments, used to calibrate the model, may not be accurate under windy and pest-infected field conditions.

RESULTS

The specific objectives of this study were to measure the change in simulated crop yields under the three GCM scenarios and to use the data as part of a world trade economic model.

Sensitivity Analysis

A sensitivity approach to climate change impact analysis is removed from the processes which influence climate. However, it has the advantage of simulating a controlled experiment and therefore provides a good understanding of the factors affecting responses; furthermore, it can identify temperature and precipitation thresholds for crop production. We used combinations of temperature increases of 0°C, +2°C, and +4°C and precipitation changes of -20%, 0%, and +20% and superimposed them on the baseline climate. For each scenario, the wheat model was run under current (330 ppm) and elevated (555 ppm) CO_2 levels (Table 4).

Table 4 shows that the decrease in yields associated with a 2°C temperature increase could be compensated for when the direct effects of CO_2 were taken into account (this result occurred at three of the four sites). With a 4°C temperature increase, however, wheat yields were significantly lower (particularly at Jhelum), even with the direct effects of CO_2. These yield decreases were a consequence of a shorter season length, and in some cases, water stress to the crop. A temperature of 2°C above the baseline implied that the season length would be reduced by 8-14 days at all sites tested; a 4°C increase reduced it by about 20 days at all sites.

An increase in the temperature also increased the moisture stress of the wheat crop (i.e., the difference between precipitation and evapotranspiration). The simulated evapotranspiration (ET) decreased in most cases, despite large increases in temperature and in potential evaporation. This was due to the shorter growing season, which reduced the total amount of ET, and by decreased demand by the crop because it was not growing as well. Irrigation demand generally decreased for the same reasons. Most of the sites' modeled wheat yields were not very sensitive to precipitation changes (see section on continuous vs. noncontinuous water balance).

Climate Change Scenarios

Currently, high temperatures and low precipitation limit present-day wheat production in Pakistan. The sensitivity study showed that temperature increases of 2°C and higher resulted in a reduction of crop yields throughout the country, especially in the main wheat-producing region of Punjab. In this section we consider the possible impact of the climate change scenarios generated by the three GCMs on wheat production in four sites distributed throughout Pakistan. The results show the degree to which the impacts may vary within the regions. Table 5 shows the yield changes under doubled CO_2 climate change scenarios for all of the sites for both dryland and irrigated conditions with and without the direct effects of CO_2. At *Jhelum* and *Khanpur*, the two major sites, irrigated and dryland results were very similar, showing major reductions—up to 80%—in yields. Reductions in yields were projected with all three scenarios, but the reductions were more significant with the UKMO scenario. Even when the direct effects of CO_2 are included, reductions in yields were still generally significant. At *D.I. Khan* and *Gilgit*, results were mixed, with some increases in yields.

Yield decreases were driven primarily by the increase in temperature, which causes the duration of the crop-growth stages (particularly the grain-filling period) to be shortened. The season length was greatly reduced by about four weeks under the three scenarios (Table 6). Tables 7 and 8 show that simulated ET and irrigation demand generally decreased under the climate change scenarios.

Continuous vs. Noncontinuous Soil Water Balance

The assumption that the soil-moisture profile was full at the beginning of each growing season is one that may be acceptable under moist conditions, but it is unrealistic in dry or marginal areas, leading to an overestimation of the available soil water. To determine how sensitive the yield results are to soil-water conditions, a series of tests was run using a continuous water balance in addition to the normal method of resetting the soil moisture to full every growing season. Under the continuous water balance method, the soil moisture is never reset and is allowed to continue, as computed, from one year to the next. These experiments were carried out at Jhelum and D.I. Khan for the 29 years under both the current climate and the GISS climate change scenario.

At Jhelum, the continuous water balance made very little difference on crop yields. This is because Jhelum receives copious amounts of monsoon rainfall just prior to planting. At D.I. Khan, where precipitation amounts are lower, the continuous water balance resulted in decreased yields under current climate conditions. However, the GISS scenario yields also decreased, so the relative changes from base yields remained similar (+16.3% for the normal reset run; +21.6% for the continuous soil-moisture run). Only relative yield changes were contributed to the world food trade study.

Changes in Management under Climate Change

This study determined the possible causes of losses in wheat yields under different climatic conditions (GCM climate change scenarios and sensitivity analysis) as the first step in the analysis of adaptation to climate change. Adaptation strategies included changes in the management practices of the wheat cultivars currently used (planting date and irrigation) and changes in the cultivar. All adaptation strategies were simulated in Jhelum under UKMO, the most unfavorable climate change scenario (Table 9). The results of the simulation show that there was no significant benefit from full irrigation at this site under the UKMO scenario (a -61% yield decrease in dryland conditions and a -56% yield decrease under full irrigation). This result was not very surprising, since Jhelum was found to be insensitive to changes in precipitation.

A likely response of farmers to warmer temperatures would be to shift the planting dates to avoid high temperatures during the grain-filling period and increase the crop-growing season. In Jhelum, a simulated shift in the planting date to 10 days earlier (from Oct. 20 to Oct. 10) increased the yield losses under the UKMO scenario (Table 9), probably because the new planting date falls in a very hot period. Nevertheless, a delay in the planting date to Nov. 1 or Nov. 15 was beneficial for wheat yields in Jhelum (a -61% yield loss under present management conditions and a -30% yield loss if the planting is postponed to Nov. 15).

Two cultivars were tested as possible alternatives to Mexipak: Sonalika (widely used in India) and Anza. Sonalika, planted on Nov. 15, resulted in larger yield losses than Mexipak planted on Nov. 15 (a -42% yield decrease with Sonalika and a -30% with Mexipak). Anza, planted on Nov. 15, was the most favorable strategy tested. In this case, yields decreased under the UKMO scenario by -20%.

DISCUSSION

Conclusions. Projected climate change caused simulated wheat yields to decrease dramatically both in dryland and irrigated production, due to a shorter season length caused by temperature increases. Yield decreases were somewhat counteracted by the physiological effects of CO_2, as simulated in this study, but the effect was not enough to offset yield decreases under the climate scenarios. The overwhelming impact of temperature increases, especially when coupled with precipitation decreases, would reduce the time required for crop maturation and thus reduce wheat yields. If global climate change brings warmer and drier conditions to Pakistan, additional problems would arise for water supplies for irrigation in the region.

In comparison to simulated climate change agricultural impacts in other hot and dry regions, the Pakistan study found more severe yield decreases in response to the same climate change scenarios tested elsewhere (Adams *et al.* 1990; Smith and Tirpak 1989; Rosenzweig 1990). It is possible that Pakistan may be one of the regions more severely affected by climate change, and national wheat production may decrease substantially in the future if climate change occurs as predicted by GCMs. This study suggests that the development of new cultivars that are more heat-resistant than the present ones is essential to improve the resiliency of Pakistani wheat production to possible increases in temperature.

The adaptation strategies tested in Jhelum under the UKMO scenario did not compensate fully for the yield reductions, but a shift in cultivar combined with a later planting date decreased yield losses under irrigated conditions. With the known pool of cultivars and current resources (water and fertilizer), full adaptation seems unlikely in Pakistan since the temperature changes suggested by some GCM scenarios would exceed the temperature the wheat plant can tolerate physiologically.

Further research needs. Possible future adaptations need to be analyzed so that farmers will be able to adapt their practices in response to altered climate conditions. These studies should include detailed changes in planting date, fertilizer, and irrigation. Studies should also focus on the effect of the altered calendar crop on the agricultural system in the region, particularly where more than one crop is harvested each year.

The possible increase in climatic variability under future climate change scenarios may be an important factor in determining production losses. Since crop yields exhibit a nonlinear response to heat and cold stress, any change in the probability of extreme temperature events can be significant. Therefore, a variability study on possible future yields is important. Because insect pests and diseases are also an important component of production losses under the present climate, any possible change in pest and disease patterns under climate change conditions should be analyzed.

Finally, it is important to analyze the potential extension of, or shifts, in the areas of crop production, the soil constraints in these potential agricultural regions, economic tendencies, and other environmental factors. Based on the results of the present study, the effects of potential climate change in Pakistan could have dramatic consequences for agricultural production and it is important to analyze the impact in a larger number of sites and for other major crops, such as rice. Finally, further research should be done on simulating the annual water balance more accurately in order to estimate future water availability for irrigation.

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Table 1. Wheat production (1981–89).

Region	Site	Production	Area	Yield
		t x 1000	ha x 1000	t ha^{-1}
Punjab	Jhelum	9,345	5,404	1.73
Sind	Khanpur	2,189	1,032	2.12
NWFP	D.I. Khan Gilgit	939	791	1.19
Baluchistan		445	252	1.79
Pakistan		12,918	7,478	1.73

Table 2. Average annual changes in temperature, precipitation, and solar radiation in the GCM climate change scenarios.

	Temp. changes (°C)			Precip. changes (%)			SR changes (%)		
Site	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Jhelum	4.7	4.5	7.0	13	16	-18	-1	8	5
Khanpur	3.2	4.5	6.0	25	19	40	-2	0	-1
D.I.Khan	4.7	4.9	7.0	13	11	-18	-1	8	5
Gilgit	4.7	4.8	5.7	13	10	13	-1	17	20

Table 3 Test sites, soils, and management variables.

Site	Location	Representative Soil	Cultivar	Practice	Planting date
Jhelum	+32.97 N +73.75 E	medium sandy loam	mexipak	dryland/ irrigation	Oct. 20
Khanpur	+28.63 N +70.67 E	deep sandy loam	mexipak	irrigation	Nov. 12
Gilgit	+35.90 N +74.33 E	medium sand	mexipak	mainly dryland	Oct. 30
D.I.Khan	+31.82 N +70.93 E	medium sandy loam	mexipak	irrigation	Nov. 30

Plant population for irrigation practice = 250 plants m^{-2}
Plant population for dryland practice = 125 plants m^{-2}

Table 4. Sensitivity of irrigated CERES-Wheat yields to temperature and CO_2 changes.

CO_2 level (ppm)	Temp. Change (°C)	Simulated Yields ($t\ ha^{-1}$) Jhelum	Khanpur	D.I. Khan	Gilgit
330	0	5.28	4.79	3.73	4.54
	2	3.55	4.19	3.50	3.97
	4	2.02	3.23	3.16	3.94
555	0	6.60	5.80	4.41	5.38
	2	4.89	5.28	4.19	4.85
	4	3.22	4.29	3.86	4.42

Table 5. Effects of climate change on wheat yields.

			Percent changes in simulated yields from base					
			GCM Scenario Alone			GCM Scenario + DE		
Site	Rainfed/ Irrig.	Base Yield	GISS	GFDL	UKMO	GISS	GFDL	UKMO
		t ha^{-1}						
Jhelum	rainfed	4.81	-67	-29	-80	-41	-5	-61
Khanpur	rainfed	4.19	-45	-54	-61	-15	-33	-35
D.I.Khan	rainfed	1.94	16	-55	-11	61	-45	29
Gilgit	rainfed	0.6	20	8	-47	67	50	-20
Jhelum	irrigated	5.28	-60	-24	-74	-36	-5	-56
Khanpur	irrigated	4.79	-43	-54	-57	-19	-37	-37
D.I.Khan	irrigated	3.73	-20	33	-17	-2	60	6
Gilgit	irrigated	4.75	-17	-5	-12	-6	9	5

DE = direct effects of CO_2 on wheat yield included.

Table 6. Effects of climate change on the season length of wheat.

Site	Base (days)	Simulated season lengths (days)		
		GISS	GFDL	UKMO
Jhelum	128	100	105	94
Khanpur	122	99	96	93
D.I. Khan	122	104	98	97
Gilgit	150	132	131	133

Table 7. Effects of climate change on wheat evapotranspiration (ET).

			Percent changes in simulated ET from base					
			GCM Scenario Alone			GCM Scenario +DE		
Site	Rainfed/ Irrig.	Base ET (mm)	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Jhelum	rainfed	207	-39	1	-50	-34	2	-44
Khanpur	rainfed	226	-41	-36	-47	-35	-33	-40
D.I.Khan	rainfed	226	-9	-10	-20	-11	-10	-19
Gilgit	rainfed	166	-5	-7	-5	-5	-7	-4
Jhelum	irrigated	232	-31	25	-42	-31	18	-38
Khanpur	irrigated	267	-31	-29	-36	-32	-31	-34
D.I. Khan	irrigated	331	-22	21	-19	-27	14	-24
Gilgit	irrigated	474	-17	-9	13	-23	-17	3

DE = direct effects of CO_2 on wheat ET included.

Table 8. Effects of climate change on amounts of irrigation.

		Percent changes in simulated irrig. amounts from base					
		GCM Scenario Alone			GCM Scenario +DE		
Site	Base	GISS	GFDL	UKMO	GISS	GFDL	UKMO
	(mm)						
Jhelum	128	-45	57	-56	-43	43	-47
Khanpur	199	-31	-32	-36	-33	-33	-34
D.I.Khan	215	-28	-43	-16	-33	-33	-20
Gilgit	337	-8	4	33	-16	-7	20

DE = direct effects of CO_2 on wheat irrig. water demand included.

Table 9. Effect of changes in wheat cultivar and management on simulated yield under the UKMO climate change scenario in Jhelum. The physiological effects of CO_2 were included in all UKMO scenario simulations.

Scenario	Cultivar	Management	Planting Date	Yield	% Change from Base
				T/Ha	
BASE*	Mexipak	rainfed	Oct. 20	4.81	
BASE*	Mexipac	irrigation	Oct. 20	5.28	
UKMO**	Mexipak	rainfed	Oct. 20	1.88	-61
UKMO	Mexipak	irrigation	Oct. 20	2.35	-56
UKMO	Mexipak	irrigation	Oct. 10	0.64	-88
UKMO	Mexipak	irrigation	Nov. 1	2.56	-52
UKMO	Mexipak	irrigation	Nov. 15	3.71	-30
UKMO	Sonalika	irrigation	Nov. 15	3.08	-42
UKMO	Anza	irrigation	Nov. 15	4.25	-20

*Base conditions using current climate as scenario.

**Simulations under UKMO scenario without adaptation.

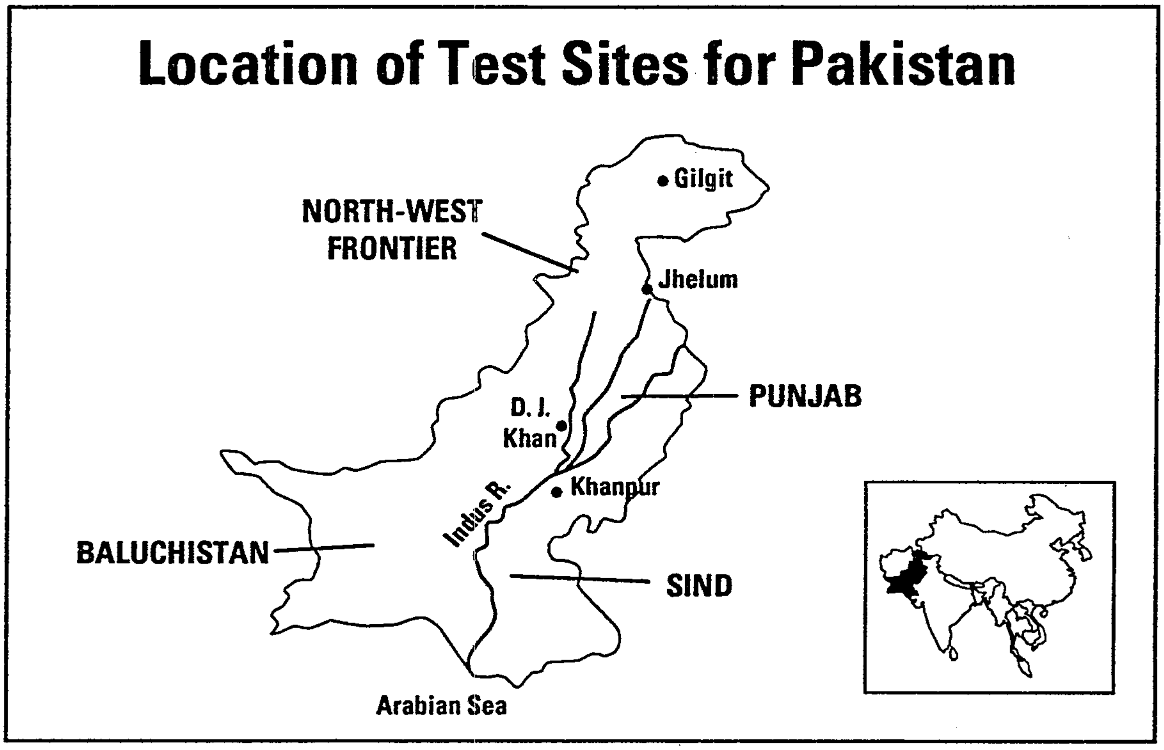

Figure 1. Map of Pakistan with sites selected for this study. The denominations used and the boundaries shown do not imply any judgement on the legal status of any territory or any endorsement or acceptance of such boundaries.

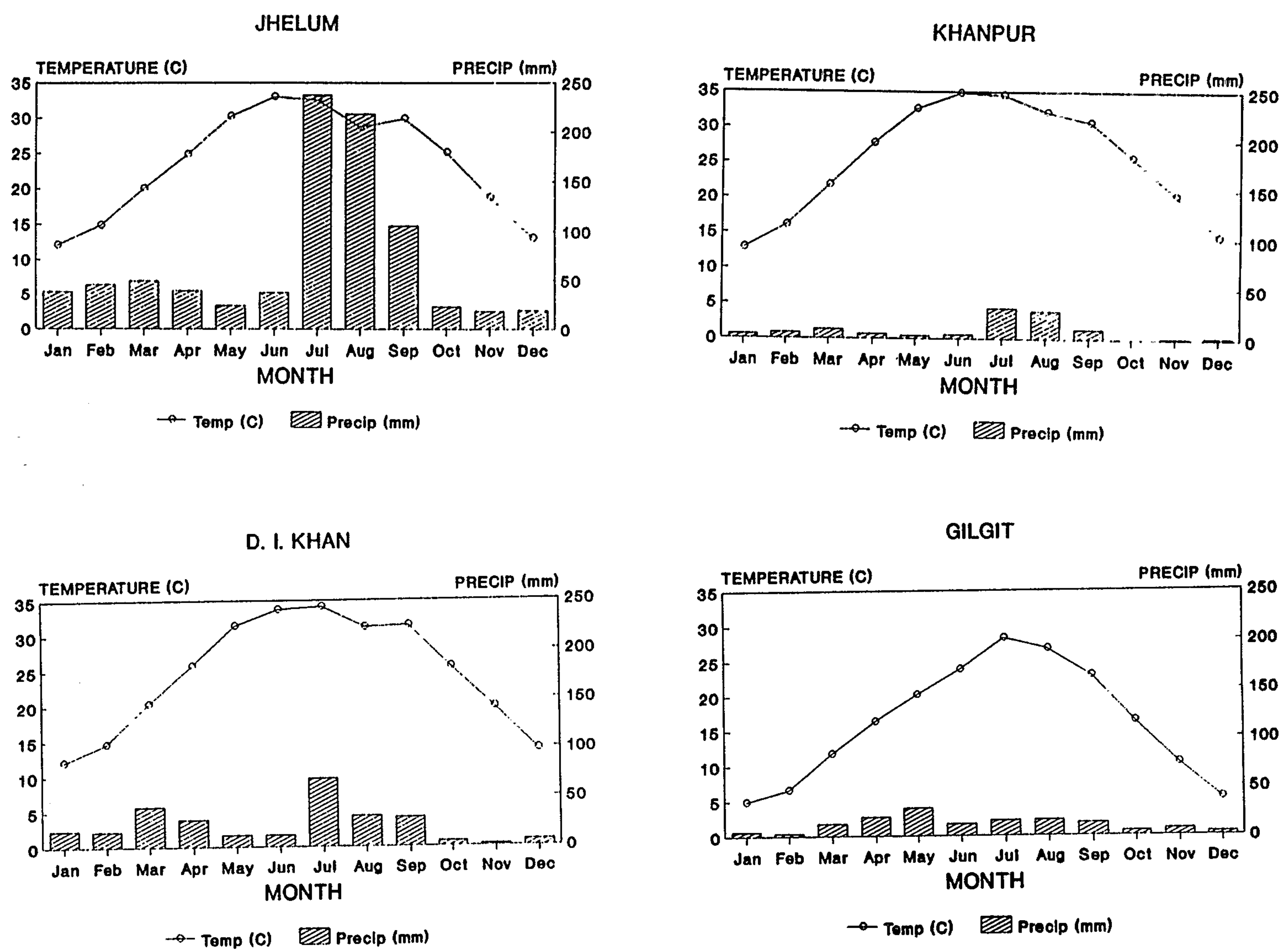

Figure 2. Observed mean monthly temperature and precipitation at selected sites.

IMPACT OF CLIMATE CHANGE ON SIMULATED WHEAT PRODUCTION IN INDIA

D.Gangadhar Rao

CRIDA, Hyderabad, India

S.K.Sinha

IARI, New Delhi, India

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SUMMARY

This study assessed the impact of climate change on wheat production at two contrasting locations in India, Delhi and Hyderabad, using the CERES-Wheat simulation model under rainfed and irrigated conditions. Climate change scenarios for each location were created from three equilibrium General Circulation Models (GISS, GFDL, and UKMO) and from the transient GISS model (for the 2010s, 2030s, and 2050s). The simulation study considered the physiological effects of increased CO_2 levels on the crop in all scenarios. In all climate change simulations, wheat yields were smaller than those in the current climate, even with the direct beneficial effects of CO_2 on crop yield considered. Yield reductions are primarily due to a shortening of the wheat-growing season, resulting from the scenario temperature increases.

INTRODUCTION

Agriculture remains an important economic sector in India, despite the development of industry and services in the post-independence nation. Seventy percent of the population is rural and depends directly or indirectly on agriculture. Agricultural failures due to natural disasters have been an important factor in the migration of the population from rural to urban areas. Today, agriculture represents 35% of India's Gross National Product (GNP). This percentage is likely to decline due to further industrialization, but agriculture will continue to occupy an important place in the Indian economy. Therefore, global climate change that could influence agriculture in the Indian subcontinent should be a cause for concern (IPCC 1990).

The Indian agricultural system includes the production of crops, animal products, fisheries, and forest products. It is impossible to present a holistic picture of the effect of climate change on the agricultural system because of the many interdependent and interactive factors. Therefore, for the purpose of the present analysis, we considered the potential effects of climate change on the primary sector of the agricultural system—crops.

Because of the different agroclimatic environments in India, it is possible to grow almost all of the important cereal, leguminous, oilseed, horticultural, and plantation crops, and it would be interesting to simulate their potential production under climate change. A simulation study, however, requires reliable input data and a reasonable model. Among the available crop models, CERES-Wheat has been widely used over different environments, and therefore is probably suitable for the agroclimatic conditions in India. Wheat is important in India because it constitutes the basis of its food security system. Although rice simulation models are also available, ecological niches for rice production in India are highly variable and would require a more elaborate study. Therefore, the present study was confined to wheat as a test system.

There is a need to have a long-term weather record and high-quality experimental data for validating any model. The two locations selected for this study (Delhi and Hyderabad), representing contrasting agroclimates, may be a good starting point (Figure 1). Delhi represents the highly productive regions of Haryana, Punjab, and Uttar Pradesh (contributing approximately 70% of the national production), and Hyderabad represents the less productive regions of Andhra Pradesh, Karnataka, and Maharashtra (contributing approximately 2.6% of the national production) (Table 1).

METHODOLOGY

Baseline Climate Data

For the simulation study daily minimum and maximum temperature, solar radiation, and rainfall data were used for twenty-eight years (1953-80) for Delhi (28°N;78°E) and for seventeen years (1964-80) for Hyderabad (17°N; 78°E). The monthly averages for these parameters are given in Figure 2.

Solar radiation was unavailable, but was computed using sunshine hours calculated from the following formula:

$$Rs = Ra\,(a + b * n / N) \quad \text{where}$$

Rs = Solar Radiation in Megajoules m^{-2}
Ra = Extraterrestrial Radiation
n/N = % Sunshine Hours
a,b = Location-specific Constants

The constants a and b were established by the India Meteorology Department.

GCM Climate Change Scenarios

Climate change scenarios for Delhi and Hyderabad were created by combining daily observed climate data with the monthly output of three General Circulation Models: the Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1983), the Geophysics Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987) (Figure 2). Similarly, transient climate change scenarios were created for the two locations for the decades of 2010s, 2030s, and 2050s with monthly output from the GISS transient run A (Hansen *et al.* 1988) (Figure 2).

The CERES-Wheat Model, Crop Inputs and Soils

Growth and development of wheat were simulated using the CERES-Wheat model (Ritchie and Otter 1985). A common wheat genotype (Sonalika) was chosen to represent the most common cultivars used at both Delhi and Hyderabad. In all the simulations the crop was sown on November 1, and a plant population of 200 plants per square meter was maintained. The irrigated simulations considered three irrigation treatments of 40 mm at the time of sowing, 30 days after sowing (vegetative stage), and 60 days after sowing (reproductive stage).

The soil characteristics used for the simulations are listed in Appendix A. For Delhi, the soils include deep, well-drained loamy soils that exhibit a regular decline in the organic carbon with depth, indicating no disturbance in the profile development. The soil characteristics used for Hyderabad included deep, mildly alkaline, moderately well-drained clayey soils.

Model Validation

The CERES-Wheat model has been validated using datasets from various wheat-growing areas of the world (Otter and Ritchie 1985). For the sites tested in India, the simulated phenology did not always replicate the observed. The average yield of the variety "Kalyansona" is about 4.3 t ha^{-1}, with adequate irrigation at New Delhi (Sinha and Swaminathan 1991); with the same management conditions, the averaged simulated yield was 5.2 t ha^{-1}. At Hyderabad, the average wheat yield is 2.6 t ha^{-1} and the average simulated yield was 2.2 t ha^{-1}.

Simulations

The simulations were conducted using the CERES-Wheat model with DSSAT (Decision Support System for Agrotechnology Transfer) (IBSNAT 1989). Both rainfed and irrigated simulations were performed under all of the climate scenarios described above. The physiological effects of CO_2 on the crop were considered in each simulation. In addition a sensitivity analysis was performed with arbitrary changes in precipitation (+20% and -20%) and in temperature (+2°C and +4°C) from the baseline climate.

