IMPACT OF CLIMATE CHANGE ON MAIZE YIELD IN CENTRAL AND NORTHERN GREECE: A SIMULATION STUDY WITH CERES-MAIZE

G. KAPETANAKI[1] and C. ROSENZWEIG[2]
[1]*National Agricultural Research Foundation, Institute for Soils Classification and Mapping, Larissa, Greece*
[2]*NASA/Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, New York, USA*

(Received 23 May 1996; accepted in final form 31 May 1996)

Abstract. The potential impacts of climate change on the phenology and yield of two maize varieties in Greece were studied. Three sites representing the central and northern agricultural regions were selected: Karditsa, Naoussa and Xanthi. The CERES-Maize model, embedded in the Decision Support System for Agrotechnology Transfer (DSSAT 3.0), was used for the crop simulations, with current and possible future management practices. Equilibrium doubled CO_2 climate change scenarios were derived from the GISS, GFDL, and UKMO general circulation models (GCMs); a transient scenario was developed from the GISS GCM transient run A. These scenarios predict consistent increases in air temperature, small increases in solar radiation and precipitation changes that vary considerably over the study regions in Greece. Physiological effects of CO_2 on crop growth and yield were simulated. Under present management practices, the climate change scenarios generally resulted in decreases in maize yield due to reduced duration of the growing period at all sites. Adaptation analyses showed that mitigation of climate change effects may be achieved through earlier sowing dates and the use of new maize varieties. Varieties with higher kernel-filling rates, currently restricted to the central regions, could be extended to the northern regions of Greece. In the central regions, new maize varieties with longer grain-filling periods might be needed.

Key words: Greece, maize, climate change, CO_2 effects, adaptation, crop simulation.

1. Introduction

Increased concentration of carbon dioxide (CO_2) and other radiatively active trace gases are projected to produce global warming with associated changes in hydrological regimes (IPCC, 1996). If emissions continue to increase at their current rate CO_2 concentration in the atmosphere will double by 2050. Computer simulations indicate that the average global temperature will increase by 1.5°C to 4.5°C (anthropogenic sulfate aerosols in the troposphere could partially counter this warming trend, IPPC 1996). The largest warming is expected at higher latitudes, mainly in autumn and winter, although significant changes are likely to occur worldwide (Parry *et al.*, 1988). Since climate conditions directly affect the production of crops, global warming will clearly have an impact on global agricultural productivity.

Many studies have evaluated the effect of future climate change or variability on agricultural ecosystems (e.g., Parry *et al.* 1988; Rosenberg and Crosson, 1991;

Mitigation and Adaptation Strategies for Global Change **1:** 251–271, 1997.

Rosenzweig and Parry, 1994). One method of impact analysis has been developed based on dynamic crop growth simulation models that have been calibrated and validated for regional agricultural crop performance (Basci *et al.*, 1991; Rosenzweig, 1990; Rosenzweig and Iglesias, 1994; Rosenzweig *et al.*, 1995; Wolf and Van Dieppen, 1995).

The purpose of this study is to evaluate and analyze the impact of climate change on maize production in Greece, and to estimate possible adaptation responses by farmers to predicted future climatic conditions.

2. Background

Maize is one of the main crops grown in the European Union (EU). Approximately 85% of the total maize area in the EU is located in Spain, Italy and France. The EU maize area has increased slightly (about 5%) during the last 20 years, due to an increase in cultivated areas in Spain, Germany and Greece (Wolf and Van Dieppen, 1995).

Greece is a Mediterranean country, with hot, dry summers and cold, wet winters. Approximately 85% of the annual precipitation falls between October and April, totaling about 430 mm during these months. Temperature and solar radiation during the growth cycle of the maize crop (spring and summer) are favorable for maize production.

Maize, an important national crop, is cultivated under irrigation and high fertilizer levels in almost every region of Greece. However, production is concentrated mainly in central and northern regions (87% of the total) (Figure 1). Fertilizer applications during the growing period average 150 kg N/ha, but application levels can reach up to 350 kg N/ha in order to achieve yields of 10000 kg/ha.

Greece produces about 1.7 million tons of maize every year. In the last decades, the average yield has increased rapidly, from 3100 kg ha^{-1} in the 1960s, to 4800 kg ha^{-1} in the 1970s, to 9600 kg ha^{-1} in the 1980s, due to new varieties and improved technology. Yields in central and northern Greece show a sharp increase in yield beginning in 1980 and 1981, probably due to a changeover from older varieties such as Pioneer 3707 to improved varieties with higher rates of kernel-filling such as Pioneer 3183.

3. Methods

The CERES-Maize model (Jones & Kiniry, 1986; Ritchie *et al.* 1989) embedded in the Decision Support System for Agrotechnology Transfer (DSSAT) v.3.0 by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1989; Tsuji *et al.*, 1994) was used to simulate the phenology and yield of current maize varieties at three sites. DSSAT v.3.0 is a useful tool for running and validating

Climatic characteristics of study sites.

Sites	Karditsa	Naoussa	Xanthi
Period	1980-89	1983-92	1978-85
Mean daily min. temperature (°C).	8.60	8.94	10.51
Mean daily max. temperature (°C).	23.25	19.70	19.50
Annual precipitation (mm)	744.00	626.00	788.00
Mean annual solar radiation (W.m^{-2})	147.00	153.00	166.00

Figure 1. Map of Greece showing the three simulation sites and their climatic characteristics.

crop models, for conducting sensitivity analyses and for evaluating risks associated with various climate change scenarios and management practices (Tsuji *et al.*, 1994).

Baseline conditions were simulated first, using observed meteorological data and current management conditions. Changed climatic conditions were then tested, using sensitivity analyses, and climate change scenarios derived from general circulation models (GCMs). Additionally, the study evaluated possible adaptation strategies such as changes in sowing date and cultivar that might reduce unfavorable effects of climate change on yield.

3.1. Sites and Data

Three sites were selected, representing the main agricultural regions of maize production (central and northern Greece): Karditsa (39° 22′ N, 21° 55′ E; 111m elevation); Naoussa (40° 39′ N, 22° 04′ E; 115 m); and Xanthi (41° 07′ N, 24° 53′ E; 65 m) (Figure 1). The meteorological data (daily maximum and minimum temperatures, precipitation, and solar radiation) at Karditsa and Xanthi were provided by the Tobacco Research Organization (TRO, 1995) for the period 1980–1989, and 1978–1985 respectively; at Naoussa, data were provided by National Agricultural Research Foundation (NAGREF, 1995) for the period 1983–1992. At all three sites irrigation is the predominant management practice.

Karditsa, located in the Thessalia region, is characterized by the highest spring and summer temperatures of the three sites. It represents a large cultivated area of about 5000 ha, with an average annual yield of 9500 kg ha^{-1} over the period 1980–1989.

Naoussa, in northern Greece, represents the Imathia region. It is characterized by lower mean daily maximum temperatures than Karditsa. It also represents a large fertile region with an average grain yield of 10000 kg ha^{-1}.

Xanthi, in north-eastern Greece, represents the largest maize-growing area (about 15000 ha), and has an average yield of 9500 kg ha^{-1}. In this region spring precipitation is higher than in the other two regions.

3.2. Crop Models

The CERES-Maize model (Jones & Kiniry, 1986; Ritchie *et al.*, 1989) simulates maize growth, development and yield as a function of plant genotypes, weather and soil data, and crop management practices. The model has been modified to simulate the physiological effects of higher atmospheric CO_2 – changes in photosynthesis and evapotranspiration (ET) – based on experimental literature (Peart *et al.*, 1989; Rosenzweig, 1990). Further details about the model can be found in Tsuji *et al.* (1994).

The input weather variables are daily solar radiation (MJ m^2 day^{-1}, which we calculated using sunshine hours data), minimum and maximum temperatures (°C) and precipitation (mm day^{-1}). Representative soil profiles for each site were created with the soil utility program in DSSAT 3.0, using data obtained from the Institute for Soil Classification and Mapping in Greece. The management factors for the CERES-Maize model were determined for each site according to information provided by the local Department of the Ministry of Agriculture. Management factors

Table 1

Genetic coefficients of PIO 3707, PIO 3183, K1 and K2 varieties used as inputs for the CERES-Maize model.

Coefficient	PIO 3707	PIO 3183	K1	K2
P1: Duration of the juvenile phase (degree-days).	200.0	260.0	260.0	260.0
P2: sensitivity to photoperiod (days).	0.700	0.500	0.500	0.500
P5: duration of kernel filling period (degree-days).	750.0	750.0	750.0	750.0
G2: maximum number of kernels per plant (kernels/plant).	590.0	600.0	780.0	600.0
G3: maximum rate of kernel-filling (mg/day).	6.3	8.5	10.0	9.0

PIO 3707 until 1980 at Xanthi.

PIO 3183 from 1980 until 1985 in the three study sites.

K1 calibrated from 1986 until 1989 at Karditsa.

K2 calibrated from 1986 until 1992 at Naoussa.

and practices used in the simulations included planting date (April 1 at Karditsa and Naoussa and the April 20 at Xanthi), sowing depth (7.0 cm), plant population (7.5 plant m^{-2}), row spacing (62 cm), irrigation management and fertilizer management practice (N:330 kg ha^{-1}, P:80 kg ha^{-1} and K:80 kg ha^{-1}). Simulations were done with automatic irrigation using the sprinkler method, assuming 100% efficiency of application and availability of water; and application of irrigation when soil moisture fell to 50% of field capacity.

3.3. Calibration and Validation

Ceres-Maize was calibrated through a number of independent tests for different genetic coefficients that characterize the maize varieties presently cultivated in Greece (Table 1). An existing maize variety (Pioneer 3183), the principal variety used in Greece between 1980–1985, was selected from the genetic data file in the DSSAT 3.0 program. Its genetic coefficients were used as input for the initial runs of the model, at Karditsa for the years 1980–1985, and at Naoussa for the years 1983–1985.

For the following simulation years (1986–1989 at Karditsa and 1986–1992 at Naoussa), the Pioneer 3183 (PIO 3183) genetic coefficients G2 (maximum possible number of kernels per plant) and G3 (kernel-filling rate during the linear grain-filling stage) at Karditsa and G3 at Naoussa were modified to improve the fit of the model (i.e., the minimum deviations between observed and estimated yields and duration of the growing season). Thus, we estimated the two calibrated varieties, K1 and K2, at these two sites respectively for the later simulation period (Table 1).

At Xanthi, the cultivar Pioneer 3707 (PIO 3707) was used for the years 1978–1980. A small modification was made to the PIO 3707 photoperiod sensitivity (P5) genetic coefficient at this site. The original PIO 3183 was used for 1980–1985.

4. Climate Change Scenarios

Climate change scenarios for the three regions were derived based on calculated monthly changes in maximum and minimum temperatures, precipitation, and solar radiation between current and predicted future climatic conditions. Climate change scenarios included sensitivity analyses, and equilibrium and transient scenarios derived from GCM doubled CO_2 experiments.

4.1. Sensitivity Scenarios

A sensitivity analysis of CERES-Maize was made using systematic changes in minimum and maximum air temperatures, solar radiation, and CO_2 levels. Sensitivity scenarios were created by combining step changes in the different climate variables. The model was run for five minimum and maximum temperature changes, (0°C, +1°C, +2°C, +3°C and +4°C); four solar radiation levels; (−20%, −10%, +10%, +20%); five combinations of the mean temperature and solar radiation changes; and two CO_2 levels: ambient, 330 ppm; and elevated, 550 ppm, at all three sites. The latter CO_2 concentration corresponds to a doubling of radiative forcing from 330 ppm, including the effects of greenhouse gases other than CO_2. The response variables analyzed were yield and season length.