The CO_2 levels and the photosynthetic factors used for the climate change scenarios are:

Climate Change Scenario	*CO_2 Level*	*Photosynthetic Factor*
GISS, GFDL, UKMO	555	1.17
2010	405	1.05
2030	460	1.10
2050	530	1.15

RESULTS AND DISCUSSION

Sensitivity Analysis

This section presents the sensitivity of the CERES-Wheat model to changes in precipitation (+20% and -20%) and temperature (+2°C and +4°C). Figure 3 shows that temperature is the main factor responsible for yield changes. Both grain yields and biomass decline with increasing temperatures, although there is a small yield increase when the rainfall is increased by 20%. Field experiments (at the Indian Agricultural Research Institute and other sites) indicate that wheat yields are very sensitive to elevated temperatures, particularly during the grain-filling period. The simulation analysis shows similar results.

Wheat Responses to Climate Change at Delhi

At Delhi, the GISS and GFDL climate change scenarios project an increase in the amount of rainfall from June to October (Figure 2). The air temperature increases under all GCM scenarios throughout the year and particularly during the post-rainy season. No appreciable change in the solar radiation is observed under climate change conditions. The GISS transient scenarios show gradual increases in monthly temperature of at least 5°C by 2050 and sharp increases in rainfall during July (Figure 2). Solar radiation increases slightly in January and February during the 2030s and 2050s.

Under the GCM equilibrium scenarios alone (not considering the direct CO_2 effects), simulated wheat grain yields were largely reduced in comparison to the base values. Under the transient scenarios, yield reductions were smaller (Figure 4). When the physiological effects of CO_2 are included in the yield simulations, they partially offset the yield decreases (Figure 4). In fact, under the GISS scenario and the 2010 transient climate, there was a marginal increase in the simulated grain yields under rainfed conditions. Nevertheless, under irrigated conditions, yield decreases from the base were apparent even when the direct CO_2 effects were included. The transient scenarios predicted a greater reduction in the response of the crop to irrigation as we pass from the 2010s to the 2050s. Simulated biomass followed a similar trend, but in this case the marginal increase in the dryland simulations under the GISS scenario with CO_2 effects were not observed (Figure 4).

Temperature increases under the scenarios decreased the length of the growing period and total evapotranspiration in the crop model simulations (Figure 4). The length of the growing season was not affected by the physiological effects of CO_2. In general, the climate change scenarios predict a greater percent reduction in evapotranspiration under irrigated conditions.

Wheat Responses to Climate Changes at Hyderabad

All GCMs show an increase in the average monthly air temperature at Hyderabad. The UKMO model projects the largest increases—up to 5°C from January to March (Figure 2). The rainfall increases during the rainy season (May to November) under all scenarios. The solar radiation shows considerable reduction in the GFDL scenario from June to December (Figure 2) because this scenario predicts higher precipitation during those months. The transient scenarios show an increase in the mean average temperatures, which reach an average of 35°C (Figure 2) during August. Rainfall shows no particular trend and solar radiation shows small increases from June to December in 2050.

As in the case of Delhi, simulated wheat yields and season length decreased under all GCM scenarios of climate change (Figure 5). The largest reductions were under the GISS and UKMO scenarios. The transient scenarios projected a 20% decrease in the 2010s and a 60% decrease in the 2050s. The same trend was observed with respect to biomass production, except under the GFDL scenario. As in the case of Delhi, the evapotranspiration was lower.

Adaptation Strategies

Possible strategies to increase wheat yields under climate change conditions are: increasing irrigation, using more fertilizer, or increasing the plant population. These strategies were tested at Delhi under the equilibrium GCM scenarios, but only slightly reduced the negative impacts of climate change on simulated yield (data not shown).

To further evaluate possible adaptive strategies to climate change, two approaches could be tried:
(a) Evaluate the impacts of the climate change scenarios on other Indian wheat cultivars. However, the tremendous variability in germoplasm requires accurate estimates of the genetic coefficients that describe each cultivar in the CERES-Wheat model, and these coefficients are not readily available for many of the Indian genotypes.
(b) Design hypothetical new cultivars that will adapt to climate change conditions, using the CERES-Wheat model as a tool. Possible breeding objectives could be established by analyzing the genetic coefficients in order to define a theoretical cultivar that is adapted to climate change.

Implications of Climate Change for Wheat Production in India

The results presented in this report suggest that wheat yields would decrease under equilibrium and transient climate change conditions at Delhi and Hyderabad. These yield decreases could have a serious impact on food security, especially in view of the increasing population and its demand of food grains. Since most of the wheat production comes from the northern plains, where it is almost impossible to increase the present area of wheat under irrigation, climate change could lead to shortages in food supplies. Furthermore, the simulated changes in wheat yields could be indicative of the possible impacts of climate change on other similar crops grown during the same season.

Before considering the above scenario, it is important to evaluate some important limitations of this study:

(a) Poor simulation of the present climate by the GCMs in this region.

(b) Poor validation of the CERES-Wheat model for some of the Indian wheat cultivars. For example, the cultivar "Kalyansona", under irrigation at Delhi, has an average growing period of 150-160 days, but the simulated growing period was always under 116 days in the present study. In addition, the yield components are not simulated adequately.

Because of these uncertainties, it would be premature to draw final conclusions on the impact of climate change on India's food security system. However, the results of this simulation study suggest possible negative consequences of climate change for the crops in India, and thus, further research needs to be encouraged through both national and international efforts. It is essential to conduct further research using the wheat model, and efforts are needed to develop models for crops such as chickpeas, rapeseed, mustard, and barley. This would require extensive field experiments to generate crop phenology data.

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Table 1. Area and production of wheat in various states of India.

State	86-87 Area	86-87 Prodn.	87-88 Area	87-88 Prodn.
Andhra Pradesh	10.60	6.90	11.80	4.20
Arunachal Pradesh	2.10	6.90	2.10	6.90
Assam	120.00	125.80	98.30	105.80
Bihar	1839.70	2863.10	1934.90	2776.60
Gujarat	315.10	661.70	192.40	351.20
Haryana	1782.00	5055.00	1731.00	4861.00
Himachal Pradesh	377.10	492.00	374.90	351.20
Jammu&Kashmir	222.40	272.10	238.40	212.00
Karnataka	306.50	148.80	262.40	133.90
Madhya Pradesh	3251.30	3865.00	3549.10	4328.80
Maharastra	735.50	536.40	732.70	633.40
Meghalaya	4.80	6.70	4.80	6.70
Orissa	46.80	83.30	45.70	80.90
Punjab	3189.00	9458.00	3126.00	11066.00
Rajastan	1843.20	3401.60	1533.80	2909.80
Sikkim	10.20	16.50	11.20	17.70
Tamilnadu	0.40	0.20	0.10	0.10
Tripura	2.70	4.30	3.20	2.70
Uttar Pradesh	8311.50	16078.50	8339.80	16462.90
West Bengal	397.70	682.70	374.20	673.90
Delhi, Dadra & Nagar Haveli	41.20	119.60	37.30	107.20
TOTALS	22820.30	45576.50	22604.20	45095.50

Area (x 1000 ha)
Prodn. (million t)

Appendix A. Soil physical properties used for CERES-Wheat simulations at Delhi and Hyderabad.

SOIL AT DELHI

DLAYR	LL	DUL	SAT	SW	BD
10.	.156	.262	.362	.262	1.37
15.	.166	.262	.362	.262	1.37
15.	.167	.262	.362	.262	1.37
15.	.157	.262	.362	.262	1.37
30.	.148	.261	.361	.261	1.38
30.	.110	.260	.360	.260	1.38
30.	.111	.259	.359	.259	1.39
30.	.112	.258	.358	.258	1.39
30.	.112	.258	.358	.258	1.39
-1.	.00	.00	.00	.00	.00

SOIL AT HYDERABAD

DLAYR	LL	DUL	SAT	SW	BD
10.	.313	.480	.560	.480	1.35
15.	.313	.479	.559	.479	1.36
15.	.314	.479	.559	.479	1.36
15.	.316	.477	.557	.477	1.37
15.	.316	.477	.557	.477	1.37
30.	.318	.476	.556	.476	1.37
30.	.320	.474	.554	.474	1.38
-1.	.00	.00	.00	.00	.00

DLAYR = Thickness of the soil layer
LL = Lower limit plant extractable water
DUL = Drained upper limit soil water content
SAT = Saturated water content
SW = Defaulted soil water content
DB = Moist bulk density of soil

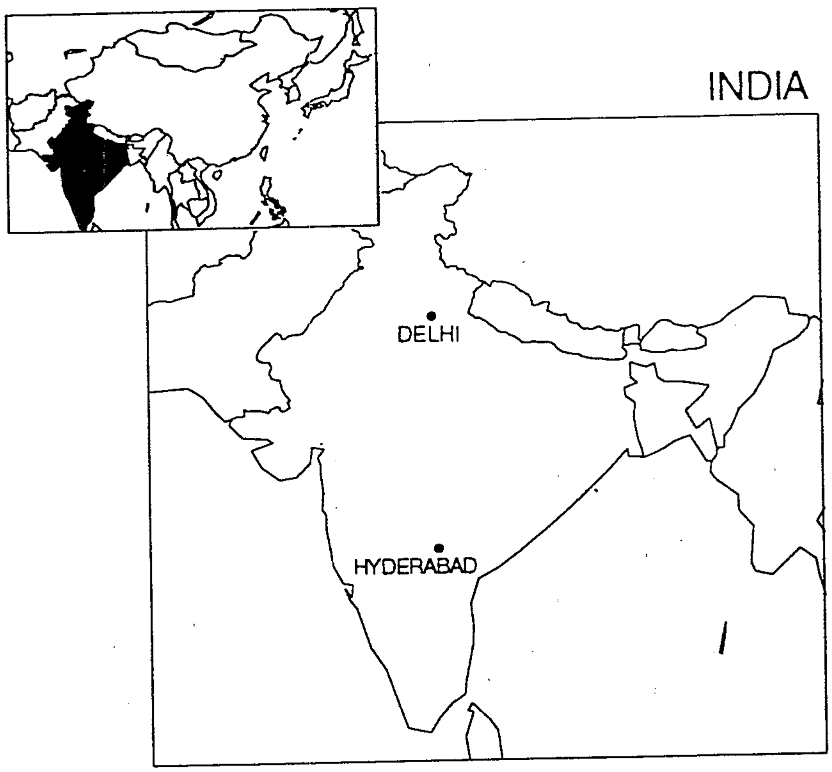

Figure 1. Map of India and location of the sites selected for the study.

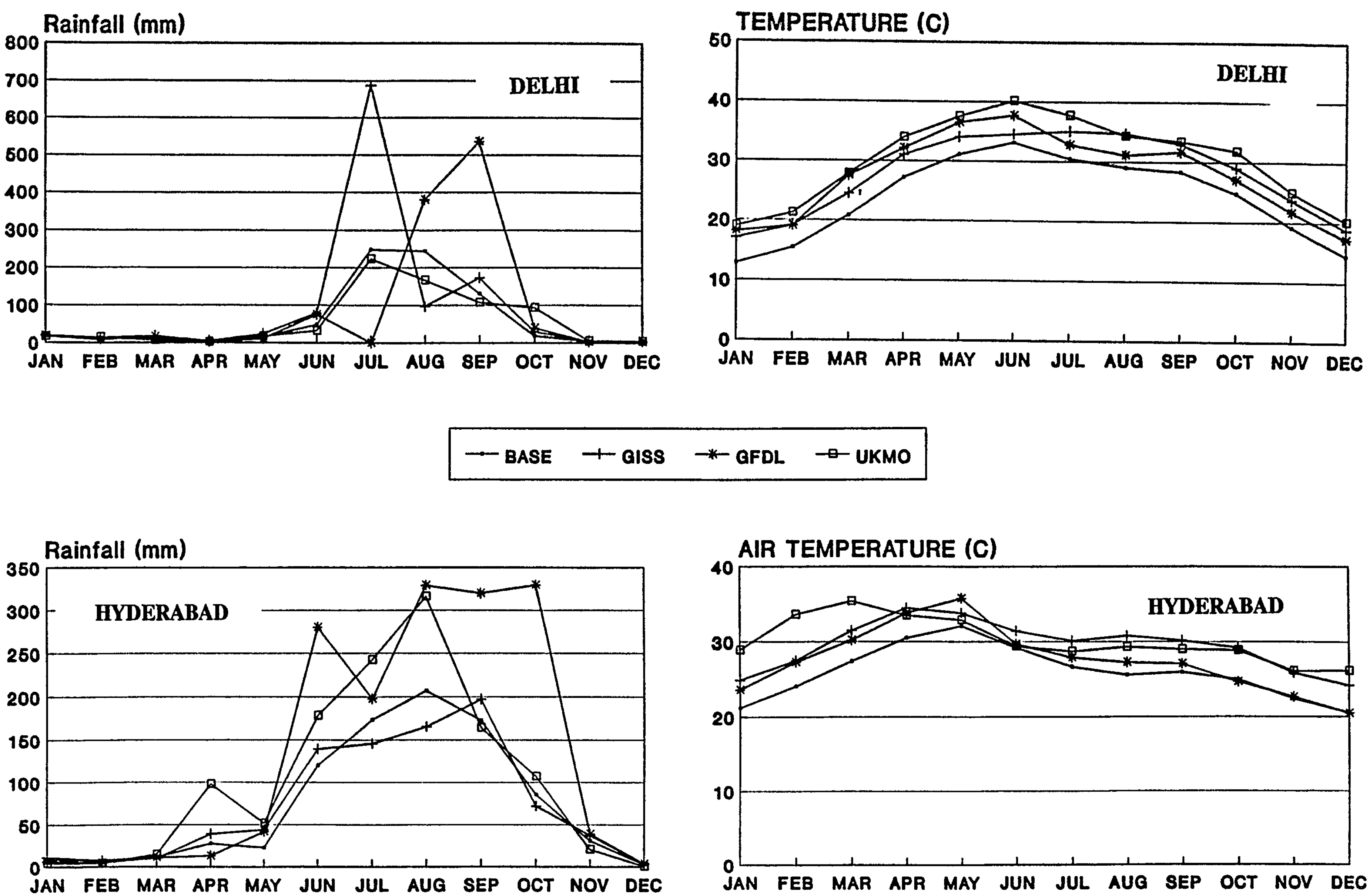

Figure 2a. Average monthly temperatures and precipitation observed (BASE) and projected by three equilibrium scenarios (GISS, GFDL, and UKMO).

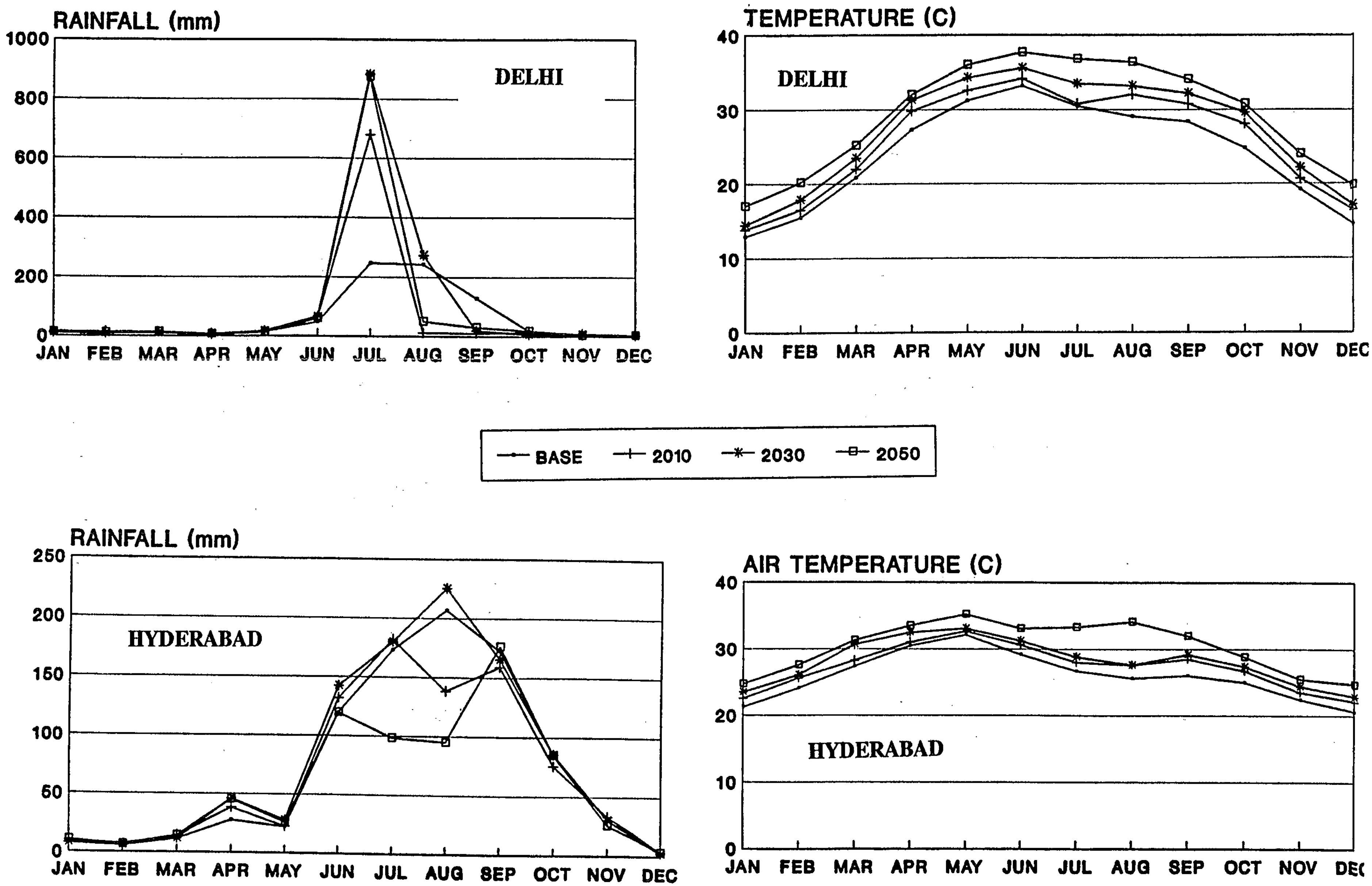

Figure 2b. Average monthly temperatures and precipitation projected by the GISS transient scenario.

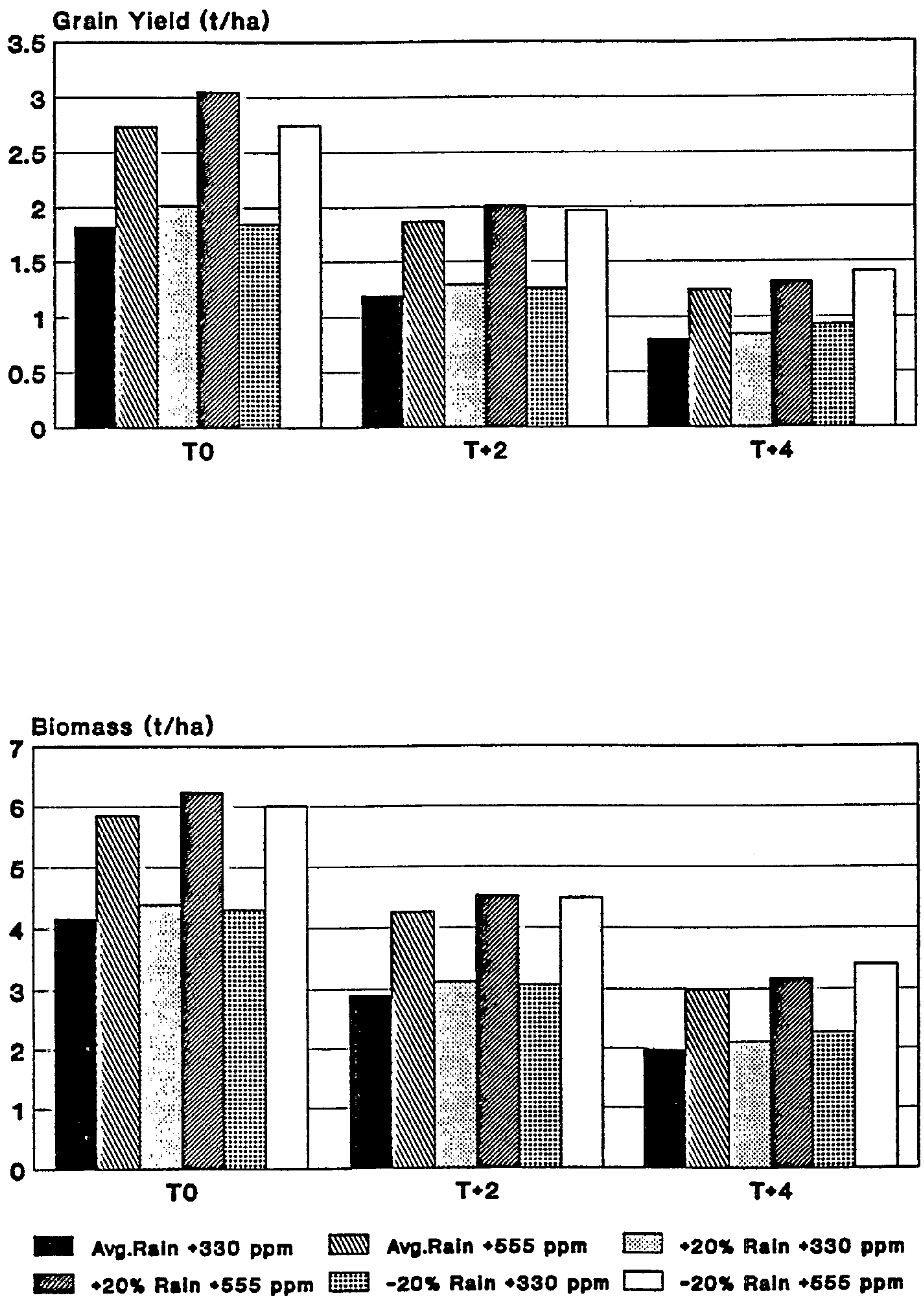

Figure 3. Sensitivity analysis of CERES-Wheat to temperature, precipitation, and CO_2 at Delhi.

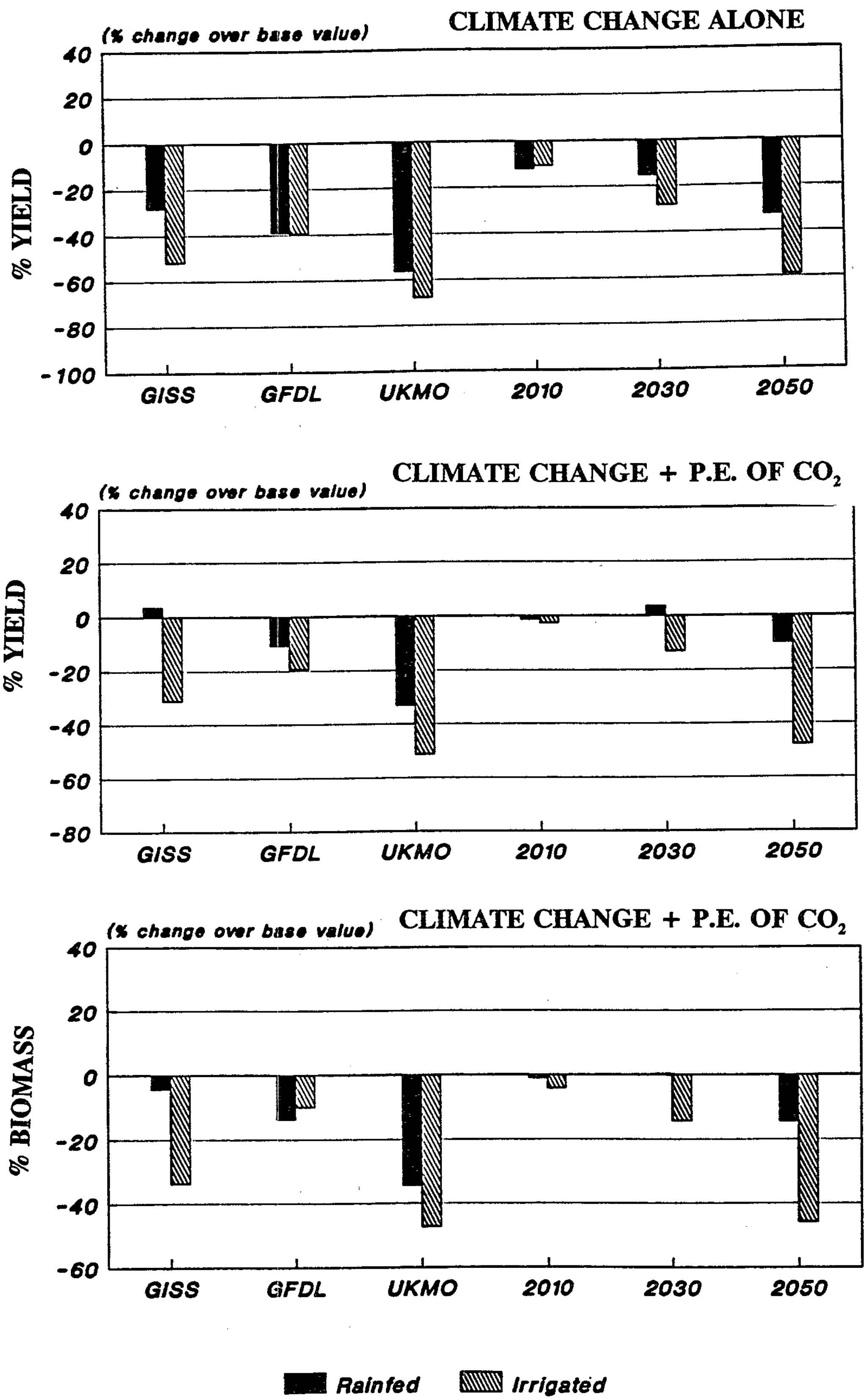

Figure 4a. Effect of climate change on simulated yield and biomass at Delhi.