4.2. Equilibrium Scenarios

Three GCMs were used to derive climate change scenarios: those developed at the Goddard Institute for Space Studies (GISS; Hansen *et al.*, 1983) the Geophysical Fluid Dynamics Laboratory (GFDL; Manabe and Wetherland, 1987), and the United Kingdom Meteorological Office (UKMO; Wilson and Mitchell, 1987). For equilibrium climate change scenarios, runs of the GCMs depicting the current climate used current atmospheric CO_2 levels ($1 \times CO_2$). Then, GCMs were run until climatic equilibrium was reached following an instantaneous equivalent doubling of CO_2 ($2 \times CO_2$). Mean monthly temperature differences, and precipitation and solar radiation ratios were calculated for the gridboxes in Greece between the $2 \times CO_2$ and $1 \times CO_2$ GCM runs. These monthly changes were then applied to the daily observed baseline climate datasets to create climate change scenarios for each site, which were then used as input for CERES-Maize.

Temperature increased considerably under the three GCMs at all sites, with the largest annual increases occurring under the UKMO scenario (7.0°C and 7.6°C) at the northern sites (Xanthi and Naoussa). The GFDL and GISS scenarios predicted annual temperature changes ranging from 4.0°C to 4.6°C (Table 2).

Table 2

Changes in annual mean temperature (°C), precipitation (%), and solar radiation (%) in the equilibrium 2 × CO_2 and transient climate change scenarios.

	Equilibrium 2 × CO_2 scenarios			Transient scenario		
	GISS	GFDL	UKMO	2010	2030	2050
Temperature (°C)						
Karditsa	4.0	4.2	4.6	1.6	2.9	4.2
Naoussa	4.0	4.6	7.0	1.6	2.9	4.2
Xanthi	4.0	4.6	7.6	1.6	2.9	4.2
Precipitation (%)						
Karditsa	+20	+9	−6	−10	−13	−6
Naoussa	+20	+10	+5	−10	−13	−6
Xanthi	+20	+10	+2	−10	−13	−6
Solar radiation (%)						
Karditsa	+1	+4	+4	0	+2	+2
Naoussa	+1	−1	+7	0	+2	+2
Xanthi	+1	−1	+9	0	+2	+2

The three GCMs generally predicted increases in precipitation, although there was a wide range of projections. The UKMO model predicted close to zero precipitation change on average, while the GISS and GFDL scenarios had large precipitation increases (about 20%).

Small increases in solar radiation were predicted by the GCMs, with an average annual increase of 3% in the GFDL and the UKMO scenarios at Karditsa and an increase of about 8% on average in the UKMO scenario at the other two sites. GISS predicted less than 1% increase in solar radiation for all sites.

4.3. Transient Scenario

A transient climate change scenario was also derived from a run of the GISS GCM with gradually increasing trace-gas forcing (Hansen *et al.*, 1988). This scenario was generated for 2010, 2030 and 2050, and assumed CO_2 concentrations of 405, 460, and 530 ppm, respectively, for these decades. The transient climate change scenario was developed using the same procedure as for the equilibrium scenarios.

In the transient scenario, each time-step implies a further temperature increase (Table 2). The temperature increases were fairly linear, reaching a maximum mean annual increase of 4.2°C by 2050. In general, changes in annual precipitation were slightly negative, while predicted annual solar radiation values increased slightly (2%).

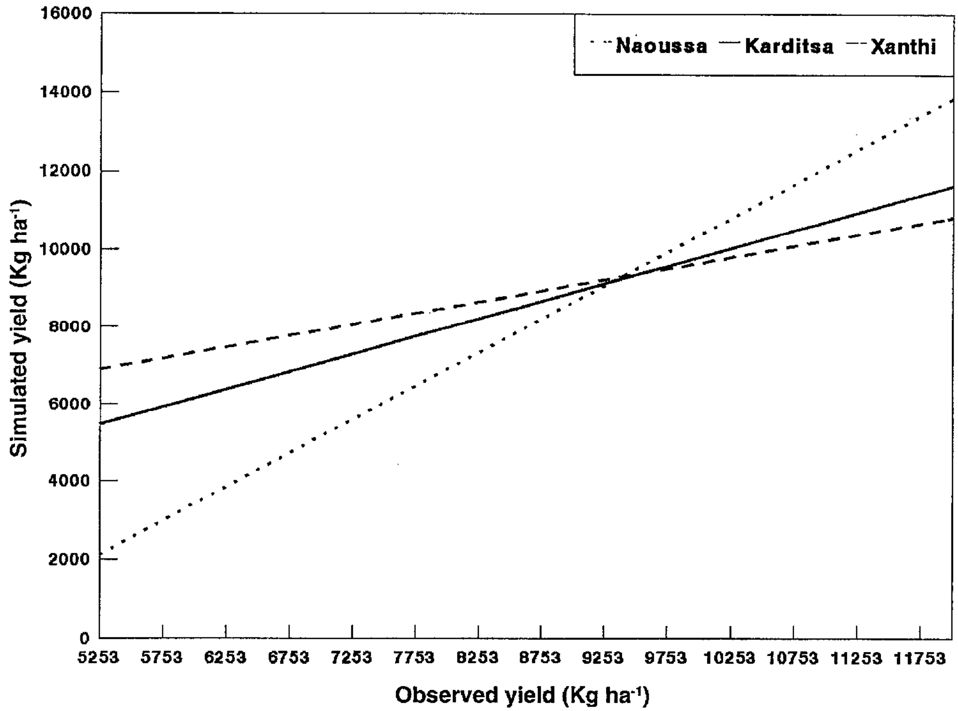


Figure 2. Observed and simulated yields cultivated at the three sites using regression analysis.

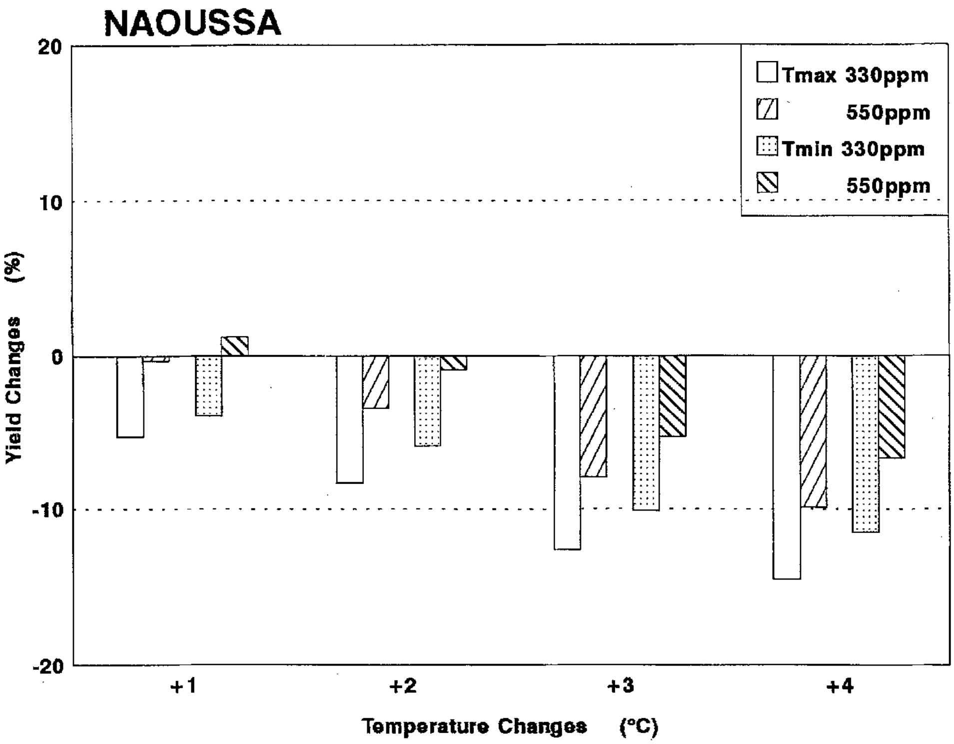
5. Results and Discussion

5.1. Calibration and Validation

Simulated yields were compared with observed yields over the same periods for each location (Figure 2). The coefficients of determination between simulated and observed values were 0.76, 0.55 and 0.60 for Karditsa, Naoussa and Xanthi respectively. The high values of the R^2 were deemed adequate for use of the calibrated maize model for the climate change impact study.

5.2. Sensitivity Analysis

Minimum and maximum temperature. Increases in temperature were found to decrease simulated yield. In the case of climate change alone (CO_2 level 330 ppm), an increase in maximum temperature of 2°C decreased yields by 4.5% at Karditsa and 8.5% at Naoussa and Xanthi; an increase in maximum temperature of 4°C resulted in yield decreases of approximately 15% at Naoussa and Xanthi and 4.3% at Karditsa (Figure 3).



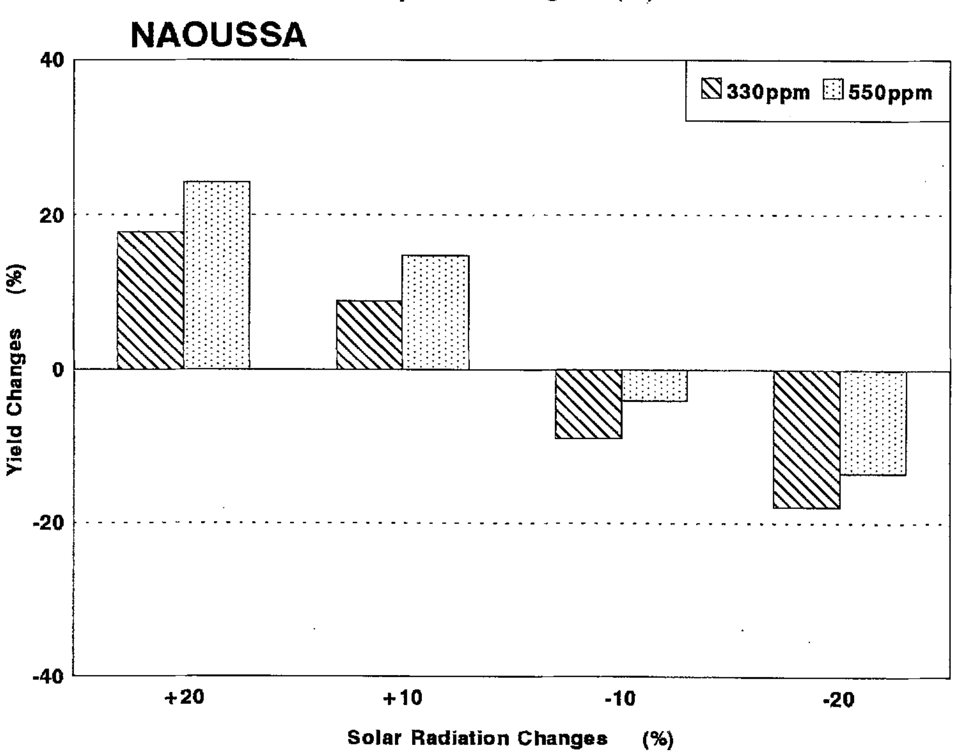


Figure 3. Sensitivity of simulated maize yield (K2 variety at Naoussa) to changes in maximum and minimum temperature (a) and in solar radiation (b) without and with direct CO_2 effects.

Increasing the minimum temperature by 1 to 4°C resulted in yield reductions of between 1% and 11.5%. The largest decreases accompanied the +4°C changes in northern Greece (Xanthi and Naoussa sites). At the Xanthi site the yield reductions that accompanied increasing maximum temperature were approximately twice those that accompanied increasing minimum temperature. This result for maize is consistent with the simulation results reported by Rosenzweig and Tubiello (1996) for wheat.