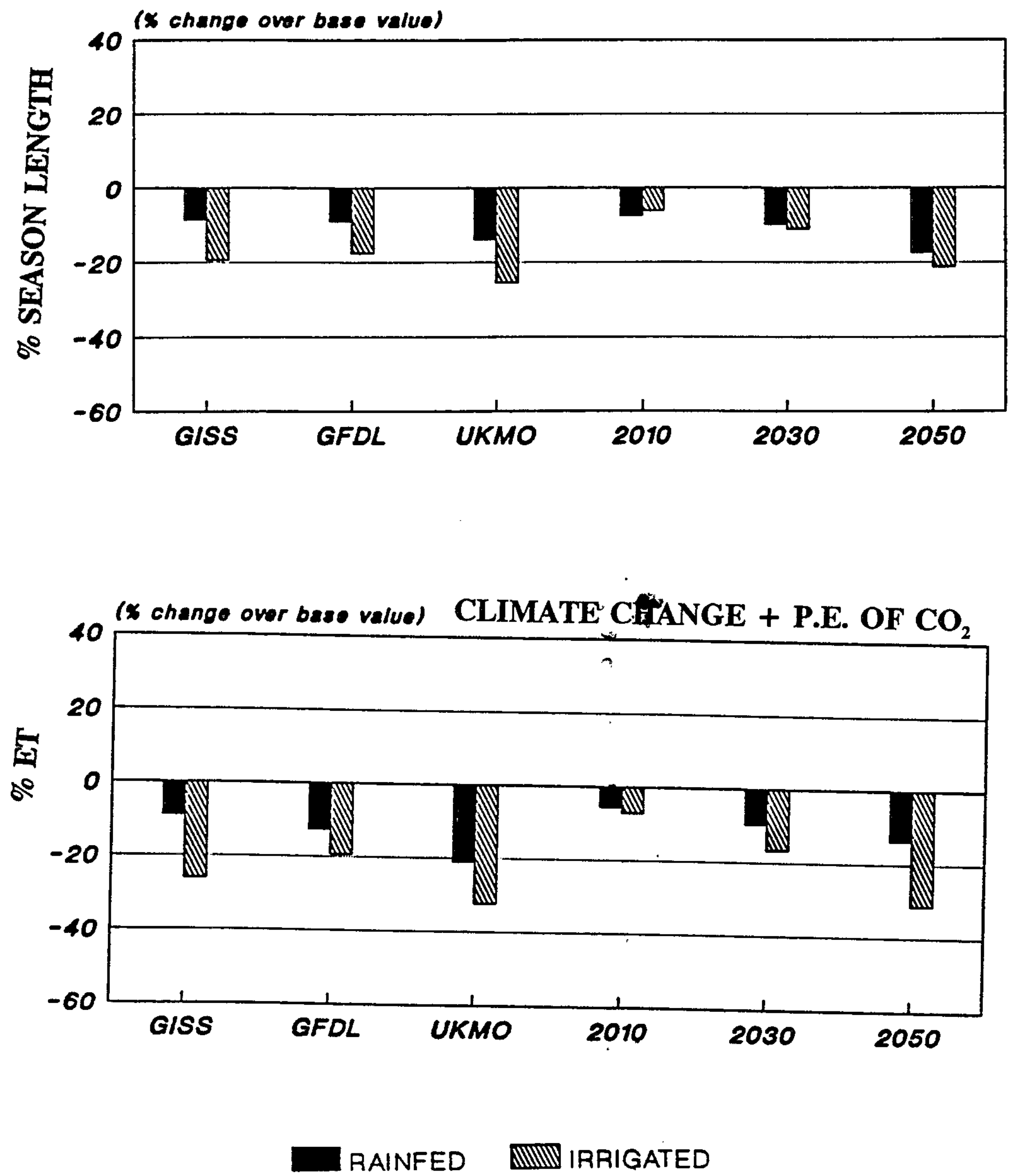

Figure 4b. Effect of climate change on season length and total crop evapotranspiration (ET) at Delhi.

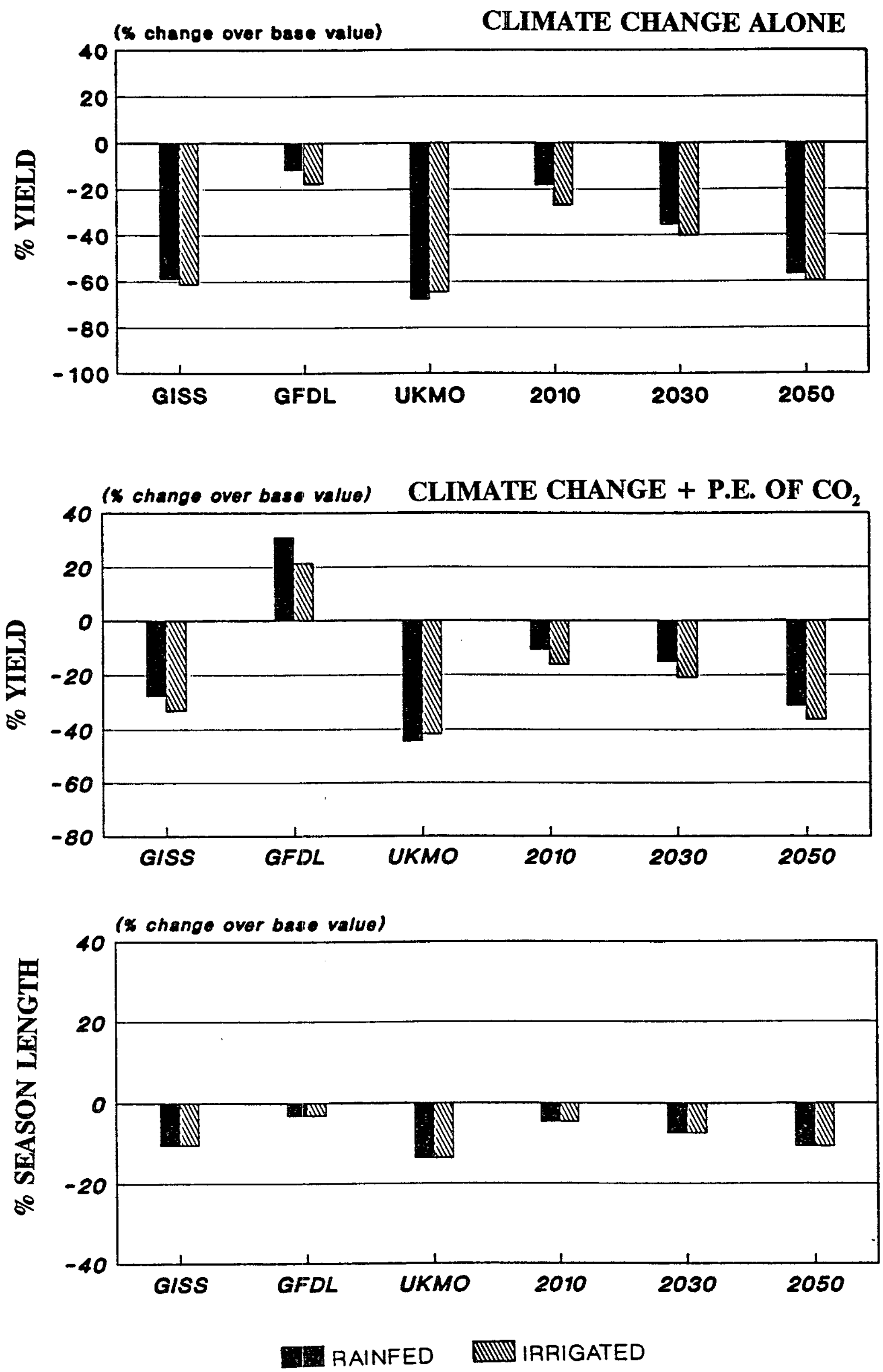

Figure 5. The effect of climate change on simulated yield and season length at Hyderabad.

IMPACT OF CLIMATE CHANGE ON THE PRODUCTION OF MODERN RICE IN BANGLADESH

Z. Karim, M. Ahmed, S.G. Hussain, and Kh.B. Rashid

Bangladesh Agricultural Research Council
Dhaka, Bangladesh

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SUMMARY

Bangladesh is located in a region that is vulnerable to environmental hazards, frequent floods, droughts, cyclones, and storm surges that damage life, property, and agricultural production. This study uses climate models combined with crop simulation models to determine the possible effects of climate change on rice production in major agricultural regions of the country.

Sensitivity simulations showed that rice yields decreased significantly with temperature increases in the two sites considered. The rice yields under the GCM climate scenarios alone decreased at both sites. When the physiological CO_2 effects were considered, the yield decreases under the climate change scenarios were offset. If the physiological CO_2 effects are not as positive as simulated in this study, rice production in Bangladesh could be damaged under climate change conditions. A decrease in rice production, combined with the rapidly increasing population, would threaten the country's food security.

INTRODUCTION

Background

Bangladesh occupies an area of about 55,598 square miles near the Tropic of Cancer between latitudes 20.25°N-26.38°N and longitudes 88.01°E-92.40°E (Figure 1). For its relatively small size, Bangladesh encompasses a wide range of environmental conditions. Land, soil, hydrology, and climatic variability occur at the national level and also in small areas of the country. The country is divided into 30 agroecological regions (FAO 1988) according to physiography, characteristics and length of seasonal flooding, length of the cool winter period, and frequency of extremely high (>40°C) summer temperatures.

A variety of crops are grown in the country (Statistical Yearbook 1990), but local and modern varieties of rice represent the dominant crop. Rice is the staple food in the country, currently grown on about 10.3 million hectares of land with production of about 18 million tons. Other important crops are jute and wheat. Wheat is becoming increasingly significant especially in the northern regions. This study considers the possible impacts of climate change on modern rice production in two contrasting locations in Bangladesh (Figure 1) that represent major rice-growing regions.

Climate Vulnerabilities in Bangladesh

Monsoon rainfall occurs everywhere in the country, although the amount and intensity of the rain varies greatly. About 90% of the precipitation occurs during four months (June-September), but the distribution within these months differs at different sites (Figure 2). Annual rainfall ranges from 1,400 mm in the dry Rajshahi (Northwest) region to more than 5,000 mm in the wet Sylhet (Northeast) region. Regional cropping patterns are primarily determined by the seasonal monsoon flooding regime. There are three seasons with different hydrological regimes: the wet season from June to November (called "kharif"), the dry season (called "rabi"), and a transitional season (called "prekharif"). The winter temperatures are moderate, but the summer temperatures are extremely high and may exceed 40°C.

The country is highly vulnerable to climatic events; floods and droughts are very frequent and damaging. The recent severe floods of 1987 and 1988 produced colossal damages to crops and property. In 1988, about 2.5 million tons of food grain were damaged by floods. Due to the uncertain and uneven distribution of rainfall, droughts of different intensities may occur and cause large crop losses. During the wet season, the crop most affected by drought is rice. In the areas that are most severely affected (about 2.3 million ha), yield losses can represent a 45% decrease from the achievable yield (Karim *et al.* 1990; Karim and Akhand 1982). During the dry season, wheat, potato, and mustard are most affected by drought. Possible climate changes (IPCC 1990) may bring more unfavorable conditions for agriculture in Bangladesh, as has been previously suggested (Mahtab 1990).

Aims and Design of the Study

Since climatic variability is the most important factor determining agricultural production in Bangladesh, it is important to study the potential impacts of climate changes on rice production. This study uses climate change scenarios generated by General Circulation Models (GCMs) and is part of a global research project funded by the U.S. Environmental Protection Agency.

Two contrasting locations, Mymensingh (Lat. 24.46°N and Long. 90.23°E) and Barisal (Lat. 22.42°N and Long. 90.23°E), were selected for the study (Table 1). Mymensingh represents the old Brahmaputra, young Brahmaputra, and Jamuna floodplain regions. This location includes a relatively large proportion of high and medium highlands ideally suitable for transplanted modern rice cultivars. Barisal represents 2.85 million hectares of the coastal areas of Bangladesh and constitutes about 30% of the net cultivable area of the country. The Ganges tidal floodplain is the major agroecological region represented by Barisal, and part of this region is seasonally inundated by tides.

METHODS

Climate Data and Climate Change Scenarios

Daily maximum and minimum temperatures, precipitation, and hours of sunshine data were obtained for the two sites. Daily solar radiation values were calculated from sunshine hours using the weather-generating program included in DSSAT (Jones *et al.* 1990). Figure 2 shows the monthly average temperatures and precipitation for Mymensingh and Barisal.

The climate change scenarios used in this simulation study were created from three GCMs: Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1983), Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), and United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987). The UKMO scenario projects the largest annual temperature increases (4.3°C) (Table 2), while GISS and GFDL predict smaller annual temperature changes. Annual precipitation is projected to increase considerably at the two sites (up to 41%) except at Barisal, where annual precipitation is projected to decrease slightly under the GISS scenario. The study also includes a sensitivity study to changes in temperature (+2°C and +4°C).

Crop Model, Cultivars and Management Variables

The simulation of rice growth and yield was performed using the CERES-Rice model (Godwin *et al.* 1992). Since the climate change scenarios have higher levels of CO_2 than the current climate GCM simulations, the CERES-Rice model includes an option to simulate the physiological effects of CO_2 on photosynthesis and water-use efficiency that results in an increase in yield, as documented experimentally (Acock and Allen 1985). The physiological effects of CO_2 were also considered at both sites.

The Bangladesh Rice Research Institute has developed a number of crop varieties; BR11 and BR3 are the two most extensively used. The cultivar BR11 is grown during the wet season (June-November) and is transplanted (called "transplanted Aman"). The cultivar BR3 is the main cultivar grown during the dry season (called "Boro" rice) and is generally irrigated. Occasionally the cultivar BR3 is grown during the wet season as transplanted Aman.

The management variables for the simulation model were determined according to current practices in the two regions considered in this study. Rice growth was simulated under the "automatic irrigation" option of the model to provide the crop with a nonlimiting water situation. A limitation of this choice of simulation is that the yield losses due to insufficient water for the crop are not simulated, and therefore the yield could be overestimated. Nevertheless, relative yield changes under climate change conditions compared to baseline climate could still be analyzed.

RESULTS

Sensitivity of the Rice Yields to Temperature Increases

Table 3 shows that simulated rice yields decreased significantly with increases in temperature at the two sites considered. During the transplanted Aman season, rice yields were reduced about 2 t ha^{-1} by a temperature increase of 4°C at both locations. Similar effects were also observed with the cultivar BR3 in the Boro rice season. In all cases, the high temperatures result in a reduced season length that partially accounts for the reduced yields. The crop may also experience heat stress due to the very high temperatures considered in these sensitivity scenarios, especially during the transplanted Aman season (warmest season). During the Boro season, base temperatures are lower and rice yields were somewhat less reduced under the high-temperature scenario. When the direct effects of 555 ppm CO_2 were included in the yield simulations, they compensated for the negative effects of a 2°C temperature increase but not for the effects of a 4°C temperature increase.

Rice Yields Under GCM Climate Change Scenarios

Rice yields decreased significantly at both sites under the three climate change scenarios compared with the base yields under current climate (Table 4). During the Boro season, the UKMO scenario projected the largest decreases in yields at the two sites because of the higher temperature projections. In the transplanted Aman season, simulated yield losses under the GCM scenarios were larger than in the Boro season. Simulated season length decreased under the three GCM scenarios considered due to the acceleration of phenological growth stages by high accumulated temperature. When the direct effects of CO_2 (555 ppm) were included in the yield simulation, they compensated for the yield decreases under the climate change scenarios in most cases.

IMPLICATIONS OF THE RESULTS

The current rice production could be damaged under climate change conditions as projected by the GCMs. Although the simulated direct effects of CO_2 may compensate for yield reductions in general, the full extent of these effects has not been clearly established under field conditions. Another cause for concern in regard to climate change is the potential for increases in sea-level leading to flooding of low-lying coastal regions. These regions support high populations and extensive agricultural production. Any possible decrease in rice production in Bangladesh would have severe consequences on the food resources available to the country and thus threaten food security. The Bangladesh Planning Commission estimates that the country's population will increase to 137 million by the year 2000 and to 155 million by the year 2010, leading to further reduction of the land-person ratio from the low current level of 0.13 ha per person.

In view of the results of this study, serious consideration should be given to reduce population growth, to develop research strategies to increase rice production, and to limit greenhouse gas emissions. The development of rice cultivars that are more tolerant to heat and require a shorter growing season is one of the possible strategies for adaptation to climate change. Policymakers should seriously consider population growth regulations as well as qualitative improvements in agronomic research and technology to sustain the country's economic development.

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Table 1. Characteristics of the land resources and inundation land type in Bangladesh.

	Land Type (ha)				
	Highland	Medium Highland	Medium Lowland	Lowland	Very Lowland
Bangladesh Total	4,199,952	5,039,724	1,771,102	1,101,560	193,243
Mymensingh Region	156,022	138,303	63,243	7,821	--
Barisal Region	12,117	135,580	23,593	4,566	--

Highland: Land above normal inundation level.
Medium Highland: Land normally inundated up to about 90 cm deep.
Medium Lowland: Land normally inundated up to 90-180 cm deep.
Lowland: Land normally inundated up to 180-300 cm deep.
Very Lowland: Land normally inundated deeper than 300 cm.

Table 2. Annual temperature and precipitation changes from base under GCM scenarios.

Site	Lat/Long	Temp. Changes (°C)			Precip. Changes (%)		
		GISS	GFDL	UKMO	GISS	GFDL	UKMO
Mymensingh	24.75 N 90.38 E	2.8	2.8	4.3	27	33	41
Barisal	22.68 N 90.33 E	4.0	2.8	4.3	-7	33	41

Table 3. Sensitivity of CERES-Rice to temperature and CO_2 changes at selected sites.

CO_2 level (ppm)	Temp. (°C)	Yield ($t\ ha^{-1}$)	Season L. (days)	Yield ($t\ ha^{-1}$)	Season L. (days)
		Rice Cultivar BR11, transplanted Aman			
		Mymensingh		Barisal	
330	0	6.28	139	7.74	152
	2	5.14	128	6.59	140
	4	4.39	127	5.71	138
555	0	7.69	140	9.43	153
	2	6.51	131	8.17	141
	4	5.74	129	7.29	139
		Rice cultivar BR3, Boro Rice			
		Mymensingh		Barisal	
330	0	6.39	156	6.81	138
	2	5.77	150	6.31	131
	4	4.94	147	5.65	129
555	0	7.61	156	8.13	138
	2	6.98	150	7.61	131
	4	6.09	148	6.91	129

Table 4. Simulated rice yield (a) and season length (b) under current climate and yield changes under climate change scenarios in Bangladesh.

(a) Yield (t ha^{-1})

Site	Type of rice	BASE	GISS	GISS	GFDL	GFDL	UKMO	UKMO
			% change from base					
		t ha^{-1}	330	555	330	555	330	555
Mymensingh	BR 11 Aman	6.28	-22	0	-27	-6	-22	0
	BR 3 Aman	4.61	-23	0	-27	-6	-21	1
	BR 3 Boro	6.37	-14	5	-18	1	-25	-6
Barisal	BR 11 Aman	7.74	-19	2	-24	-3	-20	1
	BR 3 Aman	5.7	-18	4	-24	-3	-19	2
	BR 3 Boro	6.81	-11	8	-14	5	-23	-4

(b) Season Length (days)

Site	Type of Rice	BASE	GISS	GFDL	UKMO
Mymensingh	BR 11 Aman	139	130	127	127
	BR 3 Aman	138	130	127	127
	BR 3 Boro	156	147	148	145
Barisal	BR 11 Aman	152	138	139	137
	BR 3 Aman	152	138	138	138
	BR 3 Boro	138	131	129	125

330 - Climate change alone
555 - Climate change with physiological CO_2 effects.

Figure 1. Map of Bangladesh and location of the sites used in the simulation study.

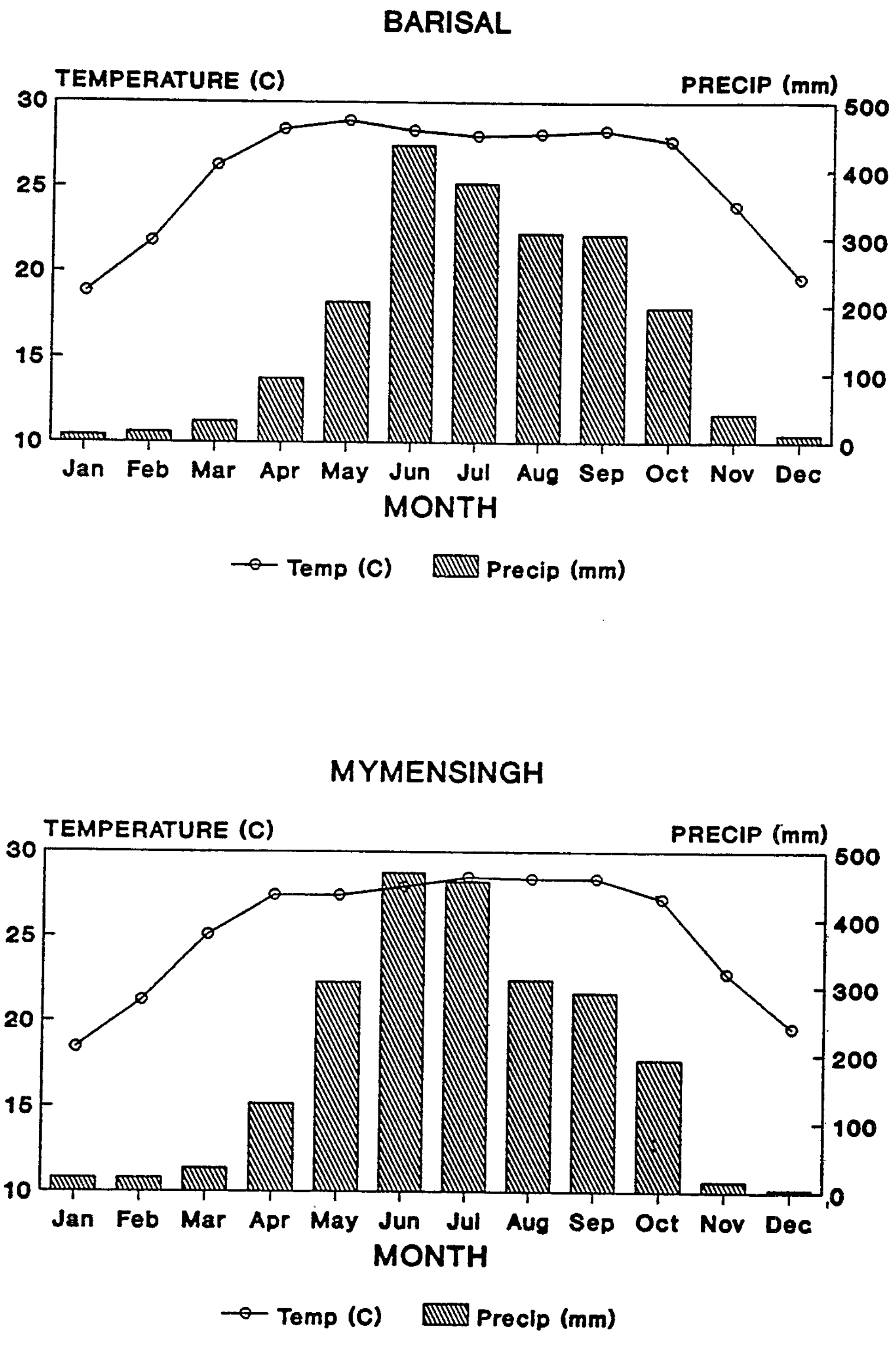

Figure 2. Observed monthly averaged temperature and precipitation for selected sites.

IMPACT OF CLIMATE CHANGE ON SIMULATED RICE PRODUCTION IN THAILAND

C. Tongyai

Soil Science Division, Dept. of Agriculture
Ministry of Agriculture and Cooperatives, Thailand

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SUMMARY

This study used global climate models and crop dynamic models to estimate the potential effects of climate change on the rice production of Thailand. Projected climate change caused simulated rice yields (both upland and paddy rice) to decrease dramatically, due to temperature increases. Yield decreases were partially counteracted by the physiological effects of CO_2, as simulated in this study. The high temperatures of the climate change scenarios had a negative effect on crop growth even when an adequate water supply was available. We found that in spite of the differences among the GCM scenarios, the locations simulated, and the agricultural practices of the regions, rice yields under climate change scenarios dramatically decreased in comparison with base-line yields. The results may be indicative of the potential impacts of climate change on the agricultural systems in Thailand.

INTRODUCTION

Thailand, located in Southeast Asia, extends over a large latitudinal range (latitude 5°40'N to 20°30'N) and from longitudes 97°20'E to 105°45'E (Figure 1). The total area of the country comprises 513,115 km^2. Six regions are defined and characterized by their landforms: the Northern Ranges and Valleys, the Northeast Plateau or Khorat Plain, the Central Plain, the Western mountains, the Southeast coast, and the Peninsular South. Agriculture is a main contributor to the Thailand economy. Agricultural systems (arable crops, rangelands, forestry, and fisheries) employ more than 60% of the labor force during the cropping season and account for 20% of GNP. Crop production accounts for more than 50% of the agricultural revenues. Rice is the main food crop and the main agricultural export commodity. It is grown in all regions of the country during both the wet and dry seasons. In some regions additional water for irrigation is provided when necessary. Although both long-grain (Thai) and glutinous rice are grown throughout the country, the long-grain rice is the main crop in most regions and accounts for all rice exports (Table 1).

Floods are an important cause of crop production losses. Natural disasters (tropical or depression storms and landslides) also account for the destruction of crops and damage to agricultural infrastructure. The greenhouse effect could lead to higher global surface temperatures and changed hydrological cycles (IPCC 1990). Previous research has suggested that the possible impacts of climate change in Southeast Asia could be severe (Parry *et al* 1988). In Thailand a change in the rainfall pattern or an increase in temperature could lead to soil moisture deficits for the rainfed rice crop, and result in limited irrigation water supply for the second crop. This study analyzed the simulation of rice production with scenarios of climate change, generated by General Circulation Models (GCMs), and compared the results to simulations under the current climate. The study also evaluated the physiological effects of CO_2 on rice yields.

To represent the varied range of agricultural practices and regions of the country, simulations were carried out at four contrasting locations and included a combination of different management practices and soils. The regions selected for the simulation study are the upper and lower Northern regions and the Central Plain. The lower Northern region encompasses broad differences in climatic conditions, therefore two sites were selected in this region (Phitsanulok and Nankhon Sawan). The upper Northern region is represented by Chiang Mai, and the Central Plain is represented by Bangkok (Figure 1). These sites are representative of the major rice production areas in Thailand.