Minimum and maximum temperature plus CO_2. The physiological effects of CO_2 on crop growth partially compensated for the adverse impacts of temperature increases on simulated yields. In northern Greece (Xanthi and Naoussa), a 4°C increase in maximum temperature resulted in an average 13.5% decrease in yield with no increase in CO_2 (330 ppm), and in a 9.5% decrease when temperature change was coupled to elevated CO_2 (550 ppm) (Figure 3). At Karditsa, yield reductions due to maximum and minimum temperature changes with a 330 ppm CO_2 level were the lowest among all sites. Changes in yield were slightly positive when the direct effects of CO_2 were taken into account. The calibrated maize variety K1 used at this site appears to be less sensitive to temperature increases than the varieties used at the other sites, due to its longer grain-filling period.

Solar radiation. Increases in solar radiation produced positive yield changes, while decreases in solar radiation decreased yields. Responses to solar radiation were similar at all sites, and results were similar for both CO_2 concentrations (Figure 3). Yield increases for +10% and +20% radiation were +9% and +18% at 330 ppm and +15% and +24% at 550 ppm; yield decreases for −10% and −20% solar radiation were −9% and −18% at 330 ppm and −4% and −14% at 550 ppm.

Combined temperature, solar radiation, and CO_2. Maize yields generated from various combinations of temperature and solar radiation changes, both with and without the direct effects of CO_2, are shown in Figure 4 for the Karditsa site. At this site, the combination of temperature and radiation increases (1°C to 3°C and +10% and 20%, respectively) caused yield increases, both with and without direct CO_2 effects. This is probably due to the high kernel-filling rate during the linear grain-filling stage (coefficient G3; see Table 1). For the northern sites, increases of 1°C to 3°C combined with a +20% change in radiation and the direct effects of 550 ppm resulted in small yield changes that are close to zero. Generally, no significant interactions among these variables were found for these simulations.

Discussion. Maize is a C_4 plant and responds to increases in solar radiation by increasing its rate of photosynthesis due to high light- saturation levels (Jones, 1992; Maytin *et al.*, 1995). CERES-Maize uses a linear relationship between dry matter production rate and daily solar radiation (Jones and Kiniry, 1986); thus

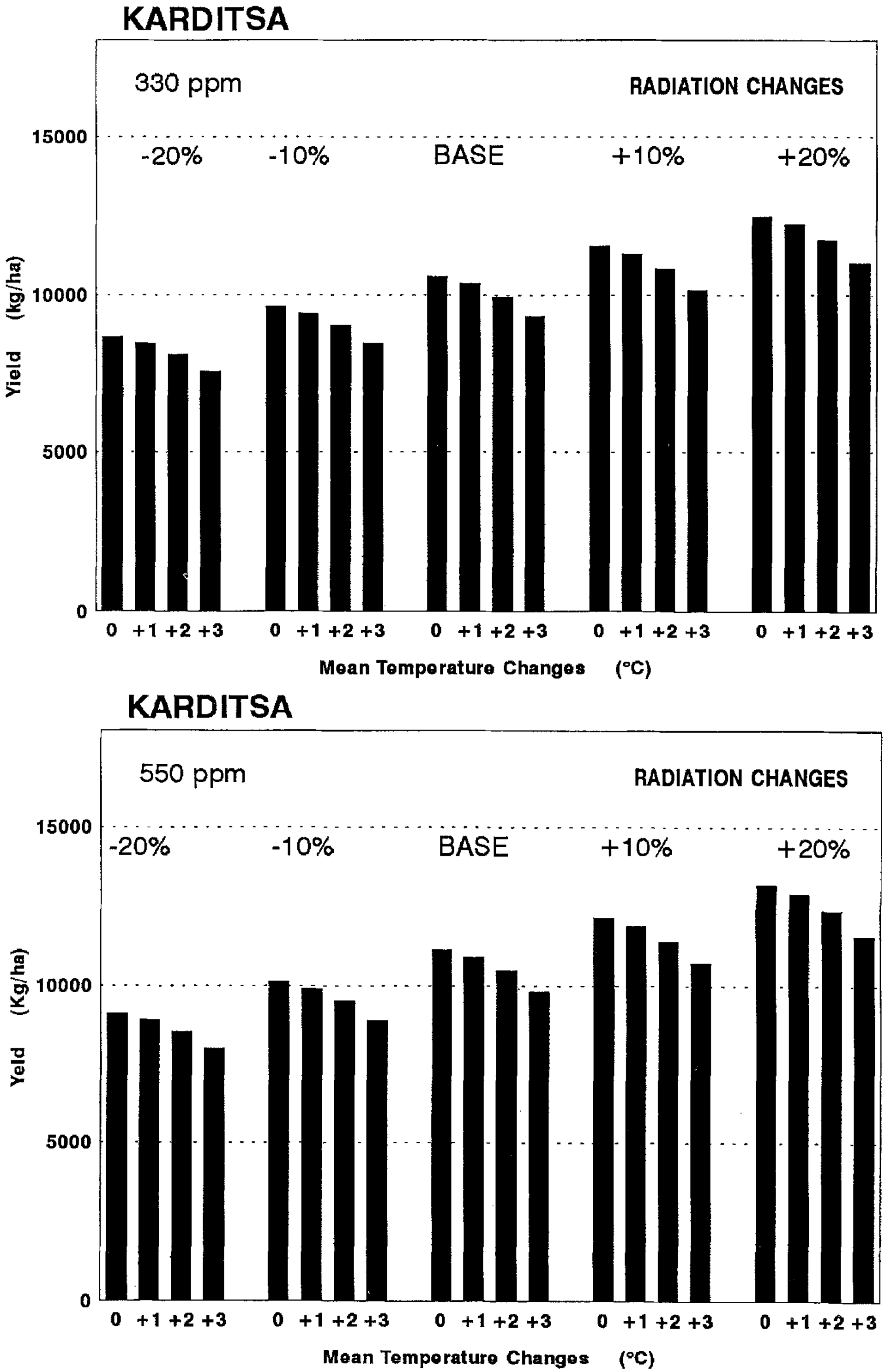


Figure 4. Sensitivity of simulated maize yield (K1 variety at Karditsa) to changes in mean temperature and solar radiation, without (a) and with (b) direct CO_2 effects.