METHODS

Observed Climate

Climate data for the four sites included in this study were obtained from the Thailand Meteorological Observatory (1956-1989), and included daily maximum and minimum temperatures and daily precipitation. Daily solar radiation was estimated from sunshine hours by the WGEN program (Richardson and Wright 1984).

Thailand experiences extreme seasonal climate fluctuations, although its climate is generally humid. Figure 2 shows the monthly temperature and precipitation averages for the 1956-89 period for the site of Bangkok. Two seasons can be distinguished: wet (May to October) and dry. The mean temperature is always over 25°C except in the coldest regions (represented by Chiang Mai), and the maximum temperature often exceeds 30°C.

GCM Climate Change Scenarios

The General Circulation Models compute climatic variables for spatial gridboxes across the earth's surface, but they do not account for the variations within the gridbox. Climate change scenarios for each site were created based on the GCM gridbox output of climate variables applied to the daily observed climate at the study sites. The method employs the differences between 1xCO_2 and 2xCO_2 monthly temperatures, and the ratios between 2xCO_2 and 1xCO_2 monthly precipitation and solar radiation amounts. (1xCO_2 refers to current climate conditions, and 2xCO_2 refers to the climate which would occur with an equivalent doubling of CO_2.) Three equilibrium GCMs were used in this study to create the climate change scenarios for each site: the Goddard Institute for Space Studies model (GISS) (Hansen *et al.* 1983), the Geophysical Fluid Dynamics Laboratory model (GFDL) (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office model (UKMO) (Wilson and Mitchell 1987). Scenarios were also generated with output from a transient climate change scenario (GISS transient run A, Hansen *et al.* 1988).

The climate change scenarios show some major differences when compared with the observed climate. Figure 3 shows monthly differences between observed climate and climate change scenarios for each site. The temperature increases are very similar at the four sites and in general larger temperature increases are simulated by the UKMO climate change scenario. With all climate change scenarios, the largest changes in the seasonal temperatures occurred during the dry season. The scenario precipitation changes vary among the sites and the distribution of the projected seasonal rainfall was very different from site to site. The largest increases in projected precipitation usually correspond to the early wet season.

Crop Model and Management Variables

Potential changes in rice physiological responses (yield, season length, evapotranspiration, and irrigation water demand) were estimated with the CERES-Rice model (Godwin *et al* 1992) under different climate scenarios. The software for the climate change simulations of the rice crop was developed by IBSNAT (IBSNAT 1989, Jones *et al* 1990). The model was run using 30 years of baseline climate and GISS, GFDL, and UKMO climate change scenarios under dryland and irrigated conditions.

Cultivars. The cultivar RD23 was selected for the study because it represents the most common long-grain cultivar in Thailand (Table 2). The genetic coefficients of RD23 were taken from the DSSAT database (Jones *et al* 1990). In the upper North region (Chiang Mai), the glutinous cultivar NSPT was also used in this study (Table 2). These cultivars have been calibrated for many different climate conditions, including Thailand.

Management Variables. Rice was planted in early to mid- August, and the plant population was 25 plants m^{-2}. Both upland and paddy rice practices were simulated. For the irrigated simulations, the automatic option of the CERES-Rice model was used to provide the crop with a nonlimiting water situation. The water demand was calculated assuming: 100% efficiency of the automatic irrigation system; 1 m irrigation management depth; and automatic irrigation when the available soil water is 50% or less of capacity. The initial soil water content for each layer was determined for each type of soil (see below).

Soils and Initial Soil Water Conditions. The input soil parameters, nutrient levels, and initial soil conditions (determined for each layer of soil and for all soils employed in this study) were obtained from a soil data survey from the Soil Physics Research Group at the Department of Agriculture (Table 3).

Physiological Effects of CO_2. Many crops may benefit from the higher levels of atmospheric CO_2 (Acock and Allen 1985). Because the climate change scenarios have higher amounts of CO_2 than the present climate, the CERES-Rice model includes an option to simulate the physiological effects of CO_2 on the rice (i.e., an increase in photosynthesis and water use efficiency). The physiological effects of CO_2 were considered in all scenarios and at all sites.

Validation of the CERES-Rice Model

The CERES-rice model was validated at Bangkok using observed crop and weather datasets for the years 1985, 1986 and 1987. The rice cultivar used was RD23 (long-grain Thai). The initial soil water conditions were set to realistic values for the years of the simulation. Observed and simulated yield, biomass, and season length were compared. Table 3 shows the close correspondence between the simulated and the observed parameters during the years of the validation experiments.

RESULTS

Sensitivity Analysis

This section characterizes the sensitivity of the CERES-Rice model to changes in temperature at the four sites selected for the study in Thailand. The direct beneficial CO_2 effects on rice growth were simulated for each set of conditions. Table 4 shows the sensitivity results under irrigated conditions. The temperature increases resulted in decreases in crop yield and season length at all sites. In the rainfed simulations (not shown) the relative changes in yields and season length produced by the temperature increases were comparable to the irrigated simulation.

Effect of GCM Climate Change Scenarios on Rice Growth

This section analyzes changes in simulated crop yield for the GCM climate change scenarios, using the current climate and management variables as the base reference. Each climate scenario included crop simulations with 330 ppm CO_2 (representing the effects of climate change alone on the crop) and with 555 ppm of CO_2 (representing the effects of climate change with the direct beneficial effects of CO_2 on yield and crop water use).

Simulations were conducted to represent different crop management conditions, soils, and initial water conditions of the soils. There were large decreases in simulated yields under the climate change scenarios alone compared to the baseline yield (Table 5). These were comparable at all sites and with the different crop conditions, probably because the negative effect of increased temperature on season length (as shown in the sensitivity analysis) is the dominant factor driving yield changes in each case. The performance of the rice cultivar RD23 was compared with the cultivar NSPT, which is a typical photoperiod-sensitive, glutinous indica cultivar planted in the upper northern region. Generally, the yield of the RD23 cultivar decreased more than that of the NSPT under the conditions that simulate rice growth in paddies (Table 5).

When the direct CO_2 effects were included in the climate change simulations, rice yields increased at all sites in comparison to the climate change scenarios alone. The direct CO_2 effects offset the yield decreases simulated under the climate change scenarios in some but not all cases (Table 6 and Figure 4). The results of these simulations imply the potential for significant changes for Thailand rice production with climate change. Yield decreases for two of the GCM scenarios tested ranged from -20% to -40%; further studies are planned to test possible adaptation strategies to yield decreases of such magnitude. The third GCM scenario implied little change. Better GCM simulations of both current climate and of regional predictions of climate change are needed to narrow the uncertainties of crucial importance to rice production in Thailand.

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Table 1. Regional rice production (1984-87).

Region	Season	Area (Ha)	Yield (T/Ha)
THAI RICE			
North Upper	Wet	55,200	2.96
	Off	12,544	3.11
North Lower	Wet	1,484,224	2.14
	Off	65,456	3.69
Northeast Upper	Wet	304,704	1.56
	Off	16,800	3.02
Northeast Lower	Wet	611,408	1.61
	Off	13,872	2.16
Central East	Wet	510,144	1.84
	Off	62,528	3.25
Central Mid	Wet	1,184,256	2.29
	Off	447,824	3.95
Central West	Wet	224,480	2.22
	Off	15,120	3.43
South Upper	Wet	475,040	1.55
	Off	27,152	2.53
South Lower	Wet	111,248	1.61
	Off	3,840	3.37
GLUTINOUS RICE			
North		576,656	2.96
Northeast Upper		196,752	1.54
Northeast Lower		910,976	1.39
Others		24,944	1.85

Representative Sites:
Chiang Mai (N. Upper); Phitsanulok and Nankhon Sawan (N. Lower); Bangkok (C. East).

Table 2. Sites, cultivars, and soil types used in the simulations.

Site	Lat/Long	Rice Cultivar	Soil Type
Chiang Mai	+18.5 N	NSPT	Hd Clay
	+98.6 E	(glutenous)	
		RD 23	Hd Clay
		(long grain)	
Phitsanulok	+16.5 N	RD 23	Wangtong
	+100.2 E	RD 23	Phimai
		RD 23	Hd Clay
		RD 23	Rb Clay
Nankhon Sawan	+15.5 N	RD 23	Np Clay
	+100.1 E	RD 23	Suphan
Bangkok	+13.4 N	RD 23	Rangsit
	+100.3 E	RD 23	Bangkok

Table 3. Validation of the CERES-Rice model for Bangkok.

Yr.	Yield ($t\ ha^{-1}$)		Biomass ($t\ ha^{-1}$)		Season Length (d)	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1985	4.23	4.40	8.93	7.89	93	105
1986	4.53	4.85	9.42	8.58	90	106
1987	4.45	4.77	8.57	8.60	91	99

Locations: Klong Luang, Rangsit, Bangkok
Crop Management Conditions:
Soil type; Rangsit Lowland fine, mixed, acid sulfic Tropaquepts
Planting date: August 15
Start of simulation: July 15
Soil water initial condition: 0.456, 0.456, 0.447, 0.414, 0.414, 0.386
Plant population: 25 plants/m^2

Table 4. Sensitivity analysis of CERES-Rice to climate and CO_2 changes. Simulations are for irrigated production of long-grain Thai rice (BR23).

CHANGES		SIMULATED VARIABLES					
CO_2 level	Temp.	Yield	Season L.	ET	Yield	Season L.	ET
(ppm)	(°C)	(t ha^{-1})	(days)	(mm)	(t ha^{-1})	(days)	(mm)
		Chiang Mai (soil: Hd clay)			Nankhon Sawan (soil: Rb clay)		
330	0	5.09	115	587	4.71	105	572
	2	3.83	105	574	3.62	101	574
	4	2.74	102	574	2.64	103	587
555	0	6.58	115	577	6.16	106	561
	2	5.31	105	569	5.07	101	569
	4	4.29	102	580	4.11	103	595
		Phitsanulok (soil: Hd clay)			Bangkok (soil: Np clay)		
330	0	4.39	104	591	4.63	103	635
	2	3.32	100	594	3.36	97	625
	4	2.44	103	620	2.44	99	642
555	0	5.85	104	582	6.14	103	624
	2	4.84	100	591	4.82	98	621
	4	3.95	103	623	3.91	99	651

Table 5. Effects of climate change on rice yield under GCM climate change scenarios at four sites with different cultivars and soils. Initial soil water was set to characteristic observed values. (DE = direct effects of CO_2 on rice yield included.)

				% CHANGE IN SIMULATED YIELD					
				GCM Scenario Alone			GCM Scenario +DE of CO_2		
Cult.	Soil	Rainfed/ Irrig.	Base Yield	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Site: Chiang Mai			t ha^{-1}						
RD23	Hd clay	Rainfed	2.28	-36	-11	-25	-6	25	10
RD23	Hd clay	Irrig	5.09	-41	-25	-39	-10	6	-10
NSPT	Hd clay	Rainfed	2.24	-34	-11	-25	-7	18	4
NSPT	Hd clay	Irrig	4.93	-29	-12	-28	-2	12	-4
Site: Phitsanulok									
RD23	Wangtong	Rainfed	1.98	-35	-15	-30	-6	23	1
RD23	Wangtong	Irrig	4.38	-41	-26	-36	-6	7	-4
RD23	Phimai	Rainfed	2.61	-39	-16	-31	-11	18	-2
RD23	Phimai	Irrig	4.55	-35	-24	-31	-3	5	-1
RD23	Hd clay	Rainfed	2.28	-38	-16	-31	-11	22	0
RD23	Hd clay	Irrig	4.39	-40	-27	-35	-4	7	-1
Site: Nankhon Sawan									
RD23	Rb clay	Rainfed	3.48	-40	-20	-36	-14	11	-9
RD23	Rb clay	Irrig	4.71	-40	-26	-38	-8	4	-7
Site: Bangkok									
RD23	Np clay	Rainfed	2.58	-42	-16	-47	-14	20	-23
RD23	Np clay	Irrig	4.63	-44	-31	-48	-12	0	-18
RD23	Suphan	Rainfed	2.08	-42	-16	-48	-12	23	-21
RD23	Suphan	Irrig	4.68	-43	-33	-47	-7	-1	-15
RD23	Rangsit	Rainfed	1.83	-44	-17	-48	-10	25	-19
RD23	Rangsit	Irrig	4.93	-37	-29	-43	-11	-2	-18
RD23	Bangkok	Rainfed	2.82	-44	-17	-48	-16	18	-23
RD23	Bangkok	Irrig	4.76	-40	-31	-46	-9	-1	-17

Table 6. Effects of climate change on rice yields under GCM climate change scenarios in four selected sites. The water soil initial conditions were set to characteristic observed values. The results presented are an average of simulations with different soils under irrigated conditions using cultivar RD23 (long grain Thai rice).

Percent Changes in Simulated Yields from Base

	GCM Climate Scenario Alone			GCM Climate Scenario Including the Physiological CO_2 Effects		
Site	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Chiang Mai	-41	-25	-39	-10	6	-10
Phitsanulok	-39	-26	-34	-4	6	-2
Nankhon Sawan	-40	-26	-38	-8	4	-7
Bangkok	-41	-31	-46	-10	-1	-17

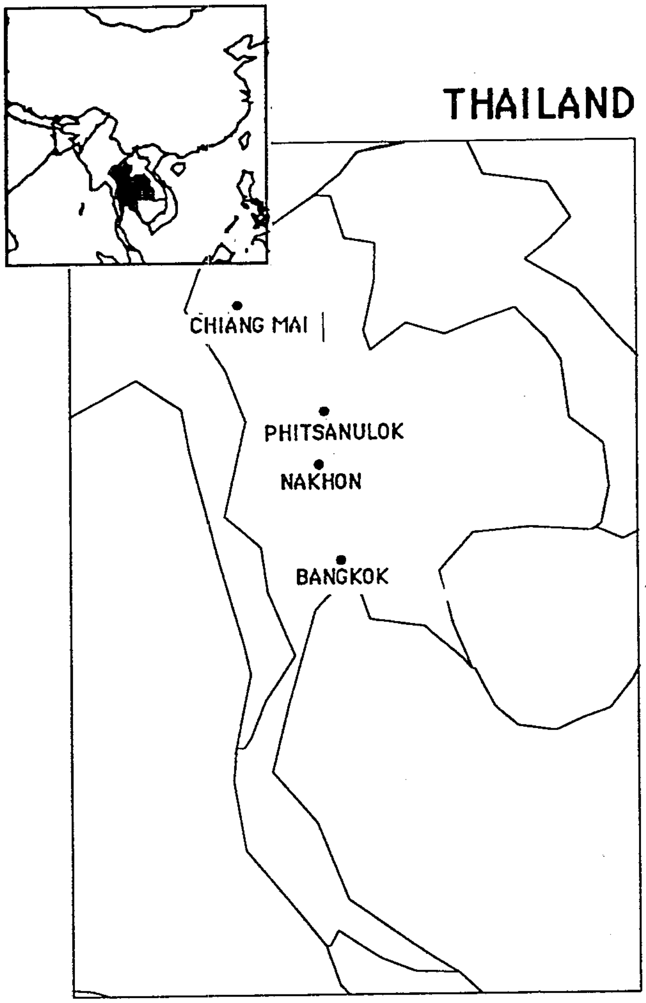

Figure 1. Map of Thailand showing the sites selected for the study.

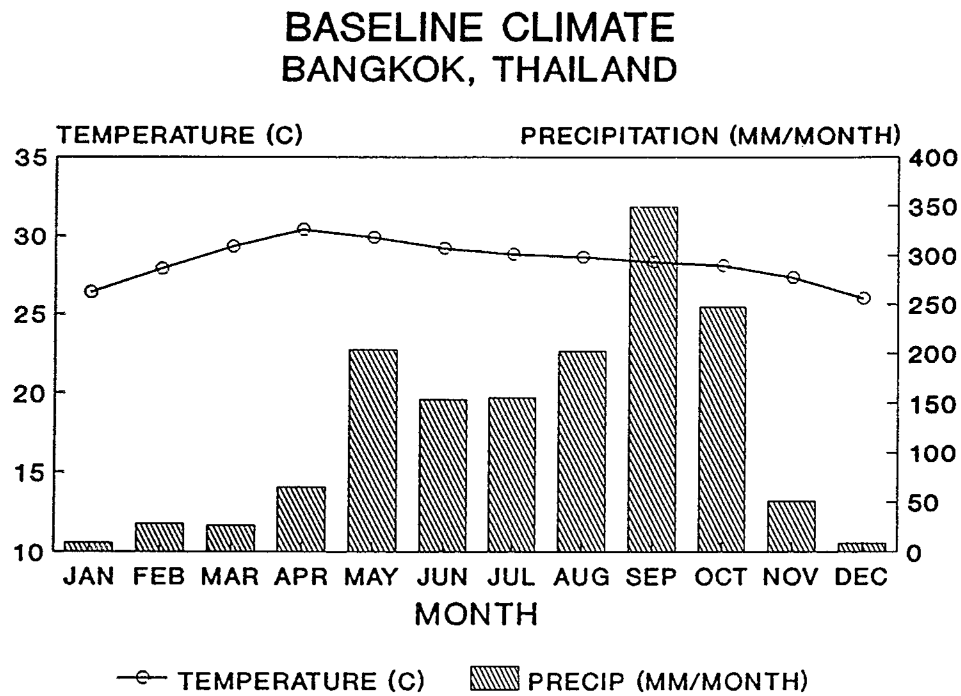

Figure 2. Observed mean monthly temperature and precipitation in Bangkok.

CLIMATE IMPACT ASSESSMENT FOR AGRICULTURE IN THE PHILIPPINES: SIMULATION OF RICE YIELD UNDER CLIMATE CHANGE SCENARIOS

Crisanto R. Escaño and Leandro V. Buendia

Philippine Council for Agriculture, Forestry and Natural Resources Res. and Dev. (PCARRD), Los Baños, Laguna, Philippines

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SUMMARY

This study used General Circulation Models (GCMs) and a crop growth model to estimate the potential impact of climate change on rice yields in two main agricultural regions of the Philippines, represented by the sites of Batac and Los Baños. Projected climate change caused simulated rice yields to decrease at both locations, but the decreases were larger at Los Baños, which has a lower latitude. The decrease in simulated rice yield at these tropical sites was caused primarily by the GCM-projected temperature increases which shorten the crop-growing cycle. When the direct CO_2 effects on crop growth were included in the simulation, the yield losses under the climate change scenarios were completely offset in Batac, but only partially offset in Los Baños. If climate change brings conditions similar to those projected by the GCM scenarios, rice production in Los Baños, an important agricultural region, could be significantly reduced. Testing of possible adaptation strategies to climate change suggested dramatic changes in the cropping patterns of rice and in the agricultural systems of the Philippines.

INTRODUCTION

Rice Production in the Philippines

The Philippines is an archipelago of about 7,000 islands scattered between latitudes 4°30' and 21°30' north and longitudes 116° and 127° east (Figure 1). The islands are located in the humid tropical belt with twelve of the 7,000 islands having individual areas of more than 1,000 km^2. About 50% of the country's 29 million hectares are cultivated lands. Agriculture is considered the economic lifeline of the Philippines. More than 50% of the working population is engaged in agriculture and more than 70% of the foreign exchange earnings are derived from exports of agricultural products. Rice is the staple food of the Filipino people (in 1980 the consumption of rice was 93 kg per capita), and the current population (more than 61 million people) depends on the rice supply from the 3.4 million ha of cultivated rice each year.

The major areas of rice production (Table 1) are in the regions of Ilocos (represented in this study by the site of Batac; 18°03'N and 120°32'E), Cagayan Valley, Central Luzon, and Southern Tagalog (represented in this study by the site of Los Baños; 14°11'N and 121°15'E). Rice management practices vary: 24% of the total area of rice is irrigated during the wet season; 19% is irrigated during the dry season; 38% is rainfed; and 19% is upland rice. The first three practices are included in the "wetland" system and the fourth practice takes place on dry land. Wetland rice production in the Philippines takes place mainly in low-elevation areas (50 m or lower), in a few areas of low-terraced paddies on intermediate upland slopes, and in isolated spots on terraces on mountain slopes. Wetland areas are typically the coastal plain regions, the river basins, and the broad depositional plains. Rice areas on dry land are located on steeper slopes and higher topographic positions.

Fully irrigated wetland rice areas produce two or more crops of rice annually. Partially irrigated wetland rice regions produce one crop of rice a year, and are frequently seeded with dryland crops during the drier part of the year. Dryland rice regions generally produce one rice crop a year, and are seeded with other crops during the drier part of the year. A shift from rice to other dryland crops, or vice versa, is dictated by the relative economic advantages of growing each crop.

Climate Restrictions to Crop Production in the Philippines

Mean annual rainfall ranges from 1,200 mm to 4,600 mm and mean annual temperature at middle- to low-elevation ranges from 25.8°C to 27.9°C. Climatic differences at middle and low elevations are primarily due to rainfall distribution from typhoons and monsoon rains. Agriculture is very vulnerable to climate hazards, such as the occurrence of tropical cyclones and floods, and to the variability in the dates of the rainy season that may cause drought during some periods. A large proportion of the potential rice production is lost each year due to tropical cyclones, floods, and droughts. For example, during the severe drought in 1973, 0.5 million t of potential rice harvest was lost. In 1979 about 1 million t of rice was lost due to floods and typhoons. In January of 1991, the Philippine weather bureau (PAGASA) confirmed that several provinces were hit by a drought related to the "El Niño" oscillation. Only 10 weeks after the onset of the El Niño drought, rice and corn crops suffered estimated damages of $752.8 million.

Scientists predict global climate changes from an increase of atmospheric CO_2 and other gases (IPCC 1990). The objective of this study was to evaluate potential climate change impacts on rice production in the Philippines.

METHODS

Baseline Climate Data

Daily maximum and minimum temperature and precipitation data for the period 1980-89 for Batac and Los Baños were used to estimate 30 years of daily weather data for each location using a weather generator program (Richardson and Wright 1984, Jones et al. 1990).

Climate Change Scenarios

Climate change scenarios were created with the output of three equilibrium GCMs combined with the daily climate data for each site. The GCMs used were: Goddard Institute for Space Studies (Hansen *et al.* 1983), Geophysical Fluid Dynamics Laboratory (Manabe and Wetherald 1987), and United Kingdom Meteorological Office (Wilson and Mitchell 1987). The mean seasonal temperature and precipitation changes projected by the GCM scenarios are presented in Table 2. The mean annual temperatures are projected to increase from 2.1°C to 3.7°C, while annual precipitation is projected to decrease by as much as 14% under the GISS and UKMO scenarios, and to increase slightly under the GFDL scenario.

Transient scenarios were created with the GISS transient model for the decades of the 2010s, 2030s, and 2050s (Hansen *et al.* 1988). The atmospheric CO_2 concentrations considered were 405 ppm, 460 ppm, and 530 ppm, for the respective decades. This study also included a sensitivity test of simulated rice yield to arbitrary changes in temperature (+2°C and +4°C).

Crop Model and Management Variables

Crop model. The simulation of rice growth was performed with the CERES-Rice model developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) (Jones *et al.* 1990, Godwin *et al.* 1992). The CERES-Rice model can simulate increases in photosynthesis and changes in evapotranspiration driven by increases in atmospheric CO_2; these responses are known as the "direct" effects of CO_2 (Acock and Allen 1985).

Cultivars and planting dates. The rice cultivar IR64 was used for the simulation at both sites with an observed growing cycle of 110 to 120 days. The population density was 25 plants m^{-2}; the row spacing was 0.2 m; and the planting dates were May 15 for Batac, and September 15 for Los Baños.

Soils. The parent materials of wetland rice soils are mainly recent alluvium and Pleistocene marine sediments. In the higher topographic positions, the soils are composed of Miocene and Pliocene sediments. The typical soil in Batac is classified as fine, montmorillonitic, isohyperthermic Udorthentic Pellustert; at Los

Baños the typical soil is fine, mixed, isohyperthermic Typic Haplaquoll. The initial soil conditions for the simulation are: (a) soil water initial condition = full; (b) soil pH = 6.8 for all layers; and (c) soil nitrogen amendment = 50 kg N ha^{-1}.

Simulations. Simulations for the GCM scenarios and sensitivity analysis included climate change alone and climate change with the physiological effects of CO_2 (Ackok and Allen 1985) at the two sites. Simulations of possible adaptive strategies were performed under the most unfavorable climate scenario in each location—GFDL for Batac, and UKMO for Los Baños.

Validation of the Crop Model

The CERES-Rice model was validated for Los Baños, comparing simulated parameters to the observed experimental data from the Los Baños Irrigation and Nitrogen Study conducted in 1980 at the International Rice Research Institute. The rice cultivar was IR36, and the observed and simulated yields were closely related (6.57 t ha^{-1} simulated and 6.90 t ha^{-1} observed).

Limitations of the Study

The 30 years of daily weather data used in this simulation study were generated from 10 years of available data. Generated weather data, although statistically comparable with observed 10-year data, may not project the actual daily occurrence of weather events over 30 years. Simulations under irrigated conditions used the automatic irrigation option of the model, but may not represent the actual practice in the Philippines and may lead to overestimated rice yields. However, because all of the simulations were done under the same conditions, the relative changes in yield under the different climate scenarios compared to the base yields may still be considered significant. The rice yields obtained in the simulation are "potential" yields because the simulation considered that nutrients are nonlimiting; weeds, insect pests, and diseases are controlled; and there are no typhoons over the simulated period.

RESULTS AND DISCUSSION

Sensitivity of Simulated Rice Yields to Temperature Increases and CO_2

A temperature increase of 2°C caused decreases in yield at both locations, a 15% reduction in Batac, and a 27% reduction in Los Baños (Table 3). An increase of 4°C above the base temperatures resulted in yield decreases of 27% in Batac and 53% in Los Baños. The physiological effects of CO_2 (555 ppm in the Table) in the +2°C scenario compensated for the yield losses due to the increase in temperatures at both locations. Nevertheless, in the +4°C scenario, the physiological effects of CO_2 only partially compensated for the yield losses, and significant yield decreases were still evident, especially in Batac (-25%).

Rice Yields Under GCM Equilibrium and Transient Climate Change Scenarios

Simulated rice yields decreased under all climate change scenarios in comparison to baseline yields (Table 4 and Figure 2). The largest yield decreases were simulated in Los Baños under the GISS and UKMO scenarios. These yield decreases may be partially a consequence of a shortened crop season due to higher temperatures. In Los Baños, the length of the rice season decreased more than two weeks under the GISS and UKMO scenarios. The shortening of the rice-growing season in Los Baños was also responsible for a decrease in simulated total crop evapotranspiration.