Table 3

Effects of GISS, GFDL, and UKMO climate change scenarios (with direct CO_2 effects) on maize yield (kg ha^{-1}), season length (days), season precipitation (mm), evapotranspiration (mm), and irrigation demand (mm).

Site Variety	Simulated variable	BASE	GISS	GFDL	UKMO
KARDITSA	Yield kg ha^{-1}	10578	10250	10530	8985
K1	S.Len. days	129	111	115	111
	S.Prec. mm	168	198	144	136
	ET mm	457	322	364	341
	Irrig. mm	329	188	252	218
NAOUSSA	Yield kg ha^{-1}	9484	8689	8487	7989
K2	S.Len. days	139	113	113	106
	S.Prec. mm	216	239	176	209
	ET mm	439	307	337	323
	Irrig. mm	209	97	149	113
XANTHI	Yield kg ha^{-1}	8872	8214	8038	6983
PIO 3183	S.Len. days	124	105	101	98
	S.Prec. mm	234	289	164	213
	ET mm	415	298	322	312
	Irrig. mm	182	69	148	103

the responses of simulated yields to varying solar radiation were not surprising (Figure 3).

In these simulation experiments, temperature change was found to have a strong influence on the length of the phenological stages, while changes in solar radiation and higher CO_2 levels had no effect on season length. Mean temperature increases of +2°C resulted in an average decrease in growing period length of 7 days at the northern sites and of 3 days at the central site. Average growing period length decreases of 13 days at northern sites and 8 days at the central site accompanied mean temperature increases of 4°C.

5.3. GCM EQUILIBRIUM CLIMATE CHANGE SCENARIOS

Simulated yield, growing period length, precipitation, evapotranspiration, and irrigation requirements for the GISS, GFDL and UKMO GCM climate change scenarios are given in Table 3 for the three sites. Only the results which included the direct of CO_2 effects are analyzed as they are assumed to be more realistic than simulations with climate change alone.

Yield. All the GCM scenarios projected reductions in maize yield when compared to present climate conditions (Table 3). The main cause for the yield decreases is a shortening of the growing period, particularly the grain- filling stage, due to more rapid accumulation of thermal units associated with higher temperatures. At the northern sites, calculated decreases of yield for the three scenarios ranged from 7.5% to 21% (Table 3). At the central site, Karditsa, the largest yield decrease was found with the UKMO scenario (15%), compared to very small (0–3%) decreases in yield with the GISS and GFDL scenarios (Table 3).

Figure 5 shows the cumulative probability of simulated maize yield calculated using the DSSAT3 statistical package (Tsuji *et al.*, 1994), under present climate conditions (baseline) and the three GCM climate change scenarios at Karditsa. The probability of obtaining present mean yield levels (10578 kg/ha) at this site decreased slightly under the GISS and the GFDL scenarios and was close to zero under the UKMO scenario. However, yield variability decreased under all climate change scenarios, making the GISS and GFDL scenarios appear more 'farmer friendly' with respect to current climate conditions. However, it must be noted that the climate change scenarios used in this study were generated by keeping the current climate variability constant, while changing mean quantities only. This study therefore does not assess the potential changes to maize yields due to changed climate variability, which may in fact characterize future climate change (Mearns *et al.*, 1996).

Length of growing period. The three scenarios resulted in a shortening of the maize growing period at all sites (Table 3). Maturity dates advanced by an average of over 3 weeks. The UKMO scenario, which is characterized by the highest temperature increases, produced a four-week decrease in the growing period at Naoussa. Maize growing periods at Karditsa were less responsive to high temperature.

Irrigation demand. The irrigation needed for the maize crop during the growing period decreased significantly under the climate change scenarios at all sites (Table 3). The GISS scenario showed the largest decreases, of around 50% on average, due in part to large increases in growing period precipitation. Although the increase in total growing period precipitation was 15%, the precipitation rate (per day) was quite a bit larger since the growing season was, on average, about three weeks shorter than the base growing period. The accompanying reduction in crop growth was also an important factor in the crop's decreased irrigation demand.

Evapotranspiration. Simulated crop evapotranspiration (ET) under the GISS, GFDL, and UKMO climate change scenarios decreased in relation to the present climate at all sites (Table 3). Total crop ET decreased due both to shortening of the crop growing period and to CO_2 effects on stomatal closure. Irrigation demand decreased due to reduced crop growth and yield. Figure 6 shows the variation of simulated daily evapotranspiration and cumulative evapotranspiration during the