When the direct effects of increased CO_2 (555 ppm) were considered in the simulations with the climate change scenarios, the negative impact of climate change on rice yield was offset in Batac. In Los Baños, the rice yield decreased significantly under the GISS and UKMO scenarios, even when the direct effects of CO_2 were considered.

A linear decrease in yields occurred under the GISS transient scenarios (2010s, 2030s, and 2050s) (Table 5). In Batac, the physiological CO_2 effects offset the yield decreases, but not in Los Baños.

Adaptation Strategies to Climate Change

Because our results indicated taht climate change may cause decreases in rice yields in some regions in the Philippines, we considered possible adaptation strategies. The strategies were evaluated under the most severe climate change scenario (the one that resulted in the largest yield decreases) for each site: GFDL in Batac, and UKMO in Los Baños. We tested a range of rice cultivars and various planting dates. Table 6 shows the results of the adaptation simulation strategies; all simulations include the direct CO_2 effects on rice yields.

In Batac, planting rice one month earlier increased simulated rice yield of all cultivars tested under the GCM climate change scenario. In Los Baños, the optimum planting date of the original cultivar (IR64) under climate change conditions was one or two months earlier than the current planting date. The highest simulated yields under climate change conditions for Los Baños were obtained by planting the cultivar IR43 one or two months before the current planting date.

September is currently the recommended planting month for rice in Los Baños for the dry season. September planting dated allow a farmer to harvest rice 4-5 times in two years. If climate conditions force farmers to plant earlier, the rice cropping pattern could be dramatically affected. Additional problems may arise when shifting the crop calendar. For example, in Batac, farmers report that a July planting date may not be appropriate for rice because strong winds in October and November affect the grain-filling stage. Thus, additional climate factors such as wind need to be considered in the development of adaptation strategies.

These adaptation experiments suggest that the negative impact of climate change on rice yields can be overcome by planting earlier and changing cultivars, but they also imply major changes to the current farming system of the Philippines. Such changes may lead to widespread and varied alterations in rural regions.

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Table 1. National and regional rice production in the Philippines (1980-89).

Region	Area ha x1000	Production t x1000	Yield T/Ha
CAR	78	170	2.21
Ilocos * BATAC	299	725	2.42
Cagayan Valley	324	826	2.64
Central Luzon	472	1,461	3.09
S Tagalog * LOS BAÑOS	378	869	2.30
Bicol	310	646	2.08
W. Visayas	464	1,112	2.40
C. Visayas	110	158	1.45
E. Visayas	198	370	1.86
W. Mindanao	136	321	2.36
N. Mindanao	120	325	2.71
S. Mindanao	186	558	3.03
C. Mindanao	243	706	2.90
NATIONAL	3,317	8,246	2.49

*Sites modeled

Table 2. Seasonal and annual temperature and precipitation changes in the GCM climate change scenarios.

SITE/ Season	Temperature changes (°C)			Precipitation changes (%)		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
BATAC						
Winter	2.3	4.3	3.0	-33	-12	31
Spring	3.0	2.4	0.9	-17	3	-49
Summer	2.7	2.5	2.3	-25	37	-9
Fall	3.5	2.3	3.1	20	-13	12
Annual	2.9	2.9	2.3	-14	4	-2
LOS BAÑOS						
Winter	3.3	2.5	4.2	13	-40	-13
Spring	3.2	2.1	4.0	11	13	-27
Summer	3.2	2.1	2.9	-47	27	-5
Fall	3.8	1.7	3.5	10	25	7
Annual	3.4	2.1	3.7	-5	6	-5

Table 3. Sensitivity of simulated rice yields to temperature increases and CO_2.

SITE	TEMPERATURE CHANGE	SIMULATED YIELD ($t\ ha^{-1}$) Climate Scenario Alone (330 ppm CO_2)	Climate Scenario + P.E. of CO_2 (555 ppm CO_2)
Los Baños	0 (base)	5.92	7.01
	+2°C	5.03	6.23
	+4°C	4.34	5.59
Batac	0 (base)	4.03	5.34
	+2°C	2.92	4.12
	+4°C	1.89	3.00

P.E. - Physiological effects of CO_2: the direct beneficial effects of 555 ppm CO_2 on rice yield are included in the simulation.

Table 4. Simulated yield, season length, and evapotranspiration (ET) under GCM climate changes scenarios.

		SIMULATED YIELD (t ha^{-1})		Simulated	Season	Simulated
SITE	SCENARIO	Scenario Alone (330 ppm CO_2)	Scenario + PE of CO_2 ppm CO_2	(days)	(mm)	(mm)
Batac	BASE	5.91	7.19	121	1,659	586
	GISS	4.99	6.19	118	1,263	637
	GFDL	4.93	6.11	118	2,151	631
	UKMO	5.51	6.77	118	1,409	343
Los Baños	BASE	3.86	5.15	120	928	421
	GISS	2.09	3.22	103	1,057	402
	GFDL	2.75	3.91	109	982	409
	UKMO	2.04	3.14	103	983	403

P.E. - Physiological effects of CO_2.

Table 5. Simulated rice yields under the GISS transient scenarios and the GISS equilibrium scenario.

		SIMULATED YIELD (t ha^{-1})	
SITE	SCENARIO	Scenario Alone	Scenario + P.E. of CO_2*
Batac	BASE	5.91	--
	GISS 2010s	5.49	5.86
	GISS 2030s	5.31	6.03
	GISS 2050s	4.81	5.86
	GISS	4.99	6.19
Los Baños	BASE	3.86	--
	GISS 2010s	3.21	3.58
	GISS 2030s	2.82	3.54
	GISS 2050s	2.12	3.20
	GISS	2.09	3.22

* See METHODS for the CO_2 levels under each scenario.

Table 6. Effect of changes in rice cultivar and planting dates on rice yields simulated with the CERES-Rice model under base climate and GCM climate change scenarios.

Site	Scenario	Cultivar	Planting Date	SIMULATED YIELD t ha^{-1}
Batac	BASE	IR 64	May 15	5.91
	GFDL	IR 64	May 15	6.11
	GFDL	IR 64	Apr 15	6.48
	GFDL	IR 64	June 15	5.75
	GFDL	IR 43	May 25	6.42
	GFDL	IR 43	Apr 15	6.83
	GFDL	IR 43	June 15	6.19
	GFDL	UPLR 15	May 15	5.01
Los Baños	BASE	IR 64	Sept 15	3.86
	UKMO	IR 64	Sept 15	3.14
	UKMO	IR 64	Aug 15	3.93
	UKMO	IR 64	July 15	4.87
	UKMO	IR 64	Oct 15	2.69
	UKMO	IR 43	Sept 15	3.39
	UKMO	IR 43	Aug 15	4.17
	UKMO	IR 43	July 15	5.03
	UKMO	IR 43	Oct 15	2.79
	UKMO	UPLR 15	Sept 15	2.02

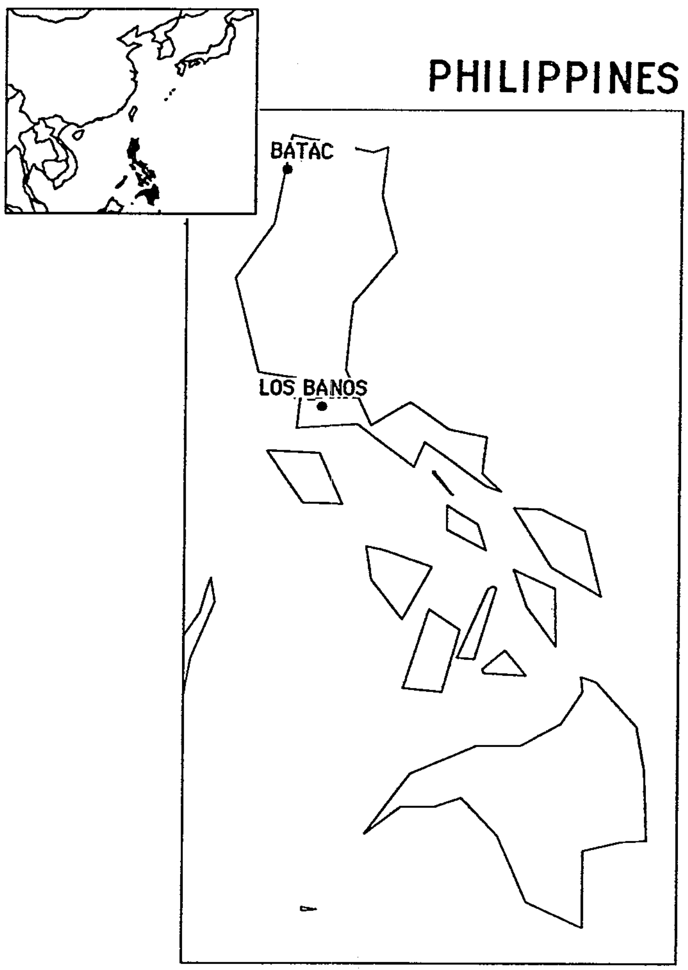

Figure 1. Map of the Philippines and location of the sites selected for the simulations.

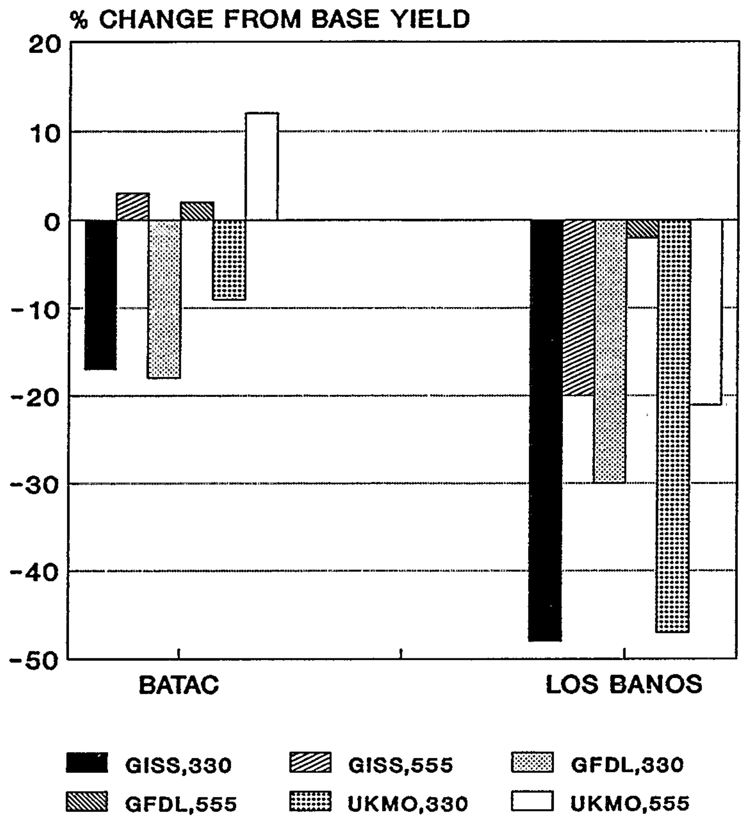

Figure 2. Simulated rice yield changes under GCM climate change scenarios.

EFFECTS OF CLIMATE CHANGE ON RICE PRODUCTIONAND STRATEGIES FOR ADAPTATION IN SOUTHERN CHINA

Zhiqing Jin, Daokou Ge, Hua Chen, and Juan Fang

Department of Agrometeorology
Jiangsu Academy of Agricultural Sciences
People's Republic of China

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SUMMARY

The CERES-Rice model was calibrated and validated for nine sites in Southern China to examine its suitability to model rice production in the region, using agronomic data from three or more successive years. After determining the genetic coefficients for the cultivars, the CERES-Rice model was run a second time for the same locations for a time period of 20-30 years. The model used local climate data (1958-86) and doubled-CO_2 climate change scenarios generated from the GISS, GFDL, and UKMO General Circulation Models (GCMs), with and without supplemental irrigation (to model paddy and upland rice, respectively). This study assessed the direct physiological effects of CO_2 on rice growth for each scenario. Finally, the study examined several strategies for adapting rice production to climate change.

The results of the study are listed below. They should not be regarded as predictions, but as plausible assessments of the potential effects of climate change on rice production in Southern China.

(1) Climate change alone

Simulated rainfed rice yields decreased under climate change alone due to increases in temperature that shorten the growing season for rice. For some sites, however, sharp decreases in precipitation were also an important factor in the decreased yield of rainfed rice.

Rice yields simulated under "automatic" irrigation also decreased. Although irrigation did not fully compensate for the negative effects of climate change, it significantly improved simulated rice yields, especially in regions where precipitation decreased under climate change conditions.

(2) Climate change with the direct effects of CO_2.

In rainfed rice, the direct effects of CO_2 compensated for the negative effects of climate change alone in most sites, except in sites where rainfall sharply decreased in the climate change scenarios.

In irrigated rice, the three GCM scenarios produced increases in modeled rice yields in comparison with the baseline yields in the northern sites, but decreases in the central and southern sites. These findings suggest that there is less compensation by the physiological effects of CO_2 in areas with high temperature.

(3) General results.

Simulated irrigated rice yields are higher and have less year-to-year variability than rainfed yields.

Under all climate change scenarios studied, the amount of water needed for automatic irrigation greatly increased in areas where precipitation sharply decreased.

Evapotranspiration (ET) for rainfed rice was usually less than that for automatic irrigated rice. Therefore, cultivation of upland rice may be extended into areas where irrigation water is not available.

An increase in temperature would increase China's rice-based cropping system. The northern limits for double-rice and triple-rice cropping systems could be moved northward about 5-10 degrees of latitude, depending on the climate scenario.

Introducing upland rice cultivars to areas where precipitation sharply decreased under the climate change scenarios significantly improved rainfed rice yields at some sites, but not at others.

For paddy rice, adjusting planting dates ameliorated the negative effects of climate change on modeled yields in the northern part of the study region, but not in the southern part.

INTRODUCTION

Since 1949, China has made great progress in food production. With only 9% of the world's cultivated land, China supports more than one-fifth of the world's population. However, with increasing population, a sharp decrease in cultivated land, lack of water resources, environmental pollution, and frequent natural disasters, it is difficult for China to continue to increase its food production.

Recently, scientists have suggested that the addition of greenhouse gases to the atmosphere will alter global climate, increasing temperatures and changing rainfall and other climate patterns (IPCC 1990). The combined effects of climate change and physiological effects of CO_2 on crops may result in a net increase in crop yields in some cases, especially in the high latitudinal regions. In low latitudes, agriculture could be negatively affected (Parry *et al.* 1988).

The objective of this study is to characterize the direction, magnitude, and degree of uncertainty of the potential impacts of global climate change on rice production in Southern China. This study is important because: (1) China is the largest rice producer and consumer in the world; (2) Southern China plays an important role in the nation's rice production; and (3) Southern China appears to be more vulnerable to climate change than the more northern regions of China (Jin *et al.* 1990).

The study is based on simulations with the CERES-Rice model. The model used actual daily weather data (about 30 years) from nine sites in seven provinces of Southern China (Figure 1) and regional climate change scenarios generated from General Circulation Models (GCMs). Rice growth is simulated for both rainfed and automatic irrigation conditions to represent some mountain rice areas without irrigation and the plains rice areas with an extensive irrigation system. Changes in rice yield, growth duration, evapotranspiration, and irrigation are estimated under baseline and climate change conditions. The physiological effects of CO_2 are also analyzed under each scenario.

The results of this study should be considered as indicators of the possible impacts of global warming.

Agroecological System

Southern China is subject to the influence of the monsoonal wind system of eastern Asia, which makes the climate wet and hot in the summer, and cold and dry in the winter. Ample rainfall combined with high temperatures and high intensity of solar radiation during the rice-growing season are generally favorable conditions for rice production.

About 1,000 rivers and more than 200 large lakes provide a copious irrigation system, and rich soil and intensive farming have made this region one of the world's greatest centers of rice production. Nevertheless, some unfavorable climate events constrain rice production. Summer and autumn droughts are rather common, and typhoons, floods, and heat waves occur frequently.

The topography in Southern China is varied and complex. Altitude drops from west to east, leaving only about 15% of the land for agricultural purposes. Consequently, the farmers must adopt a multiple-cropping system.

Southern China is comprised of 16 provinces: Anhui, Fugian, Guangdong, Guangxi, Guizhou, Hainan, Hubei, Hunan, Jiangsu, Jiangxi, Sichan, Taiwan, Tibet, Yunnan, Zhejian, and Shangai. Rice is the most important crop in all of them, except in Tibet.

Southern China can be divided into four rice subregions: the Middle and Lower reaches of the Yanzi River; the Southwest; South China; and the Yellow-Hui Rivers valleys. Table 1 shows information on land use and rice production for each subregion.

Literature Review

The impacts of 2xCO_2 climate change on agricultural crops have been studied mainly by scientists from developed countries. In North America, Robertson et al. (1987) analyzed the impacts of climate change on yields and soil erosion for selected crops in the Southern U.S., Central Prairie, and Northern Plains using the Erosion Productivity Impact Calculator (EPIC); Allen *et al.* (1987) reported that the soybean yield could increase about 32% with a doubling of CO_2; Smit (1989) studied how crop yields in Ontario (Canada) would be affected by climate change (GFDL and GISS scenarios); and Jones *et al.* (1986) used the Soybean Integrated Crop Management (SICM) model to estimate potential changes in earworm damage to soybean under climate change scenarios, concluding that earworm damage may increase in the Grain Belt region under a warmer climate. Using an agroclimatic approach, Rosenzweig (1990) suggested that the wheat cultivars in the Southern Great Plains would change from winter to spring wheats due to the lack of cold winter temperatures under the climate change scenarios, and that climate change would bring about an increased demand for irrigation.

The CERES and Soygro models have been widely used in the US: in the Great Lakes (Ritchie *et al.* 1989), the Southeast (Peart *et al.* 1989) and Great Plains (Rosenzweig 1990), to simulate change in crop yields under different climate change scenarios. Rosenzweig (1990) characterized the direction, magnitude, and uncertainty of potential climate change-induced alterations in wheat and corn yields. The study suggested that adjusting the planting dates of winter wheat and corn would not significantly ameliorate the negative effects of climate change and that change of cultivars only could be a possible adaptation strategy to compensate for yield loss at some selected sites but not others. Her study also analyzed the direct effects of CO_2 on crops (i.e. increased photosynthesis and improved water use efficiency). Ritchie et al. (1989) suggested that climate change induced maize yield reductions in the Great Lakes could be partly compensated by using new cultivars with a longer growing cycle. Parry et al. 1988 reported possible yield decreases of rice in India, and some increases in Japan under climate change conditions; Parry *et al.* (1988) reported that climate change may cause rice yield to decrease in Thailand.

At the present time there is no published comprehensive study that evaluates the potential impacts of climate change on large-scale rice production in China and that includes the beneficial direct effects of CO_2 on rice production.

METHODS

Climate Data

Daily climate data (maximum and minimum temperatures, precipitation, and solar radiation) for a period of 20-30 years (about 1957-1986) were taken from the Monthly Report of Chinese Meteorological Record on the Surface (China Meteorological Bureau) and the Daily Solar Radiation Record of China (Beijing Meteorological Bureau). The daily solar radiation at Xuzhou was not available and was calculated according to Gao and Lu (1982).

Climate data for the calibration and validation experiments were collected from the local meteorological stations in the following institutions: China National Rice Research Institute, the National Academy of Agricultural Sciences, Guangdong Academy of Agricultural Sciences, Jiangxi Agricultural University, Jiangsu Agricultural Bureau, Jiangsu Academy of Agricultural Sciences, Shaoguan Prefecture

Institute of Agricultural Sciences in Guangdon province, and Lixiahe Prefecture of Agricultural Sciences in Jiangsu province.

Climate Change Scenarios

Mean monthly temperature differences, precipitation and solar radiation ratios ($2xCO_2/1xCO_2$ GCM-generated climate) were combined with daily historic climate data to generate climate change scenarios for the various sites. The GCMs used were: Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1987); Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987); and United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987).

GCMs have several advantages over other approaches for creating climate scenarios (Smith and Tirpak 1989): (1) the models estimate how global climate may change in response to increased CO_2, and therefore, regional outputs are internally consistent with global warming associated with doubled CO_2; (2) the climate variables estimated are in agreement with physical laws; and (3) the GCMs provide the information necessary to run the crop simulation models.

GCMs, however, have some disadvantages: (1) the ocean models currently used in most GCMs are relatively simple (most GCMs treat oceans as "swamps" or only simulate their upper layers); (2) they have low spatial resolution and do not provide a good representation of major geographic features, such as plateaus, mountains and basins, which have large impacts on local climate; and (3) GCMs include some simplified assumptions about other factors, such as cloud cover, albedo, and the hydrology of the land surface.

Table 2 presents annual mean temperature and precipitation changes generated by the GISS, GFDL, and UKMO scenarios for different locations in Southern China.

CERES-Rice Crop Model

The CERES-Rice model (Godwin *et al.* 1992; IBSNAT 1989; Alocija and Ritchie 1988) was used for the study. The model simulates yield and other parameters of crop growth and development under different management and climatic conditions.

The CERES-Rice model was chosen because (1) it simulates the effects of major factors, such as climate and soil management, on rice growth, development, and yield; (2) the model also simulates the direct effects of CO_2 on crop photosynthesis and evapotranspiration; (3) the genetic coefficients that are used to characterize the different cultivars can be calibrated based on the experimental data; and (4) the model has been available and documented for several years and has been validated under a wide range of soil and climatic conditions.

Management Variables and Soils

Crop data of the local rice cultivars (sowing date, soil type, sowing depth, transplanting density, row spacing, maturity date, biomass, and grain yields) were taken from local field experiments. The following institutions provided data: China National Rice Research Institute, the National Academy of Agricultural Sciences, Guangdong Academy of Agricultural Sciences, Jiangxi Agricultural University, Jiangsu Agricultural Bureau, Jiangsu Academy of Agricultural Sciences, Shaoguan Prefecture Institute of Agricultural Sciences in Guangdon province, and Lixiahe Prefecture of Agricultural Sciences in Jiangsu province. Table 3 lists the main rice production areas of Southern China, the sites selected for the study, the local rice cultivars used for modeling, and the soil types at the various sites.

Soil data included soil type, albedo, organic matter, texture, structure, and bulk density. Representative soil types and profiles were chosen according to the *Soil Atlas of China* (Institute of Soil Science 1986) and

Chinese Soils (Xiong Yi and Li Qingkui 1988).

Calibration of Genetic Coefficients

Eight genetic coefficients define a rice cultivar in the CERES-Rice model and characterize quantitatively how that particular rice cultivar responds to environmental factors such as climate, management, and soils. The genetic coefficients for the rice cultivars used in this study were determined by contrasting the simulated results to local field experimental observations, and included growth duration, dry-matter accumulation (if available), and yield. The management variables (planting date, plant density, and spacing, etc.) for each calibration site were taken from the field experiments and local climate data for the calibration years was used. The specific genetic coefficients of a local cultivar were determined by trial-and-error so that the simulated yield and maturation date were as close as possible to the observed values.

Simulation Scenarios

The three GCM climate change scenarios were simulated at each site, and each simulation was completed under rainfed and irrigated conditions. Automatic irrigation was done to provide the crop with a nonlimiting water situation, which is similar to practice. Since the climate change scenarios involve an equivalent doubling of CO_2, the physiological CO_2 effects on crop yield and water use were also included in simulations at each site (indicated as 555 ppm CO_2 in the tables).

In addition, the study evaluated the possible adaptive strategies to rice management under future climate. Scenarios were created by altering current agricultural practices in order to maximize yields under the conditions of climate change.

Crop Index

A Crop Index has been used to evaluate different cropping systems in China (Gao *et al.* 1987). Possible changes in the index were analyzed by using simulated rice growth output under climate change conditions.

According to Gao *et al.* (1987), the rice growing season in China is defined as the number of days from the safe sowing date to the safe maturity date. It is also equal to the number of days from the safe sowing date to the safe heading period, plus 40 and 30 days for the Japonica and Indica varieties, respectively. The safe sowing date is defined as the time when the mean daily temperature is constantly above 10°C and the safe heading period is defined as the time when the mean daily temperature is above 20°C, with no temperature lower than 20°C for three consecutive days. Based on this index, it is easy to compute the lengths of the growing season for rice under the current climate and for the three GCM climate change scenarios, and to evaluate the changes in rice cropping systems in the future.

According to the China National Rice Research Institute (1988), a value of the accumulated temperatures above 10°C for different rice-based cropping systems is:

(1) 2,000°C to 4,500°C for single-rice cropping;
(2) 4,500°C to 7,000°C for double-rice cropping (the northern limit for double-rice is 5,300°C); and
(3) more than 7,000°C for triple-rice cropping.

These thermal values can also be used to estimate potential changes in the rice cropping systems under climate change scenarios.

RESULTS AND DISCUSSION

Impacts on Rice Yields

Doubled CO_2 climate change would directly influence rice yields through physiological processes and indirectly through climate.

Climate Change Alone. The simulated rice yields decreased under the three scenarios at all locations. Under the GISS scenario, rainfed yields decreased significantly (10%-78%) from baseline yield (Table 4). Under the GFDL and the UKMO scenarios, yields decreased 6%-33% and 7%-34%, respectively. The yield decreases were a result of the higher temperature under the climate change scenarios which shortened the growing cycle of rice and also caused water stress in some regions. More severe yield decreases (-78% at Chengdu) under the GISS scenario were due in part to significant growing season precipitation decreases. For example, the July rainfall at Chengdu under the GISS scenario declined 90% in comparison with the current rainfall, resulting in a growing season with total rainfall of less than 400 mm (Jin *et al.* 1990). Although the enhancement of respiration due to high temperatures may be another reason to decrease rice yields, it was not taken into account in the CERES-Rice model.

The automatic irrigation simulations under the three climate change scenarios also resulted in decreases in rice yields in comparison with the base data at all sites (Table 4): 15%-33% under the GISS scenario; 14%-37% under the GFDL scenario; and 19%-33% under the UKMO scenario. These results indicate that full irrigation did not completely offset the negative effects of increases in temperature on rice yields because of the shorter rice growth duration, particularly of the grain-filling stage. Nevertheless, the negative effects of climate change on rice yields were partially offset by full irrigation at the sites where the rainfall during the rice growing season greatly decreases under the climate change scenarios. For example, at Chengdu and Guangzhou under the GISS scenario, rainfed yields decreased 78% and 45%, respectively, and the irrigated yields declined only 32% and 16%. These results suggest that an effective strategy for adapting to climate change would be to improve the irrigation systems in such regions.

Table 4 also shows that the standard deviations of the percent yield changes—an indication of the variability (Rosenzweig 1990)—of irrigated rice yields were much lower than the standard deviations of rainfed rice yields.

Climate Change with Physiological CO_2 Effects. Table 5 shows the physiological effects of CO_2 on crop yield and water use under the climate change scenarios. Under the GISS scenario, rainfed rice yields increased at the northern sites (Xuzhou and Nanjing) and the eastern sites (Fuzhou and Nanchang). At these sites, the scenario precipitation was not a limiting factor on rice production. In Wuhan, Changsha, and Shaoguan, the direct effects of CO_2 ameliorated, to a certain degree, the negative effect of increased temperature on rainfed rice yield. However, in Chengdu and Guangzhou, because of large decreases in precipitation during the rice growing season, the yields remained significantly lower than base case yields, even with the direct effects of CO_2. In these two southern sites, the GISS scenario yields were very low in comparison with the baseline, and there were very small differences in yields simulated with and without CO_2 physiological effects (Table 4). Under the GFDL and UKMO scenarios, the direct effects of CO_2 largely compensated for the climate change impacts on rice yields in many but not all sites.

In the irrigated simulations, rice yields declined in the central-southern region (Nanchang, Changsha, Wuhan, and Shaoguan) under the three climate change scenarios (Table 5). This was a result of the large annual temperature increases projected by the GCMs in that region (4°C-7°C). In contrast, the direct effects of CO_2 resulted in an increase of the modeled irrigated yield at Xuzhou under the three climate change scenarios. These results suggest that increased temperatures would benefit rice production in the northern areas of the studied region.

As in the case of climate change alone, the yield stability (standard deviation) under the rainfed conditions was less than that under irrigated conditions.

Impacts on Season Length

The increment of temperature under all climate change scenarios caused the rice growth duration to decrease at all sites (Table 6). In the northern areas (Xuzhou, Nanjing, and Chengdu), the mean rice growth duration decreased more than in the southern areas. Because the current temperatures in the northern sites are relatively low, rice has a long growing period which is more sensitive to the temperature increase projected by the GCM climate change scenarios. In contrast, the current temperatures at the southern sites already cause the rice crop duration to be very short, and a further increase in temperature did not have a very large effect on simulated growth duration. The physiological effects of CO_2 do not influence season length, as simulated with the CERES-Rice model.

Impacts on Irrigation

An adequate water supply is one of the most important factors in rice production. The amount of irrigation required for rice depends on many factors, such as growing season rainfall, temperature, solar radiation, and evapotranspiration (Table 7), as well as crop and soil characteristics, depth of water table, and topography. Among these factors, rainfall is the most important. Table 8 shows the percent change in irrigation demand for rice under the climate change scenarios, including the direct effects of CO_2. Simulations were done with automatic irrigation (100% efficiency of application and availability of water).

Under the GISS scenario, the demand for irrigation rose at six of the nine sites. At Chengdu and Guangzhou, the irrigation demand increased six and two times, respectively, over the present levels. This increase was caused by large decreases in the summer rainfall and increases in temperature and solar radiation.

Under the GFDL scenario the irrigation demand decreased in most sites where precipitation during the local rice growing season increases. Under the UKMO scenario irrigation demand results were mixed: they increased in the sites where projected precipitation decreased, and increased at the rest of the sites.

Impacts on Cropping Systems

Under all the doubled CO_2 scenarios, the temperature, as well as the >10°C accumulated temperature index, increased and could result in an extension of the growing season for rice over large areas of Southern China. However, the increased temperature shortened the simulated lifecycle of rice and had a negative impact on yields. The combined effects of a prolonged growing season and shortened growth duration would shift the northern limits of the various rice-based cropping systems towards higher latitudes. As a result, the Crop Index in China would increase and the varieties and management systems would have to be adjusted to the new conditions.

The current climatic classification for rice production in China would no longer be applicable under climate change conditions. Table 10 lists the onset of the rice cropping season, length of the growing season, and the >10°C accumulated temperatures during the rice growing season at selected sites. Under the GISS scenario, the rice maturity dates in China advanced by an average of 19 days, the length of the rice growing season was prolonged by an average of 45 days, and the 10°C accumulated temperature increased by an average of 1,522°C. Figure 2 shows the northern limits for double- and triple-rice crops.

According to the GISS scenario, the thermal conditions at Beijing were more favorable for rice than the current thermal conditions at Nanjing, and it would be suitable to grow rice after wheat. The thermal conditions at Shenyang would be more favorable than those at Beijing, without any low temperature problems to sustain the growth pattern of the three crops in two years. In the most northern area of China, Harbin, the >10°C accumulated temperature would reach 3,696°C, with a rice-growing season of 159 days, and it would be safe to grow single-rice; early Japonica with a late maturity date.

Similar results were obtained with the GFDL scenario since the temperature scenario increases are comparable to those under the GISS scenario. The UKMO scenario resulted in an extreme situation: the northern limit for double-rice would shift to the Shenyang region, and that for the triple-rice would move to a line extended from Jinan to Zhengzhou. In the southern parts of China, triple-rice could be grown throughout the year.

Currently, Indica rice varieties are grown in the south and Japonica varieties in the north. With climate change, the patterns of rice varieties used throughout China would shift and the traditional practice of "South Indica" and "North Japonica" would no longer hold. The high-temperature-tolerant varieties would not only dominate in the southern parts of China, but would be likely to be more widely used in the north.

Based on the above analysis, a $2xCO_2$ climate change would result in a tremendous change in China's thermal conditions. Therefore, effective strategies for adapting to climate change need to be developed, such as improving crop breeding (especially the use of biotechnology to develop more heat- and drought-resistant rice varieties); expanding the use of chemical fertilizers, pesticides, and herbicides; and improving irrigation systems. These strategies might be quite costly, as they imply an increase in agriculture-related inputs.

Adaptation Strategies

This section presents and discusses some possible strategies for adaptation to climate change. The GISS scenario was chosen because it had the most negative effects on crop yield. All adaptation simulations included the physiological effects of CO_2 was analyzed (Table 9).

Using crop model simulations, the following strategies for adaptation to climate change were evaluated.

Change in rice cultivar. This strategy considers whether new cultivars would improve rice yield under climate change conditions. An upland rice cultivar (UPLR15) was simulated at the sites where precipitation declined dramatically under the scenario conditions (Chengdu and Guangzhou) (Table 9). With the new cultivar, the yield at Chengdu increased in comparison with the yield of the originally used cultivar. Compared with the baseline yield the decrease under climate change conditions was still significant (-54% with the new cultivar and -72% with the original cultivar). At Guangzhou, however, introducing the same cultivar did not improve the yield under the scenario conditions at all.

The cultivar IR43 was simulated at seven locations. At five sites (Nanchang, Fuzhou, Xuzhou, Changsha, and Wuhan), the yields of the new cultivar were higher that those of the original cultivar under the conditions of climate change. In the other two sites (Nanjing and Shaoguan), the change of cultivar did not improve modeled yields.

Adjusted planting dates. Changes in the planting dates (by 10 day intervals) of the present cultivars may increase yields under the climate change conditions. Changing the planting date caused rice yields to increase at the northern sites (Xuzhou and Nanjing), but not at the southern sites.

Changes in both cultivars and planting dates. Rice yields increased significantly when a combination and change in planting date was simulated at six of the seven locations tested (all except Nanjing). The yield increases ranged from +3% to +43%, and the mean increase was +22% (the calculations assume equal area).

Improvement of the irrigation system. Yields simulated under rainfed and irrigated conditions were compared at each site to determine if irrigation may mitigate the negative effects of high temperatures on yields.

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Table 1. Regional contribution to rice production in China (1980-86).

Regions [1]	Contribution to Total Rice Production [2]	Contribution to Total Rice Area
	(%)	(%)
Yangzi River	69.9	68.1
South China	15.7	17.7
South West China	7.6	7.8
Yellow and Huir	6.0	6.0

[1] Study sites includes in each region: Nanjing, Whuan and Changsha in Yangzi River Region; Fuzhozi, Sshaoguan and Guangzou, in South China Region; Chengdou in South West China; Xuzhou and Xiam in Yellow and Huir Region.
[2] National Rice Production in China: 32,975,000 ha, 161,770,000 t, 4.92 t ha^{-1} (average yield).

Table 2. Annual temperature changes (°C) and precipitation differences (%) projected by the GISS, GFDL and UKMO climate change scenarios for sites in southern China.

	Temp. Diff. (°C)			Precip. Diff. (%)		
Site	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Nanjing	4.1	4.6	6.5	43.7	9.3	13.1
Xuzhou	4.1	4.7	6.5	45.2	4.6	14.0
Nanchang	3.5	4.4	5.7	17.8	34.9	0.5
Wuhan	6.0	4.4	6.5	-9.1	35.0	12.3
Changsha	6.0	4.4	5.7	-7.3	30.3	-0.6
Chengdu	4.7	3.2	6.7	-20.4	89.1	34.0
Fuzhou	3.5	4.2	5.7	18.6	-11.4	1.6
Shaoguan	6.0	4.0	3.3	-7.5	6.8	26.2
Guangzhou	3.5	4.0	3.4	79.9	9.3	31.8

Table 3. Representative rice cultivars and soil types.

Region	Site	Latitude	Cultivar	Soil type
Yellow & Huir	Xuzhou	34°19' N	Y.G.#2	Fluoro-aquic
Yangzi R. Valley	Nanjing	32°00' N	S.U.#63	Yellow brown loam
	Nanchan	28°36' N	W.U.#64	Red earth
	Wuhan	30°37' N	Z.X.#26	Yellow brown loam
	Changsha	28°12' N	Z.X.#26	Red earth
South West	Chengdu	30°40' N	G.C.#2	Yellow earth
South China	Fuzhou	26°05' N	G.L.A.#4	Red earth
	Shaoguan	24°48' N	S.U.G.#33	Lateric red earth
	Guangzhou	23°08' N	G.C.#2	Lateric red earth

Table 4. Simulated yield changes (% of base yields) under GCM climate change scenarios without the direct effects of CO_2.

	RAINFED						AUTOMATIC IRRIGATION					
	GISS		GFDL		UKMO		GISS		GFDL		UKMO	
Site	Y	SD[1]	Y	SD	Y	SD	Y	SD	Y	SD	Y	SD
Nanjing	-20	10	-33	10	-33	10	-17	4	-20	4	-20	4
Xuzhou	-10	8	-31	8	-23	8	-15	3	-18	3	-19	3
Nanchang	-23	12	-5	14	-35	12	-24	4	-19	4	-33	4
Wuhan	-27	8	-14	9	-28	9	-22	5	-26	5	-26	5
Changsha	-27	12	-6	13	-11	13	-33	5	-37	5	-31	5
Chengdu	-78	5	-14	2	-28	3	-32	2	-14	2	-20	2
Fuzhou	-21	15	-19	6	-18	6	-28	5	-25	5	-27	5
Shaoguan	-33	9	-22	9	-8	10	-25	5	-30	5	-26	5
Guangzhou	-45	12	-27	4	-25	4	-16	4	-21	4	-22	4
Mean	-31	9	-21	7	-21	8	-24	4	-21	4	-24	4

[1] expressed as %

Table 5. Simulated yield changes (% of base yields) under GCM climate change scenarios with the direct effects of CO_2 included in the simulation.

	RAINFED						AUTOMATIC IRRIGATION					
	GISS		GFDL		UKMO		GISS		GFDL		UKMO	
Site	Y	SD[1]	Y	SD	Y	SD	Y	SD	Y	SD	Y	SD
Nanjing	4	11	-13	11	-12	11	3	4	-2	4	-2	4
Xuzhou	20	15	-9	8	3	8	6	3	2	3	1	3
Nanchang	2	14	39	15	-13	13	0	5	4	4	-11	4
Wuhan	-9	10	11	10	-6	10	-3	6	-5	6	-5	6
Changsha	-2	13	27	14	21	14	-12	6	-15	6	-9	6
Chengdu	-72	2	4	3	-3	4	-6	3	3	3	3	3
Fuzhou	5	7	7	7	10	7	-4	6	0	6	-3	5
Shaoguan	-14	10	5	10	9	10	-3	5	-7	6	-5	4
Guangzhou	-32	5	-6	4	19	4	3	4	-2	6	-5	4
Mean												

[1] expressed as %

Table 6. Season length changes (days??) with simulation of automatic irrigation.

	330 ppm CO2			555 ppm CO2		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Nanjing	-16	-15	-17	-15	-14	-16
Xuzhou	-22	-20	-23	-20	-19	-22
Nanchang	0	-6	-6	-1	-5	-5
Wuhan	-7	-14	-15	-7	-13	-15
Changsha	-8	-14	-13	-8	-14	-13
Chengdu	-16	-15	-26	-15	-14	-26
Fuzhou	-12	-11	-15	-11	-10	-14
Shaoguan	-7	-17	-12	-5	-15	-10
Guangzhou	-13	-21	-16	-11	-20	-15
Mean	-13	-16	-17	-11	-15	-16

Table 7. Simulated changes in evapotranspiration.

	Percent ET Changes					
	RAINFED			AUTOMATC IRRIG.		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Nanjing	15	0	8	12	4	14
Xuzhou	10	-5	5	10	2	12
Nanchang	-1	-10	-1	-5	-18	-8
Wuhan	0	-7	3	12	-14	-3
Changsha	3	-2	13	8	-17	-7
Chengdu	-27	-8	1	25	-9	16
Fuzhou	3	-6	3	0	-7	-4
Shaoguan	2	-4	-7	21	-5	-5
Guangzhou	-13	-8	-16	7	-5	-6
Mean	-1	-5	2	10	-8	1

Table 8. Simulated changes in irrigation. The direct effects of CO_2 were included in the simulation.

	% Irrigation water changes		
Site	GISS	GFDL	UKMO
Nanjing	-2	4	16
Xuzhou	8	14	22
Nanchang	11	-12	18
Wuhan	39	-41	-6
Changsha	25	-48	-22
Chengdu	603	53	69
Fuzhou	-16	-9	-22
Shaoguan	69	-8	-31
Guangzhou	194	35	0

Table 9. Simulated yield changes for different adaptation strategies with the GISS climate change scenario. The direct effects of CO_2 were included in the climate change scenario simulation.

	Strategy			
Site	CC%	CC+PD%	CC+C%	CC+PD+C%
Nanjing	3	14	-2	0
Xuzhou	6	10	10	11
Nanchang	-1	3	40	43
Wuhan	-3	-1	6	21
Changsha	-12	-10	10	25
Chengdu+	-72	--	-54	-41
Fuzhou	-4	-2	29	30
Shaoguan	-3	5	-1	3
Guangzhou+	-32	--	-47	-36

+ Rainfed, the rest are automatic irrigation.

CC - Climate change effect (GISS scenario).
CC+PD - Effect of climate change plus change in the sowing date.
CC+C - Eeffects of climate change plus change in the cultivar.
CC+PD+C - Combination effect of climate change, changes in the sowing date and change in cultivar.

Table 10. Crop Index indicators for baseline and GCM climate change scenarios. Initial possible date for growing rice (Month/Day), number of possible days per year suitable for growing rice (days), and index of more than 10°C accumulated temperature (T).

	BASE			GISS			GFDL			UKMO		
Site	(M/D)	Days	T	(M/D)	Days	T	(M/D)	Days	T	(M/D)	Days	T
Harbin	5/14	133	2848	4/24	159	3696	4/24	191	3992	4/9	216	4815
Shenyan	4/24	167	3537	4/14	198	4376	4/8	204	4772	2/24	230	5785
Beijing	4/10	189	4216	3/30	225	5215	3/27	233	5497	3/9	275	6353
Jinan	4/8	189	4979	3/24	248	6291	3/16	261	6469	3/3	291	7310
Zhengzhou	4/5	212	4822	3/20	246	6185	3/12	240	6325	3/8	293	7197
Xuzhou	4/9	221	4714	3/22	259	6041	3/16	258	6274	3/8	276	7022
Nanjing	4/5	226	5076	3/14	265	6565	3/14	254	6793	2/25	304	7598
Chwngdu	3/22	231	5361	2/27	300	7324	2/23	281	6761	2/9	340	8247
Wuhan	3/29	239	5433	3/7	281	7634	2/27	276	7168	2/26	321	8038
Nanchang	3/30	234	5831	3/10	274	7237	2/27	300	7722	2/13	313	8290
Changsha	3/26	240	5731	3/9	270	7905	2/27	278	7551	2/18	310	8103
Fuzhou	3/9	289	6740	2/15	331	8294	--	365	8839	--	365	9404
Shaoguan	3/13	263	7011	2/10	346	9465	2/6	326	8912	2/25	321	8470
Guangzhou	2/26	300	7745	2/4	359	9148	--	365	9558	2/3	359	9170
Mean	4/1	224	5289	3/13	269	6812	3/12	274	6902	2/27	301	7557

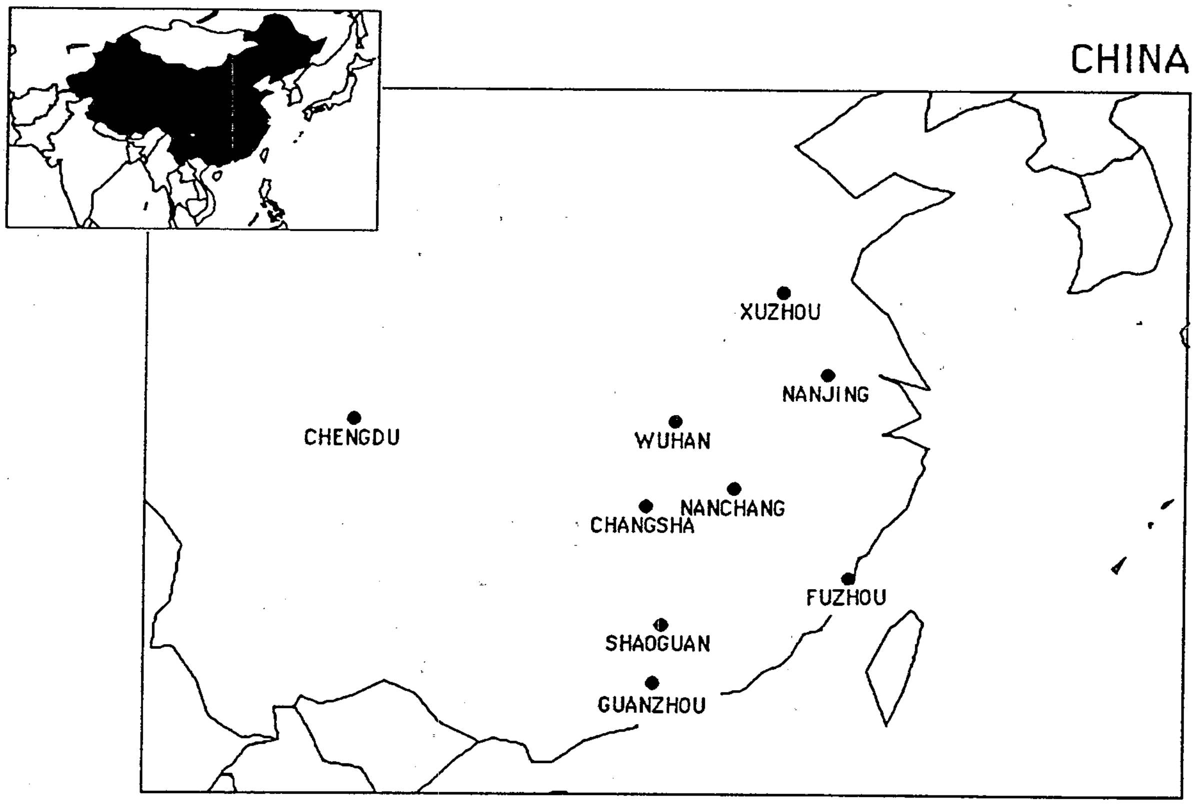

Figure 1. Map of China and location of sites selected for the simulation study.

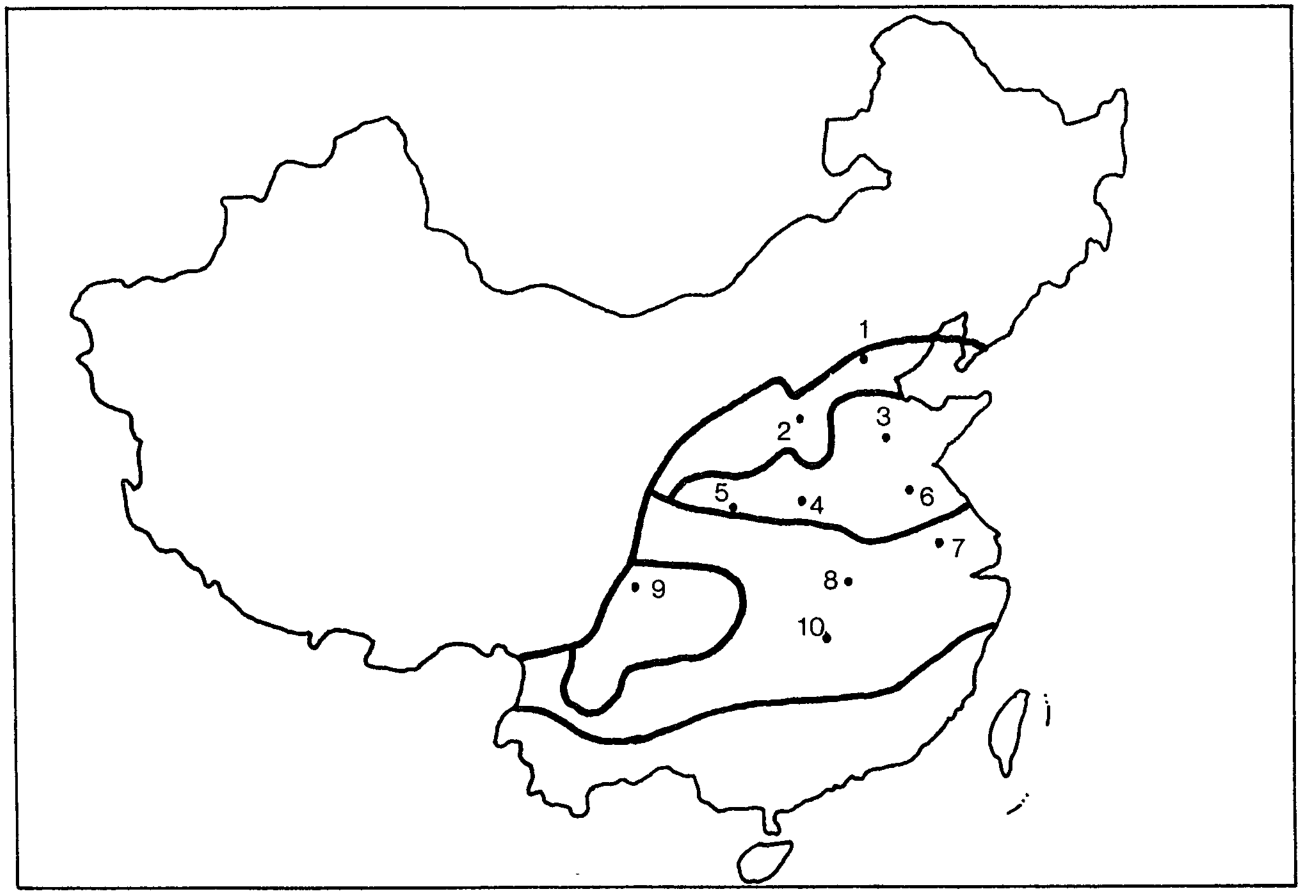

Figure 2. Effect of GCM climate change scenarios on rice distribution patterns in China. 1=Beijing, 2=Taiyuan, 3=Jihan, 4=Zhengzhou, 4=Xiam, 5=Xuzhou, 7=Nanjing, 8=Wuhan, 9=Chengdu, 10=Chnagsha.

IMPLICATIONS OF CLIMATE CHANGE FOR JAPANESE AGRICULTURE: EVALUATION BY SIMULATION OF RICE, WHEAT, AND MAIZE GROWTH

Hiroshi Seino

National Institute of Agro-Environmental Sciences
Japan

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SUMMARY

This study used climate change scenarios derived from three General Circulation Models (GCMs) to assess the possible impacts of climate change on rice, maize, and wheat production in Japan. Higher temperature decreased simulated crop yields in many regions under the current management system. While the direct beneficial effects of CO_2 compensated for the yield decreases in central and northern Japan, they did not compensate for the larger yield decreases in the southwestern part of the island, especially in Kyushu. Early planting and irrigation are possible adaptation strategies to climate change. In most cases, simulated yields increased under climate change conditions if an earlier planting date was adopted. However, in Kyushu, because of high temperature stress, an earlier planting date did not improve simulated yields; the introduction of new cultivars would be required. In Hokkaido, the major upland production area of Japan, climate change increased simulated crop yields. However, these increases were dependent on the precipitation projections of individual climate change scenarios and on the irrigation system practiced.

INTRODUCTION

Aims of the Study

The purpose of this study was to estimate changes in the yields of rice, wheat, and maize crops—in both major production areas and vulnerable regions of Japan—due to climate change projected for increasing levels of atmospheric greenhouse gases (IPCC 1990).

Description of the Agricultural Regions and Systems

The major crops cultivated in Japan are rice (2.11 million ha), wheat (0.40 million ha), potatoes (0.2 million ha), maize (0.33 million ha), and soybeans (0.16 million ha). The major rice production region is the Tohoku district, located in the north area of the main island (Honshu). Two sites, Niigata and Miyagi, were selected to represent this region (Figure 1). The production in Kyushu, in southwestern Japan, is much lower than in the northern area, but could be potentially affected by any increase in temperature as a result of global warming. Therefore, a site, Miyazaki, was selected in this region for the simulation study. In Japan, most rice fields are fully irrigated during the growing season. The soils in paddy fields are grey, lowland soils.