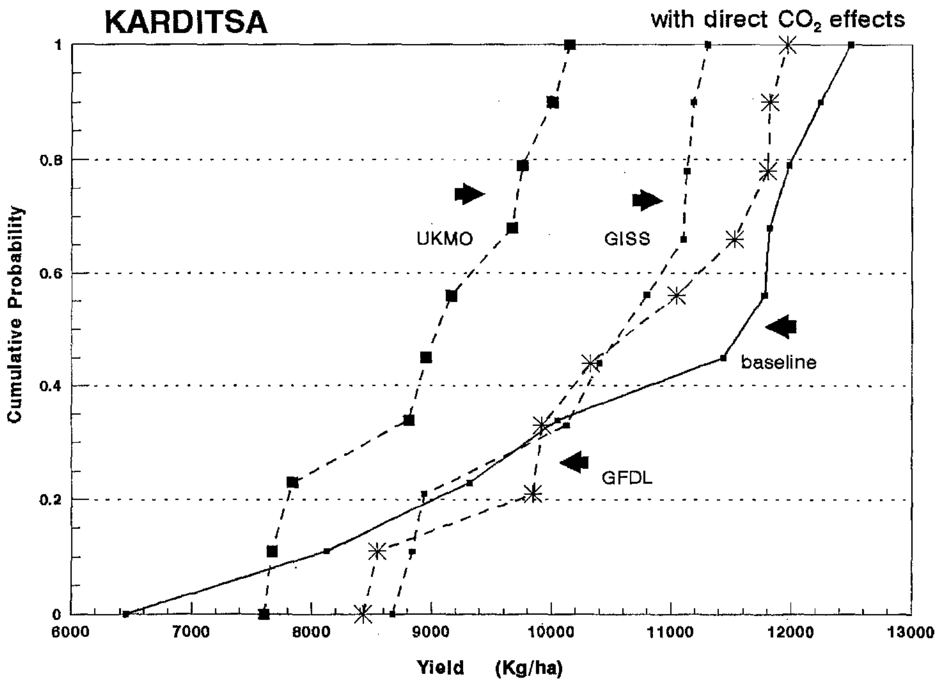


Figure 5. Cumulative probability of simulated maize yield for the present climate (baseline) and the GISS, GFDL, and UKMO climate change scenarios, with direct CO_2 effects, at Karditsa.

growing period for present climate conditions (baseline run) and the three climate change scenarios at Naoussa. Decreases in ET were similar among the sites, with average decreases of 30%, 22%, and 25% for the GISS, GFDL and UKMO scenarios respectively.

Crop water use. Higher levels of atmospheric CO_2 have been shown to increase photosynthesis, yield, and water-use efficiency (the ratio of yield to the amount of water used in evapotranspiration) in experimental settings (Acock and Allen, 1985). Simulated water-use efficiency in maize, calculated for the three scenarios, increased at all three sites. (Table 4).

5.4. Transient Scenarios

Yields of irrigated maize were also simulated at all sites for the transient climate change scenario derived from the GISS GCM, for the decades of the 2010s, 2030s, and 2050s (Table 5). Only the results that included the direct effects of CO_2 are analyzed. Generally, yields decreased with time, but the trends were not always linear.

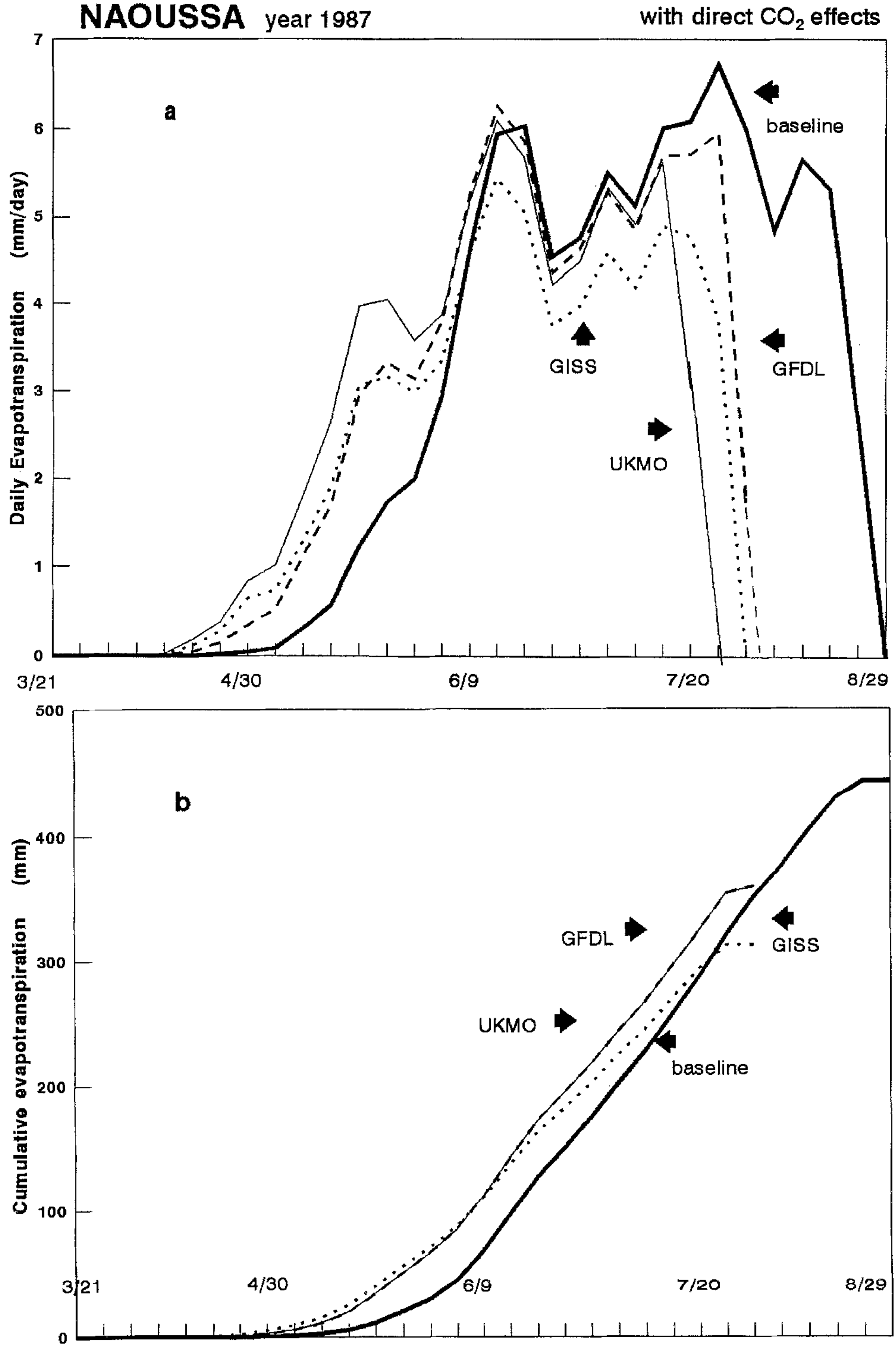


Figure 6. (a) Simulated daily evapotranspiration, and (b) cumulative evapotranspiration during the maize growing season for the present climate (baseline) and the GISS, GFDL, and UKMO climate change scenarios, with direct CO_2 effects, at Naoussa.