Major wheat production regions include Hokkaido (northern Japan), Tohoku (northern part of the main island) and Kyushu (western Japan). In Hokkaido, wheat could be sown both in the spring and autumn. In Tohoku and Kyushu, wheat is often planted in rice fields as a winter crop (i.e., sown in the autumn). The sites selected to represent the main wheat-producing regions in this study are: Kitami (Hokkaido), Morioka (Tohoku), and Fukuoka (Kyushu). While most wheat is rainfed, there are occasional, severe droughts that limit production. The representative soils in these sites are grey lowland soils and andosols (volcanic ash soils).

Maize is primarily cultivated in Hokkaido (northern Japan), in central Japan, and in Kyushu. The sites selected for this study are Obihiro (Hokkaido), Matsumoto (central Japan), and Miyakonojo (Kyushu). Most of the maize is rainfed. The main soil type of these regions is andosols (volcanic ash soils).

Food Trade and Vulnerabilities

Japan is a net food importer (Appendix 1). Since Japan depends on food imports, changes in world crop yields and prices would directly affect domestic Japanese food prices.

METHODS

Baseline Climate Data and Climate Change Scenarios for the Region

Climate data--daily maximum and minimum temperatures, precipitation, and solar radiation--from 1951 to 1988 were used as the baseline climate. Climate change scenarios were created based on the output of three General Circulation Models (GCMs). GCMs provide the most advanced tool for assessing the potential climatic consequences of increasing radiatively active trace gases. Climate models have been used to simulate the equilibrium climate effects of an equivalent doubling of CO_2. Some models have also been run with gradually increasing trace gases to predict a set of transient responses. However, GCMs have not yet been validated to project changes in climate variability, such as changes in the frequencies of drought and storms, even though these could affect crop yields significantly. Therefore, the scenarios used in this study did not include changes in variability.

Climate scenarios, which are sets of climatic perturbations, are commonly used to estimate the impacts of potential climate changes on agricultural production. In this study, GCMs were used to derive climate change scenarios for the crop models to estimate future changes in yield and other agronomically important variables. The three climate change scenarios used were the Goddard Institute for Space Studies (GISS) (Hansen *et al.* 1983); the Geophysical Fluid Dynamics Laboratory Model (GFDL) (Manabe and Wetherald 1987); and the United Kingdom Meteorological Office Model (UKMO) (Wilson and Mitchell 1987).

The characteristics of the climate change scenarios for Japan are summarized in Table 1. The GISS model predicts a 2°C to 3.5°C rise in air temperature and a 1% to 5% increase in precipitation, except on the southwestern islands. The precipitation increases are larger during the summer season (June-August). The GFDL model predicts a 4°C rise in air temperature and a 10%-20% increase in precipitation, except on the southwestern islands. The UKMO model predicts the highest temperature rise—3.5°C to 6°C. This model predicts a decrease in precipitation in many regions, except during the summer season in eastern Hokkaido. The solar radiation changes under the three GCM scenarios are less than 10%.

Crop Models and Management Variables

Crop models. The crop models used are the Crop Environment Resource Synthesis Models: CERES-Rice (Ritchie *et al.* 1986), CERES-Maize (Ritchie *et al.* 1989), and CERES-Wheat (Ritchie and Otter 1985).

Soils and management. All soil data (type, initial soil water condition, etc.) were taken from soil survey data (National Institute of Agricultural Science 1976). The organic carbon content, bulk density, and aluminum saturation were estimated for each soil by the soil-data-retrieval program of the Decision Support System for Agrotechnology Transfer (DSSAT). The planting date, row spacing, plant population, fertilizer, and cultivar were taken from published data.

Irrigation. In Japan, most rice is well irrigated, and therefore, the option for automatic irrigation in the crop model was chosen to provide the simulated crop with a nonlimiting water supply. Maize and wheat are grown under rainfed conditions in all locations. Irrigation was tested as a possible adaptation to climate change for these crops.

Crop Model Validation

The crop models were validated at nine locations by comparing experimental field data to simulated crop yields and season lengths (Table 2). The simulated data correspond well with experimental observed data, suggesting that the CERES models can be used for the simulation of rice, wheat, and maize growth in Japan.

RESULTS AND DISCUSSION

Sensitivity Analysis

Arbitrary scenarios were created by applying changes in temperature and precipitation to the baseline climate series. The physiological effects of 555 ppm of CO_2 were considered in each of the scenarios. Tables 3, 4, and 5 show the changes in yield and season length for the three crops under the scenarios.

Rice. Because most rice fields are fully irrigated, the automatic irrigation option was selected in the CERES model. Therefore, changes in precipitation did not affect rice. Rice yields decreased with a 2°C to 4°C increase in temperature, and the length of the season from planting to maturity also decreased. With the physiological effects of CO_2, the simulated yield increased in each scenario. These increases compensated for the negative effects of a 2°C increase in temperature and resulted in a net yield increase (6% to 10%) in comparison with the baseline yields. However, a 4°C increase resulted in decreases in rice yields, even when the physiological effects of 555 ppm of CO_2 were taken into account.

Maize. In Japan, maize is grown under rainfed conditions. The effects of temperature increases on maize production (Table 4) were quite different from those on rice production. Maize yields at Obihiro (in Hokkaido) increased under a +2°C scenario, and even under a +4°C scenario there was a small increase. The yield increases were intensified both by increases in precipitation and by the additional physiological effects of CO_2. These results suggest that current low temperatures limit the growth of the variety cultivated in Obihiro, and that a moderate warming would have beneficial effects on maize production in that region. However, associated precipitation (especially during the growing season) is an important factor in determining the crop's final yield.

Wheat. Most wheat in Japan is cultivated under rainfed conditions. Wheat yields decreased under the +2°C and +4°C scenarios at all locations. However, a precipitation increase combined with the higher temperature scenarios produced increases in yields.

Crop Changes under GCM Climate Change Scenarios

The climate variables under each GCM are different, and therefore, the effects of climate change on crop production depend strongly on GCM climate change scenario.

Rice. The rice yields at the three sites decreased under the $2xCO_2$ climate change scenarios with climate change alone (Table 6). Under the GISS scenario, the physiological effects of CO_2 compensated for the negative effects of climate change alone at the three sites. However, under the GFDL scenario in Miyagi and Niigata, and the UKMO scenario in Miyazaki, rice yields remained below the baseline yield, even with the direct effects of CO_2. At all locations, the length of the growing season was shortened by the temperature rise associated with the climate change scenarios. The UKMO scenario produced the shortest season length of rice.

In fully irrigated paddy fields, there are very small differences among rice yields at each site. The direct effects of CO_2 increased simulated rice yields up to 20%. In rainfed upland fields, the direct effects of an increased concentration of CO_2 depended on the cultivar used and the site selected.

Maize. Table 7 shows changes in maize yields under the climate change scenarios considered. Maize yields in Obihiro (Hokkaido) greatly increased under the GISS and GFDL scenario conditions, but dramatically decreased under the UKMO scenario due to the lack of rain during the summer season. The yields in Matsumoto (Kanto) decreased under climate change scenarios alone, but recovered if the direct effects of CO_2 were included in the simulation. In contrast, in Miyakonojo (Kyushu), maize was subject to high temperature stress under all scenarios, and the yield decreases were not compensated when the the direct CO_2 effects were included in the climate change simulation. Maize season length was shortened everywhere due to the temperature increases associated with the GCM scenarios.

Wheat. The results of the simulation of wheat under the GCM climate change scenarios (Table 8) were similar to those of maize. The severe yield decreases under the UKMO scenario were caused by precipitation decreases in the summer season in eastern Hokkaido. The yield decreases in Morioka and Fukuoka were not offset by the direct CO_2 effects.

Adaptation Strategies to Climate Change

In this study, early planting dates (15 and 30 days earlier) and irrigation were analyzed as possible adaptation strategies to counteract the negative effects of climate change. The amounts of irrigation needed to maintain soil moisture were calculated with the water balance submodel included in the crop models. In the case of rice, we analyzed only the effect of early planting. We did not test irrigation, because most of the rice production currently occurs without water restrictions, and it was assumed that water would be available for irrigation in the future.

Table 9 shows that early planting was a very effective method of increasing rice yields under climate change in northern Japan, but not effective in southern Japan (e.g., Miyazaki in Kyushu). Maize yields in Obihiro (Hokkaido) increased with an early planting date and full irrigation, while the same practices did not recover yield decreases in the Matsumoto region. In Miyakonojo (Kyushu), early planting improved yields; however, irrigation did not have any effect since water is not limiting during the maize growing season at that site (both in the current climate and in the climate change scenarios). We considered irrigation and early planting date for spring wheat and late planting date for winter wheat. These strategies improved yields for spring wheat in Kitami (Hokkaido), but they were not effective for winter wheat yields in Morioka and Fukuoka.

IMPLICATIONS OF THE RESULTS

The results of this study suggest that climate change could affect regional agricultural production in Japan. Increases in temperature decreased crop yields in many regions in the simulations with the present management system. While the direct beneficial effects of CO_2 compensated for yield decreases in central and northern Japan, they did not compensate for the larger yield decreases in southwestern Japan, especially in Kyushu. These results imply shifts in regional production patterns.

Early planting and irrigation are possible adaptation strategies to climate change in Japan. In most cases, simulated rice, wheat, and maize yields increased under climate change conditions if an earlier planting date was adopted. However, in Kyushu, because of high temperatures, an earlier planting did not improve simulated yields, and the introduction of new cultivars better adapted to the climate change conditions would be required. In Hokkaido, the major upland production area of Japan, climate change increased simulated crop yields. However, the simulated yield increases are dependent on the scenario's precipitation level and on regional irrigation systems. Potential future water availability under changed climate needs to be investigated to improve agricultural projections.

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Table 1. Average seasonal change in temperature and precipitation for the GCM climate change scenarios.

	SPRING (MAM)	SUMMER (JJA)	FALL (SON)	WINTER (DJF)	ANNUAL
		Temperature changes (°C)			
Myyazaki, Fukuoka, Miyakonojo					
GISS	4.0	3.8	3.3	3.0	3.6
GFDL	4.6	3.6	4.1	4.6	4.2
UKMO	4.1	5.2	4.3	3.7	4.3
Matsumoto, Morioka, Miyagi, Niigata					
GISS	3.2	2.9	2.8	2.3	2.8
GFDL	4.5	3.7	4.4	4.0	4.2
UKMO	7.0	4.8	4.9	5.3	5.5
Obihiro, Kitami					
GISS	4.3	3.1	3.1	3.5	3.5
GFDL	4.2	3.5	5.4	4.2	4.3
UKMO	5.8	7.0	6.9	5.0	6.2

		Precipitation Changes (%)			
Myyazaki, Fukuoka, Miyakonojo					
GISS	15	-6	1	-5	1
GFDL	7	18	5	9	10
UKMO	-25	35	15	-8	4
Matsumoto, Morioka, Miyagi, Niigata					
GISS	7	-4	22	3	7
GFDL	19	14	24	7	16
UKMO	2	7	-23	-13	-7
Obihiro, Kitami					
GISS	12	-4	9	2	5
GFDL	37	38	1	1	19
UKMO	-8	-18	9	7	-3

Table 2. Simulated and observed yields and season lengths.

Crop	Site	Data (year)	S. Length (d) OBS	S. Length (d) SIM	Yield ($t\ ha^{-1}$) OBS	Yield ($t\ ha^{-1}$) SIM
Rice	Miyagi	75-87	145.8	143.1	4.95	4.99
Rice	Niigata	80-88	134.7	136.8	5.74	5.34
Rice	Miyazaki	80-88	118.0	119.8	5.64	5.49
Maize	Obihiro	76-86	136.3	134.0	11.16*	11.33*
Maize	Matsumoto	68-82	125.6	127.3	16.64*	16.67*
Maize	Miyakonojo	70-82	114.3	113.5	3.95	3.82
Wheat	Kitami	67-83	103.3	102.8	2.59	2.53
Wheat	Morioka	70-86	288.1	285.6	3.64	3.18
Wheat	Fukuoka	72-87	196.8	191.6	3.83	3.81

* Total biomass

Table 3. Sensitivity of simulated rice yields and season length to temperature and CO_2. Rice was simulated under the automatic irrigation option of the CERES model.

Site	Temp. Change (°C)	330 ppm CO_2		555 ppm CO_2	
		Yield Change (%)	S. Length (d)	Yield Change (%)	S. Length (d)
Miyagi	+2	-13	-15	+6	-14
	+4	-22	-23	-5	-22
Niigata	+2	-9	-12	+10	-11
	+4	-16	-12	+1	-17
Miyazaki	+2	-9	-7	+9	-7
	+4	-16	-12	+1	-12

Yield= percent changes from base; Season Length = differences from base.

Table 4. Sensitivity of simulated maize yield, season length and evapotranspiration to temperature (°C), precipitation (%), and CO_2 changes.

Site	T	PP	330 ppm CO_2 Yield (%)	330 ppm CO_2 SL (d)	330 ppm CO_2 ET (%)	555 ppm CO_2 Yield (%)	555 ppm CO_2 SL (d)	555 ppm CO_2 ET (%)
Obihiro	+2	0	+43	-4	+1	+63	-4	-14
	+4	0	+17	-19	-10	+35	-19	-22
	+2	-20	+34	-4	-3	+60	-4	-17
	+2	+20	+48	-4	+3	+66	-4	-13
	+4	-20	+8	-19	-14	+30	-19	-24
	+4	+20	+21	-19	-7	+37	-19	-20
	0	-20	-8	0	-4	+11	0	-18
	0	+20	+3	0	+2	+14	0	-14
Matsumoto	+2	0	-12	-13	-8	+8	-12	-17
	+4	0	-20	-18	-10	-5	-18	-19
	+2	-20	-27	-15	-13	-3	-13	-21
	+2	+20	-3	-12	-4	+15	-11	-14
	+4	-20	-31	-19	-15	-12	-19	-22
	+4	+20	-14	-18	-6	-1	-18	-16
	0	-20	-18	-4	-7	+11	0	-14
	0	+20	+11	+1	+4	+36	+3	-8
Miyakonojo	+2	0	-20	-7	-7	-15	-7	-19
	+4	0	-32	-13	-12	-27	-13	-24
	+2	-20	-20	-7	-7	-15	-7	-20
	+2	+20	-19	-7	-6	-15	-7	-19
	+4	-20	-32	-13	-13	-27	-13	-24
	+4	+20	-31	-13	-11	-27	-13	-23
	0	-20	-1	0	-1	+6	0	-14
	0	+20	+1	0	+1	+6	0	-13

Yield = percent changes from base; SL = season length differences from base; ET = percent evapotranspiration from base.

Table 5. Sensitivity of simulated maize yield, season length and evapotranspiration to temperature (°C), precipitation (%) and CO_2 changes.

Site	T	PP	330 ppm CO_2 Yield (%)	330 ppm CO_2 SL (d)	330 ppm CO_2 ET (%)	555 ppm CO_2 Yield (%)	555 ppm CO_2 SL (d)	555 ppm CO_2 ET (%)
Kitami	+2	0	-17	-8	-5	+10	-8	-9
(SW)	+4	0	-30	-14	-9	-7	-14	-13
	+2	-20	-27	-8	-12	0	-8	-16
	+2	+20	-12	-8	+1	+14	-8	-5
	+4	-20	-38	-14	-17	-14	-14	-19
	+4	+20	-25	-14	-4	-1	-14	-8
	0	-20	-10	0	-7	+22	0	-11
	0	+20	+4	0	+5	+31	0	-2
Morioka	+2	0	-7	-4	+2	+9	-4	-5
(WW)	+4	0	-15	-7	+4	0	-7	-2
	+2	-20	-10	-4	0	+8	-4	-7
	+2	+20	-7	-4	+4	+9	-4	-5
	+4	-20	-18	-7	+1	-1	-7	-5
	+4	+20	-15	-7	+5	0	-7	-1
	0	-20	-4	0	-2	+16	0	-10
	0	+20	+1	0	+1	+18	+3	-9
Fukuoka	+2	0	-14	-3	-2	+3	-3	-8
(WW)	+4	0	-27	-5	-2	-13	-5	-7
	+2	-20	-18	-3	-5	-1	-3	-11
	+2	+20	-11	-3	0	+5	-3	-7
	+4	-20	-31	-5	-6	-17	-5	-11
	+4	+20	-24	-5	0	-10	-5	-6
	0	-20	-4	0	-3	+15	0	-9
	0	+20	+2	0	+2	+22	0	-5

Yield = percent changes from base; SL = season length differences from base; ET = percent evapotranspiration from base.

Table 6. Changes in rice yield, season length and total season precipitation under GCM climate change scenarios.

Site		330 ppm CO_2			555 ppm CO_2		
		Yield (%)	SL (d)	PP (%)	Yield (%)	SL (d)	PP (%)
Miyagi	GISS	-12	-19	-19	+7	-18	-19
	GFDL	-27	-22	-6	-11	-22	-5
	UKMO	-17	-25	-24	+1	-25	-24
Niigata	GISS	-7	-15	-16	+12	-15	-16
	GFDL	-21	-18	0	-5	-18	+1
	UKMO	-11	-21	-21	+6	-21	-21
Miyazaki	GISS	-12	-12	+5	+6	-12	+5
	GFDL	-17	-12	-3	0	-12	-3
	UKMO	-19	-14	-5	-2	-14	-5

Yield= percent changes from base; SL= season length differences from base; PP= recipitation percent from base.

Table 7. Change in maize yield, season length, evapotranspiration and total season precipitation under GCM climate change scenarios.

Site		330 ppm CO_2				555 ppm CO_2			
		Yield (%)	SL (d)	PP (%)	ET (%)	Yield (%)	SL (d)	PP (%)	ET (%)
Obihiro	GISS	+24	-15	-16	-2	+51	-14	-16	-15
	GFDL	+25	-16	+9	-9	+38	-16	+9	-23
	UKMO	-32	-29	-45	-16	+5	-29	-45	-22
Matsumoto	GISS	-19	-17	-19	-7	+3	-16	-18	-16
	GFDL	-14	-17	+18	-15	-5	-17	+18	-26
	UKMO	-15	-20	-17	-7	-2	-21	-17	-16
Miyakonojo	GISS	-28	-12	+6	-11	-23	-12	+6	-23
	GFDL	-34	-13	-4	-16	-31	-13	-4	-28
	UKMO	-31	-15	-11	-8	-27	-15	-11	-20

Yield= percent changes from base; SL= season length differences from base; ET= percent cahnge of total season evapotranspiration PP= recipitation percent from base.

Table 8. Change in wheat yield, season length, evapotranspiration and total season precipitation under GCM climate change scenarios.

Site		330 ppm CO_2				555 ppm CO_2			
		Yield (%)	SL (d)	PP (%)	ET (%)	Yield (%)	SL (d)	PP (%)	ET (%)
Kitami	GISS	-21	-11	-18	-7	+6	-11	-18	-10
	GFDL	-17	-12	+8	-5	+8	-12	+8	-11
	UKMO	-59	-21	-43	-22	-41	-21	-45	-23
Morioka	GISS	-16	-7	-1	+5	-1	-7	-1	-2
	GFDL	-20	-7	+2	+3	-7	-7	+2	-3
	UKMO	-31	-12	-23	+6	-18	-12	-23	0
Fukuoka	GISS	-24	-8	-8	-4	-8	-8	-8	-9
	GFDL	-33	-5	-6	0	-20	-5	-6	-4
	UKMO	-40	-5	-28	-2	-27	-5	-28	-7

Yield= percent changes from base; SL= season length differences from base; ET= percent cahnge of total season evapotranspiration PP= recipitation percent from base.

Table 9. Evaluation of potential adaptation strategies: changed planting dates and levels of irrigation.

Site	Worst GCM	Irrigated/ Rainfed	Planting	Base Yield	Scenario Yield with Adaptation	Irrigation amount (mm)
		RICE				
Miyagi	GFDL	irrigated	15 d. early	4.30	4.62	
		irrigated	30 d. early		4.90	
Niigata	GFDL	irrigated	15 d. early	5.44	5.72	
		irrigated	30 d. early		5.99	
Miyazaki	UKMO	irrigated	15 d. early	5.56	5.60	
		irrigated	30 d. early		5.68	
		MAIZE				
Obihiro	UKMO	rainfed	15 d. early	5.81	5.82	
		rainfed	30 d. early		6.02	
		irrigated	15 d. early		8.37	114.68
		irrigated	30 d. early		8.64	116.34
Matsumoto	GFDL	rainfed	15 d. early	4.87	4.61	
		rainfed	30 d. early		4.35	
		irrigated	15 d. early		4.64	38.39
		irrigated	30 d. early		4.36	38.32
Miyakonojo	GFDL	rainfed	15 d. early	2.64	3.05	
		rainfed	30 d. early		3.38	
		irrigated	15 d. early		3.05	4.18
		irrigated	30 d. early		3.38	6.24
		WHEAT				
Kitami	UKMO	rainfed	15 d. early	1.60	2.02	
		rainfed	30 d. early		2.22	
		irrigated	15 d. early		3.14	169.29
		irrigated	30 d. early		3.36	167.05
Morioka	UKMO	rainfed	15 d. late	2.69	2.69	
		rainfed	30 d. late	2.69	2.68	
		irrigated	15 d. late	2.69	2.71	74.49
		irrigated	30 d. late	2.69	2.70	74.16
Fukuoka	UKMO	rainfed	15 d. late	2.94	2.88	
		rainfed	30 d. late	2.94	2.80	
		irrigated	15 d. late	2.94	2.88	2.24
		irrigated	30 d. late	2.94	2.80	2.24

Appendix 1. Food balance in Japan in 1987 (x 1000 t).

Commodity	Domestic Production	Imports	Exports
Cereals	11,870	28,187	0
Rice	10,627	39	0
Wheat	864	5,133	0
Barley	326	1,988	0
Naked Barley	27	0	0
Sweet corn	1	16,602	0
Sweet potatoes	1,423	0	0
Potatoes	3,955	323	0
Starches	2,357	119	0
Pulses	469	4,797	0
Vegetables	16,598	1,114	4
Fruits	5,974	2,260	48
Meat	3,607	1,171	4
Hen eggs	2,394	36	0
Milk&milk products	7,427	1,767	0
Fish&Shellfish	11,800	3,299	1,583

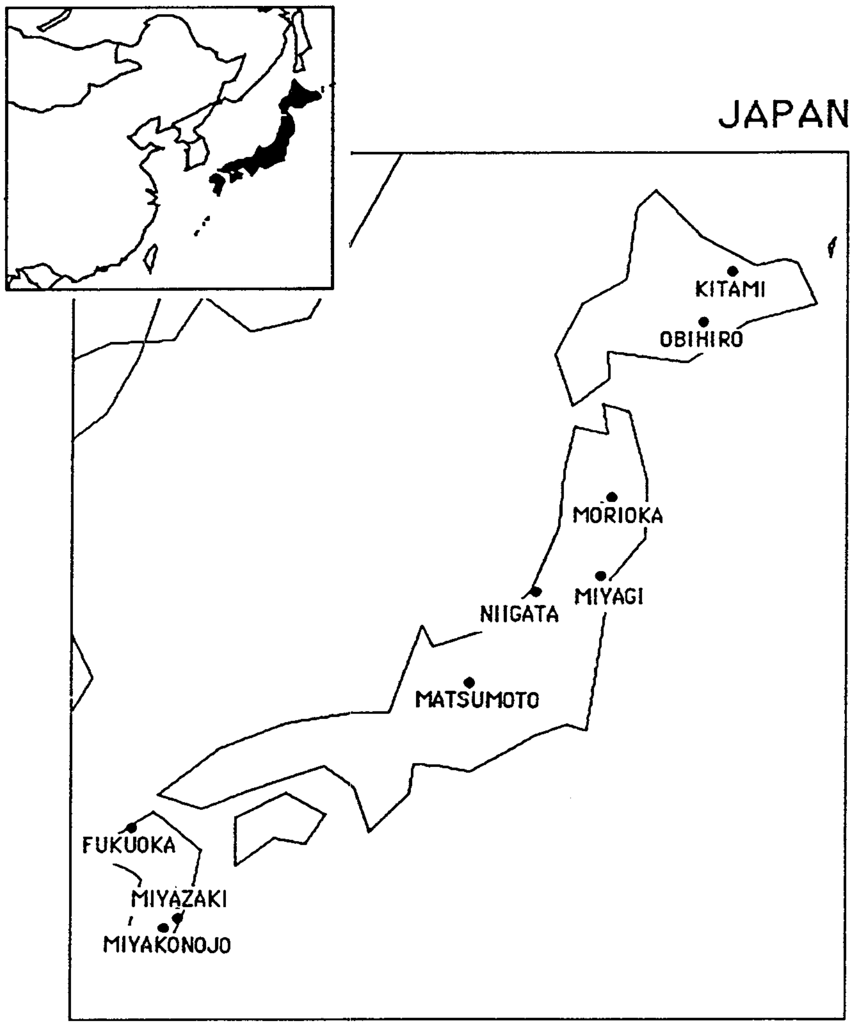

Figure 1. Map of Japan and location of the sites selected for the study.

SECTION 7: AUSTRALIA

POSSIBLE EFFECTS OF GLOBAL CLIMATE CHANGE ON WHEAT AND RICE PRODUCTION IN AUSTRALIA

Brian D. Baer

Department of Crop and Soil Science
Michigan State University, USA

Wayne S. Meyer

Division of Water Resources
Griffith Laboratory
CSIRO, Australia

David Erskine

Division of Water Resources
Griffith Laboratory
CSIRO, Australia

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SUMMARY

This simulation study uses crop models and climate change scenarios generated from General Circulation Models (GCMs) to determine the possible impacts of climate change on rice and wheat production in Australia. The beneficial direct effects of CO_2 on crop yield and water use are taken into account in the simulations. In most sites, dryland wheat yields increase when the scenario projects a rainfall increase. However, in the scenarios with the largest GCM temperature increases, yields generally decreased due to a shortening of the crop growing season. Irrigated wheat yields also decreased due to the temperature increases. Paddy rice yields decreased slightly under climate change conditions.

Simulation experiments showed that the most successful adaptation strategy to climate change was changing the variety of rice to a more tropical one. Also, adjusting the sowing dates for dryland wheat to obtain maximum water availability was helpful.

INTRODUCTION

Aims

The purpose of this study is to estimate the possible impacts of climate change on yield and irrigation water demand of wheat and rice in different sites in Australia using simulation crop growth models and climate change scenarios generated from GCMs.

Sites and Current Climate

Wheat is grown in the semi-arid regions of southern and eastern Australia, while rice is mainly confined to inland southern New South Wales (NSW) (Figure 1). The main constraint on the extent of these agricultural regions is water availability. In the southern part of the country, the rainfall pattern has a winter maximum; in the middle regions of the eastern wheat belt, rainfall is evenly distributed throughout the year. Winter rainfall is stored in the soil and is available to the wheat crop during the following winter until early summer. In the north of Australia, the dominance of summer rainfall and the limited areas of suitable soils restrict agriculture. Winter temperatures in the mainland are mild and do not present any constraint to crop growth.

Five sites were chosen to represent the major wheat regions of Australia (Figure 1). Wheat is grown under rainfed conditions in most areas; only in the Murrumbidgee Irrigation Area, represented by Griffith in NSW, is wheat grown under irrigated conditions. Griffith is also central to the major rice-producing area of southern New South Wales. The country's aridity and strong commitment of available water supplies to diverse users make it unlikely that other grain-growing regions of the country will be able to acquire water for irrigation in the future.

METHODS

Climate Change Scenarios

A series of climate data available for the period 1951-80 was obtained for each site (Wongan Hills 1966-80; Roseworthy 1957-80; Horsham 1957-59, 1961-80; Griffith 1951-80; Narrabi 1962, 1964-66, 1968-69, 1971-80). Daily maximum temperature, minimum temperature, and rainfall were available for all sites. Missing values were estimated based on the values before and after that day. Daily solar irradiance data was available for the Griffith site only. For the rest of the sites, we generated values based on maximum possible irradiation modified with observed monthly average hours of sunlight (Richardson and Wright 1984).

Climate change scenarios for each site were generated from three GCMs: the Goddard Institute for Space Studies Model (GISS) (Hansen *et al.* 1983), the Geophysical Fluid Dynamics Laboratory Model (GFDL) (Manabe and Wetherald 1987), and the United Kingdom Meteorological Office Model (UKMO) (Wilson and Mitchell 1987). The scenarios for each site were created based on the GCM output of climate variables applied to the daily observed climate. This method uses the difference between $1xCO_2$ and $2xCO_2$ monthly GCM temperatures and the ratio between $2xCO_2$ and $1xCO_2$ monthly GCM precipitation amounts. ($1xCO_2$ refers to current climate conditions, and $2xCO_2$ refers to the climate that would occur with a doubling of greenhouse gases.) Table 1 shows the seasonal changes projected under the climate change scenarios. All GCMs project temperature increases for all seasons. The GISS and GFDL models predict an average annual temperature rise of around 4.5°C, and the UKMO model predicts temperature increases of approximately 5.7°C. The GISS and UKMO models predict a slight increase in annual rainfall, while GFDL predicts a slight decrease. In most sites and seasons, the three GCMs predict a slight increase in solar radiation.

Crop Models and Management Practices

The CERES-Rice (Godwin *et al.* 1992) and the CERES-Wheat (Godwin *et al.* 1989) models were used for the crop simulations. In addition to the climate data, the crop models require a well-defined set of inputs to simulate actual crop conditions. The inputs include soil parameters and management practices. The soil parameters include data on texture, water-holding capacity, and nitrogen status of the soil. A representative soil was determined and defined for each of the five sites. In general, the representative soils chosen were clay loam soils, with the exception of a heavy clay soil for the rice growing area, a sandy loam soil for western Australia, and a cracking clay soil for Narrabri. Information on soils in the wheat-growing areas was taken from McGarity (1975). The crop management practices include sowing dates, plant population, irrigation, nitrogen applications, and plant variety. These variables were determined according to current practices.

Wheat is grown in the winter at all sites to take advantage of the low evaporation and to maximize available water. We simulated nonirrigated wheat with low inputs of nitrogen and relatively low plant populations at all sites. In addition, we simulated irrigated wheat and paddy rice in Griffith. Table 2 shows the conditions that were used for the crop simulations.

Calibration and Validation of the Crop Models

We determined the genetic coefficients that define a variety in the CERES models by comparing model runs to actual field data and calibrating the coefficients by the method of trial and error. After defining the genetic coefficients, the models were validated for use in the selected sites.

General data from a wide range of dryland wheat experiments in Australia were obtained from the data base of Rimmington *et al.* (1987) and were used to validate the wheat model for Roseworthy. For eastern Australia, validation data were compiled from the data sets of MacKenzie et al. (1985) and supplemented with more specific information from Angus *et al.* (1980) for an area similar to Narrabri. For Griffith, data for the validation were taken from Mason and Fischer (1986); for Horsham, from Rimmington et al. (1987); and for Wongan Hills, from Anderson and Smith (1990). Validation data for rice were obtained from the comprehensive experiments of Muirhead *et al.* (1989) and Humphreys *et al.* (1987). For irrigated wheat, local data published by Meyer *et al.* (1985) were used for validation.

Simulations

The simulations include the following sets of scenarios: (a) baseline climate (in all sites); (b) GCM climate change scenarios alone (in all sites); (c) GCM climate change scenarios including the direct effects of 555 ppm CO_2 in the crop growth simulation (in all sites) (Acock and Allen 1985); (d) sensitivity analysis, where base daily temperature and precipitation were modified by fixed amounts (in Roseworthy and Griffith); and (e) scenarios that incorporated possible changes in management conditions to analyze adaptive strategies to climate changes. For dryland wheat at Horsham and Roseworthy we changed the current planting dates; for irrigated rice, we replaced the current cold-resistent variety, Calrose, with a more tropical variety, IR-36.

RESULTS

Crop Yield and Irrigation Demand

Table 3 shows the yields (and standard deviations) and irrigation amounts simulated by the CERES models for dryland wheat and irrigated wheat and rice for the baseline climate and the GCM climate change scenarios. The direct effects of CO_2, as well as the climate effects alone, are shown.

Crop Yield. Climate change scenarios had varied effects on wheat yields at each of the sites (Table 3). While the UKMO model showed a decrease in yields in all cases but one, the other two models showed no general trend. From the climate effects alone, the yield changes ranged from a 15% increase in Horsham under the GFDL model to a 45% decrease in Wongan Hills under the GISS scenario. The direct effects of CO_2 increased the yield under base climate from 25% to 39%. The beneficial direct CO_2 effects on yield fully compensate for the yield losses under the climate change scenarios in most cases.

Table 3 also shows the effects of climate change scenarios on irrigated wheat at Griffith. Simulated yields decreased due to increased temperatures and a shortening of the growing season. The greatest yield losses corresponded to the scenario that projects the largest increases in temperature. In Griffith, the temperature increase was lowest under the GISS scenario and largest under the UKMO scenario. Simulated wheat yields decreased 17% and 45% under the GISS and UKMO scenarios, respectively. With the direct effects of CO_2, the corresponding yield decreases were only 2% and 29%.

Flooded rice (Table 3) was much less susceptible to temperature increases than was wheat. Under climate change alone, yields decreased from 9% (GISS) to 16% (UKMO). The direct CO_2 effects compensated for the rice yield decreases under the climate change scenarios alone.

Irrigation Demand. Two irrigated crops were simulated at Griffith. The irrigation needed for rice increased or, in the case of GISS, did not significantly change (Table 3). However, the irrigation demand for wheat showed an opposite trend under the climate scenarios, showing a decrease of more than 50% in the UKMO scenario due to a shorter growing period. In all cases, irrigation demands were smaller with the physiological CO_2 effects because of increased stomatal resistance.

Sensitivity Analysis

Table 4 shows the results of the sensitivity analysis for dryland wheat in Roseworthy. Changes in yields due to temperatures are relatively small in comparison with changes due to precipitation. There is an increase in yields with a 2°C temperature increase, but a decrease from the baseline yields with a 4°C temperature increase.

Adaptation to Climate Change

Table 5 shows the effect of changing planting dates on dryland wheat yields under climate change scenarios at two sites. Planting dates of 15 and 30 days before and after May 30 (the most common planting date) were chosen. Yields were higher with an earlier sowing date and they decreased with later planting dates. Table 5 also shows the results of the flooded rice model runs at Griffith using variety IR-36. According to the CERES model, this variety of rice produced higher average yields than Calrose (the current cultivar), even in the current climate. However, the standard deviation of the current simulated yield increased significantly. Under the climate change scenarios, yields increased substantially when using the variety IR-36, but without an increase in standard deviation.

DISCUSSION

Limitations of the Crop Models

For this study the simulations lacked two components that might have affected the outcome. First, the soil moisture was reset at the beginning of every season rather than being simulated for the entire year. Since there is not enough water to supply the demands of the dryland wheat from rainfall during the growing season, the water stored in the soil is critical to the development of the plants. The stored water comes from rain that fell during earlier months when there were few or no plants growing. In this study we partially compensated for this by starting the simulation two months before the sowing date. However, a full-year water balance would have given more accurate predictions of water in the soil during the growing season. This procedure might possibly underestimate the impacts of climate change on soil moisture.

Second, the rice model is not sensitive to cool temperatures. The rice model was mainly developed with data from tropical areas where the temperatures are warm throughout the growing season. However, in less tropical areas, such as southern Australia, there can be fairly cold nights during critical stages of the rice growing cycle. These cold temperatures can induce sterility in the plants and reduce the yield substantially. The CERES-Rice model does not account for this problem, and therefore, it probably overestimates yields in years with cold nights. This effect should be tested in future climate change impact studies.

Impact of Climate Change on Crops

Dryland wheat yields in Australia increased when the scenario projected an increase in the amount of rainfall (compared to the current rainfall). The sensitivity analysis at Roseworthy clearly shows the importance of this variable. In most Australian regions, the water stored in the soil prior to sowing provides a large percentage of the water needed by the crop, so the extra rainfall in the summer months contributes directly to increases in yields. In contrast, at Wongan Hills, under the GFDL scenario yields decrease substantially (about 30%) with the effects of climate change alone, due in part to projected decreases in rainfall.

However, in the situations where the GCMs predict large temperature increases, the effect of rainfall increases can be overcome by the effects of higher temperatures. In the cases of irrigated wheat and flooded rice crops this high temperature effect is the only one to which the models are sensitive. Warmer temperatures during the growing season decrease the length of time that the plant takes to reach maturity. This is particularly critical during the grain-filling period, the duration of which is determined by accumulated temperature. An increase in temperature stimulates the plants to mature more quickly, but with less grain yield. Figure 2 shows the effect of temperature on the length of the growing season on simulated irrigated wheat at Griffith.

An increase in atmospheric CO_2 results in larger yields due to greater net photosynthesis and better use of water by the plant due to increased stomatal resistance. In the plants that are not suffering from drought stress these effects are particularly pronounced.

The rainfall changes associated with the climate change scenarios influenced the amount of irrigation required for the crop. For irrigated wheat, the decrease in water demand is related to the shorter growing season and smaller biomass accumulation. The plants that do poorly require less water, and therefore, less irrigation. Rice, however, showed less of a decrease in yield and therefore, the water demand did not decrease as much as in the case of wheat.

A change in management practices may compensate for the negative impact of climate change on yields, as simulated in this study. In the case of dryland wheat, it is critical to grow the crop when there is water available, and therefore, sowing dates may be adjusted to the most favorable moisture regime under the climate change conditions. Changing the variety of rice may be a successful strategy for adaptation to climate change.

Australia's farmers produce more than enough wheat and rice for internal consumption, so that none of the predicted changes would threaten the food security of the country. However, farm products are major export commodities, and yield variations could have large effects on farm export earnings, leading to significant impacts on the national economy.

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Table 1. Temperature differences and precipitation and solar radiation ratios between $1xCO_2$ and $2xCO_2$ climate change scenarios at selected sites.

	Temp. Diff. (°C)			Precip. Ratio			Solar Rad. Ratio		
Site/Season	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Wongan Hill									
Summer	3.68	4.63	4.37	1.57	1.01	1.00	1.00	1.01	1.02
Autumn	4.93	4.32	4.51	1.38	0.96	1.08	1.00	1.02	1.08
Winter	5.61	3.77	4.60	0.80	0.77	1.16	1.02	1.07	1.01
Spring	5.67	4.84	4.47	1.69	0.50	1.06	1.00	1.07	1.02
Roseworthy									
Summer	4.87	5.27	6.79	1.50	0.71	1.21	1.01	1.02	1.06
Autumn	4.37	4.53	7.37	0.91	1.01	0.86	1.03	0.97	1.12
Winter	4.34	4.09	5.62	1.22	1.06	1.17	1.06	1.04	1.03
Spring	4.27	4.00	5.84	1.14	0.98	1.09	1.00	1.07	1.11
Horsham									
Summer	4.87	4.86	5.13	1.50	0.92	1.12	1.01	1.05	1.09
Autumn	4.37	4.46	5.53	0.91	0.87	1.23	1.03	1.02	1.08
Winter	4.34	4.46	5.11	1.22	1.12	1.25	1.06	0.95	1.09
Spring	4.27	4.29	5.04	1.14	0.79	1.12	1.00	1.09	1.10
Griffith									
Summer	4.34	5.27	6.03	1.13	0.71	1.29	1.02	1.02	1.03
Autumn	3.93	4.53	6.55	0.96	1.01	1.05	1.05	0.97	1.07
Winter	4.00	4.09	6.61	1.03	1.06	1.04	1.09	1.04	1.05
Spring	3.77	4.00	5.91	1.25	0.98	1.19	1.01	1.07	1.04
Narrabri									
Summer	3.34	2.36	3.35	0.75	0.75	0.99	0.66	0.66	0.67
Autumn	4.83	3.82	7.07	1.25	0.78	0.79	1.01	1.09	1.10
Winter	5.07	4.12	6.32	0.89	0.95	1.16	1.05	1.05	1.04
Spring	4.91	4.41	6.26	0.98	1.08	1.18	1.01	1.05	1.04

Table 2. Management variables used for the CERES models to simulate crop growth.

Site	Crop/Variety	Soil	Sowing Dates	Plant Population (plants m^{-2})
Wongan Hills	Dryland wheat/Gamenya	Deep sandy loam	1 May	150
Roseworthy	Dryland wheat/Egret	Red brown earth	30 May	150
Horsham	Dryland wheat/Egret	Red brown earth	30 May	150
Griffith	Dryland wheat/Egret	Red brown earth	15 May	150
Griffith	Irrigated wheat/Egret	Red brown earth	15 May	180
Griffith	Flooded rice/Calrose	Gray cracking	17 Oct	128
Narrabri	Dryland wheat/Egret	Vertisol	25 Jun	150

Table 3. Effects of climate change on simulated wheat and rice; (a) yield and (b) irrigation water.

(a) Yield (t ha^{-1})

Site		Climate Scenario Alone				Climate Scenario with Physiological CO_2 Effects			
		BASE	GISS	GFDL	UKMO	BASE	GISS	GFDL	UKMO
					Dryland Wheat				
Wonhan Hills	Yield	3.24	2.19	2.27	3.14	4.08	3.04	3.18	3.85
	SD	1.22	1.10	1.08	0.86	0.90	1.34	1.12	0.83
Roseworthy	Yield	2.48	2.57	2.45	1.94	3.40	3.26	3.11	2.64
	SD	1.17	1.24	1.42	1.15	1.01	1.22	1.40	1.39
Horsham	Yield	2.64	2.73	2.60	3.00	3.28	3.40	3.32	3.59
	SD	1.08	1.08	1.23	1.05	0.90	0.87	1.14	0.94
Griffith	Yield	2.73	2.71	2.62	1.80	3.44	3.38	3.27	2.38
	SD	1.23	1.48	1.44	1.36	1.15	1.48	1.39	1.69
Narrabri	Yield	3.55	1.96	2.47	2.27	4.74	2.82	3.43	3.13
	SD	1.96	1.43	1.73	1.40	2.15	1.74	2.10	1.63
					Irrigated Wheat				
Griffith	Yield	6.65	5.46	5.08	3.79	7.22	6.41	5.99	4.64
	SD	0.55	0.53	0.49	0.45	0.61	0.56	0.53	0.52
					Flooded Rice				
Griffith	Yield	9.16	8.30	7.80	7.66	10.10	9.12	8.60	8.54
	SD	0.42	0.77	0.58	0.51	0.54	0.77	0.82	0.70

(b) Irrigation water (mm)

					Irrigated Wheat				
Griffith	mm	240	177	169	118	202	136	133	98
	SD	83	63	65	48	80	55	50	50
					Flooded Rice				
Griffith	mm	693	689	761	747	680	675	749	731
	SD	84	105	93	110	87	104	94	112

Table 4. Sensitivity analysis of the CERES-Wheat model to changes in temperature, precipitation and CO_2 levels. Dryland wheat at Roseworthy.

Changes in Precip.	Temp.	330 ppm CO_2 Yield	330 ppm CO_2 SD	555 ppm CO_2 Yield	555 ppm CO_2 SD
(%)	(°C)	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})
0%	0	2.55	1.24	3.45	1.10
	2	2.82	1.32	3.69	1.11
	4	2.51	1.49	3.18	1.45
20%	0	3.29	1.26	4.00	0.85
	2	3.57	1.11	4.19	0.88
	4	3.05	1.27	3.75	1.15
-20%	0	1.59	0.75	2.69	1.08
	2	1.86	1.03	2.85	1.23
	4	1.66	1.12	2.51	1.45

Table 5. Adaptation strategies for climate change scenarios; effects of change in planting date on simulated wheat yield at Horsham and Roseworthy (a); effects of change in cultivar on simulated irrigated rice yield (b) and irrigation water (c) at Griffith.

(a) Dryland Wheat Yield (t ha^{-1})

		Climate Scenario Alone				Climate Scenario with Physiological CO_2 Effects		
		BASE	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Horsham	30 Apr.	3.94	2.24	1.64	2.09	3.11	2.36	3.04
	15 May	3.19	2.77	2.37	2.92	3.53	3.13	3.78
	30 May*	2.64	2.73	2.60	3.00	3.40	3.32	3.59
	15 June	2.29	2.66	2.45	2.75	3.20	3.21	3.28
	30 June	1.80	1.77	1.49	1.72	2.37	2.12	2.29
Roseworthy	30 Apr.	3.72	1.60	1.70	0.80	2.22	2.32	1.16
	15 May	3.15	2.40	2.38	1.39	3.19	3.09	2.03
	30 May*	2.48	2.57	2.45	1.94	3.26	3.11	2.64
	15 June	1.91	2.53	2.11	2.09	3.22	2.90	2.85
	30 June	1.37	1.79	1.18	1.32	2.39	1.84	1.97

(b) Irrigated Rice Yield (t ha^{-1})

Griffith	Calrose*	9.16	8.30	7.80	7.66	9.12	8.60	8.54
	IR-36	9.30	10.17	9.47	9.63	12.05	11.19	11.40

(c) Water Used for Irrigation (mm)

Griffith	Calrose*	693	689	761	747	675	749	731
	IR-36	825	728	783	769	707	760	741

*Current practice.

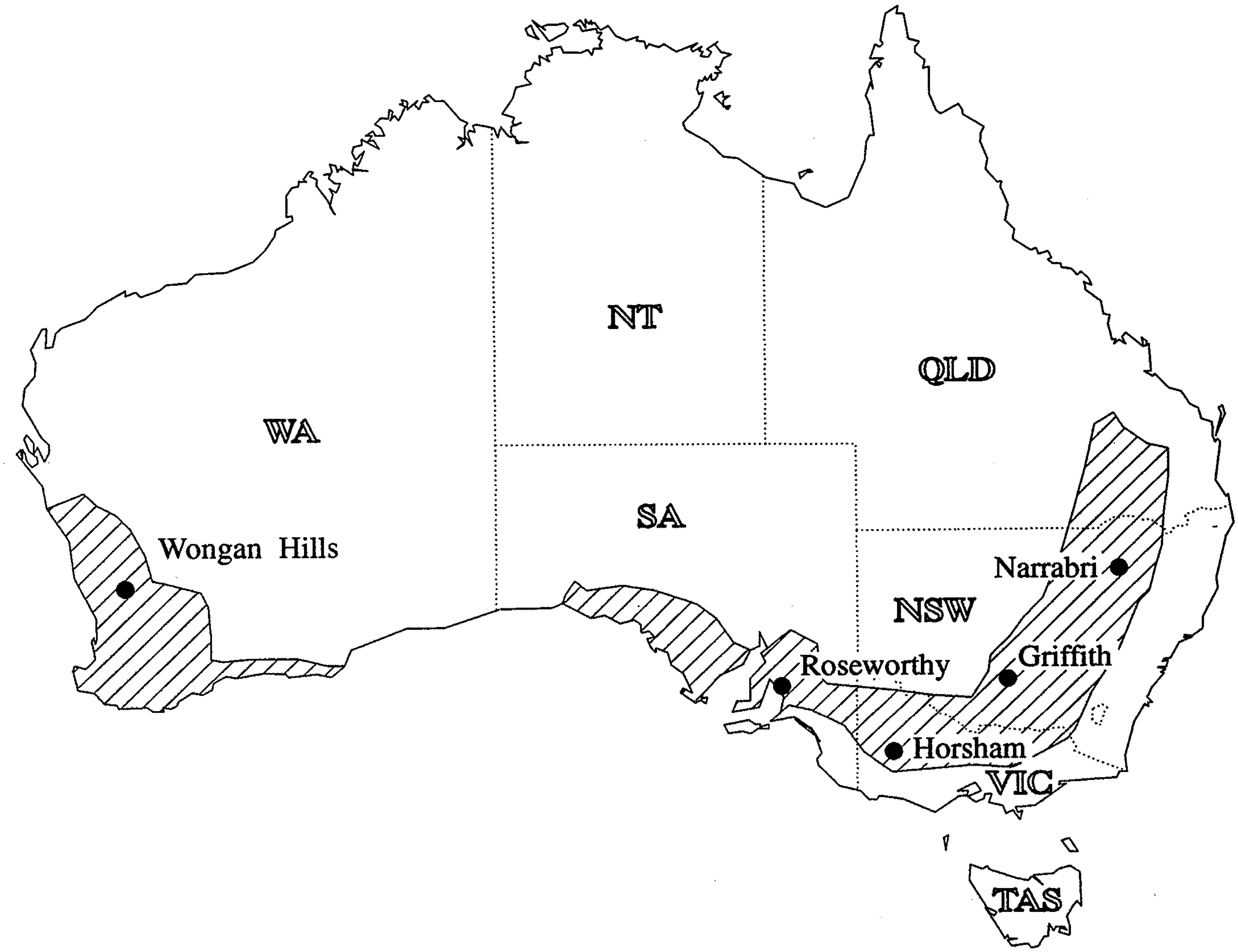

Figure 1. **Australian study sites and major grain-growing regions.**

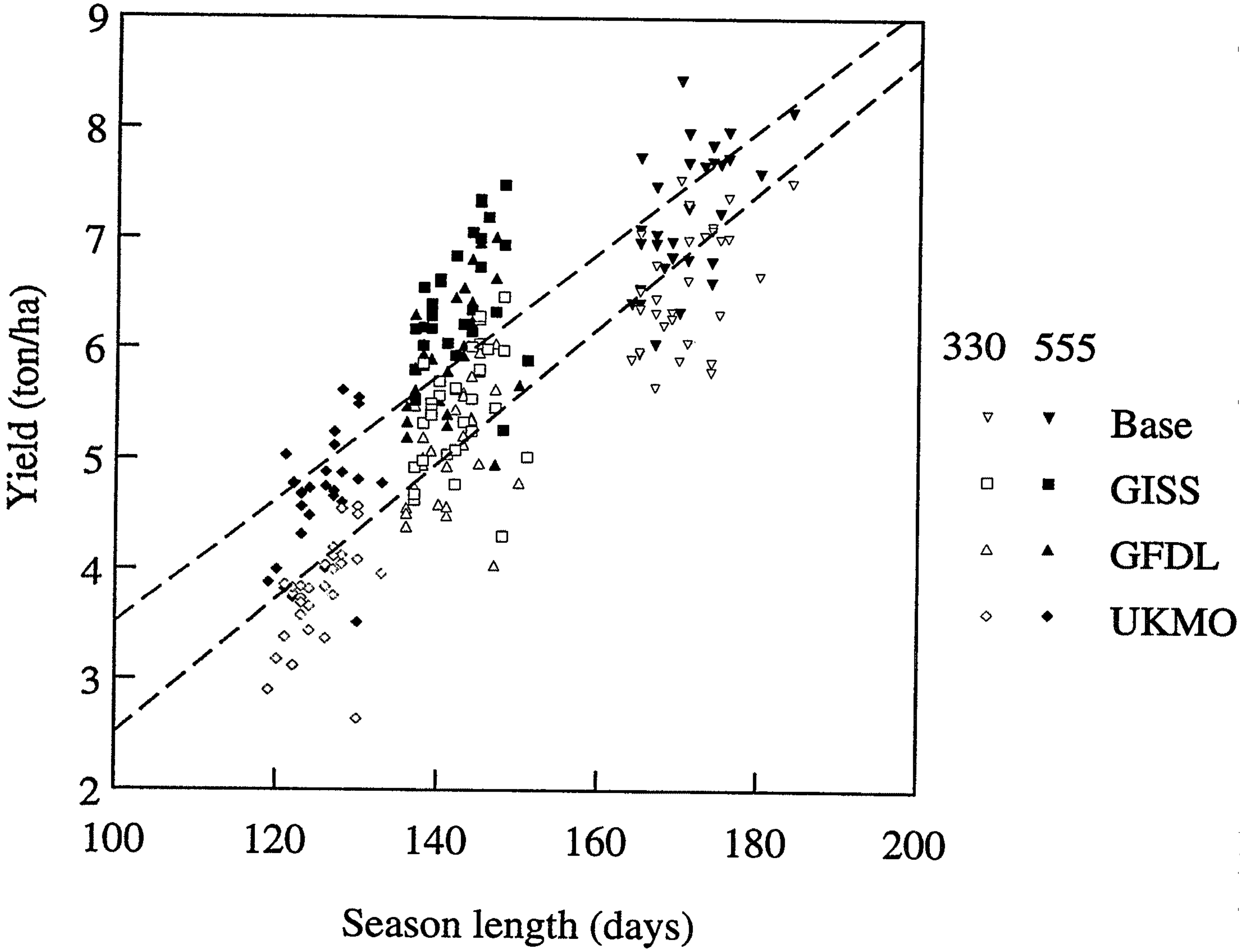

Figure 2. **Effects of season length on irrigated wheat yield at Griffith, NSW.**