Table 4

Water use efficiency calculated as yield (kg ha^{-1})/total crop evapotranspiration (mm), with direct of CO_2 effects at the three sites.

Site Variety	Baseline	GISS	GFDL	UKMO
KARDITSA K1	23.1	31.8	28.9	26.3
NAOUSSA K2	21.6	28.3	25.2	24.7
XANTHI PIO 3183	21.4	27.6	24.9	22.4

Table 5

CERES-Maize yields (kg ha^{-1}) under the baseline weather and the transient climate change scenario.

Site Variety	Baseline	GISS 2010s	GISS 2030s	GISS 2050s
KARDITSA K1	10578	10477	9740	9646
NAOUSSA K2	9484	8434	7977	8105
XANTHI PIO 3183	8872	7989	7524	7237

The largest yield decreases occurred at the northern sites (Naoussa and Xanthi), where average yield changes were −10.5%, −15.5% and −16.5% for the 2010s, 2030s and 2050s respectively. Yield decreases at the central site, Karditsa, were smaller (−1.0%, −7.9% and −8.8% for the 2010s, 2030s and 2050s, respectively) because the maize K1 variety is better adapted to higher temperatures. Figure 7 gives the cumulative probabilities of simulated maize yield under present climate conditions (baseline) and the three decades of the transient climate change scenario at Karditsa. At this site, the probability of obtaining present yield levels decreased 10% for 2010; 40% for the 2030s and approached zero for the 2050s. Temperature increases were accompanied by a shortening of the maize growing period at all sites (Table 5).

6. Adaptation Strategies

Some possible strategies for adaptation to climate change involve changes in current management practices, (e.g. shifts in planting dates and changes in crop varieties). The UKMO scenario with direct CO_2 effects was chosen for the adaptation tests because it predicted the largest crop yield decreases.

6.1. Adjusted Planting Dates

Changes in planting date (10, 20, and 30 days earlier and 10 and 20 days later than current practice) was the first adaptation strategy examined for the three sites.

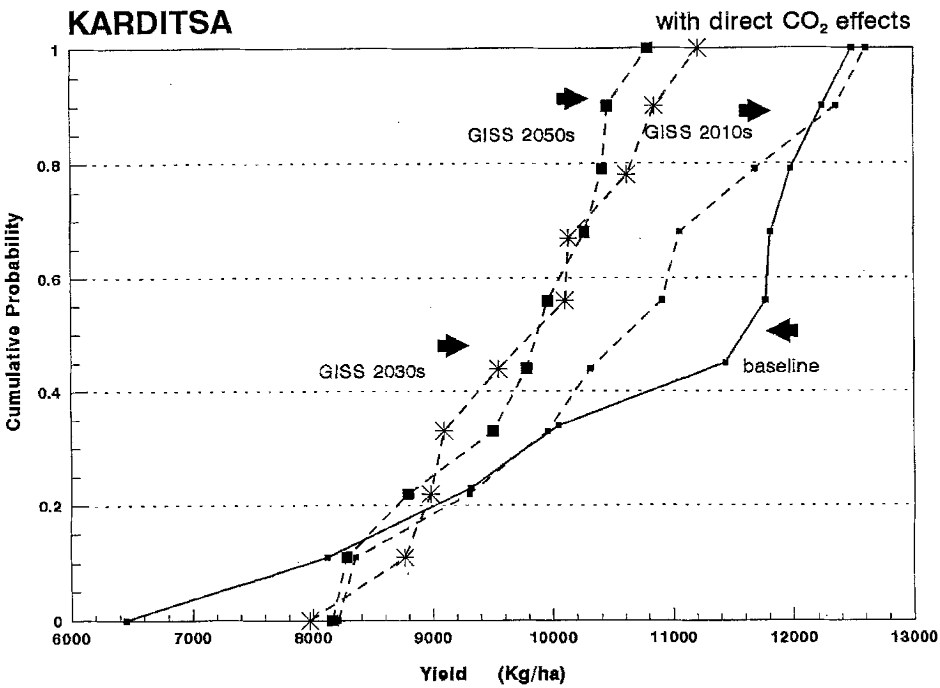


Figure 7. Cumulative probability of simulated maize yield for the present climate (baseline) and the transient climate scenarios at Karditsa.

Earlier planting dates did result in somewhat higher yields, but were not able to completely compensate for the negative effects of the UKMO climate change scenario (Figure 8). Later planting dates for the three study sites were associated with yield reductions under the UKMO scenario (Figure 8). In general, earlier planting dates allow crop development to proceed in a cooler growing season resulting in a longer duration of the grain-filling period and a higher potential yield. The cumulative probability curves for maize yield at Karditsa for earlier planting date are shown in Figure 9. The earlier planting date ameliorates the probability of obtaining adequate yields under the equilibrium UKMO scenario.

6.2. New Varieties

The second adaptation strategy tested was the use of new maize varieties having a longer duration of the kernel filling period. The three varieties K1, K2, and PIO 3183, originally used at the three sites, were modified by a higher coefficient P5 (see Table 1), from 750 to 800 degree days. The simulated new varieties, currently not available to farmers, were called maize K1-L, K2-L, and PIO 3183-L, respectively. Our analysis was based on the assumption that they might become available in the future through genetic improvement. Our calculations showed

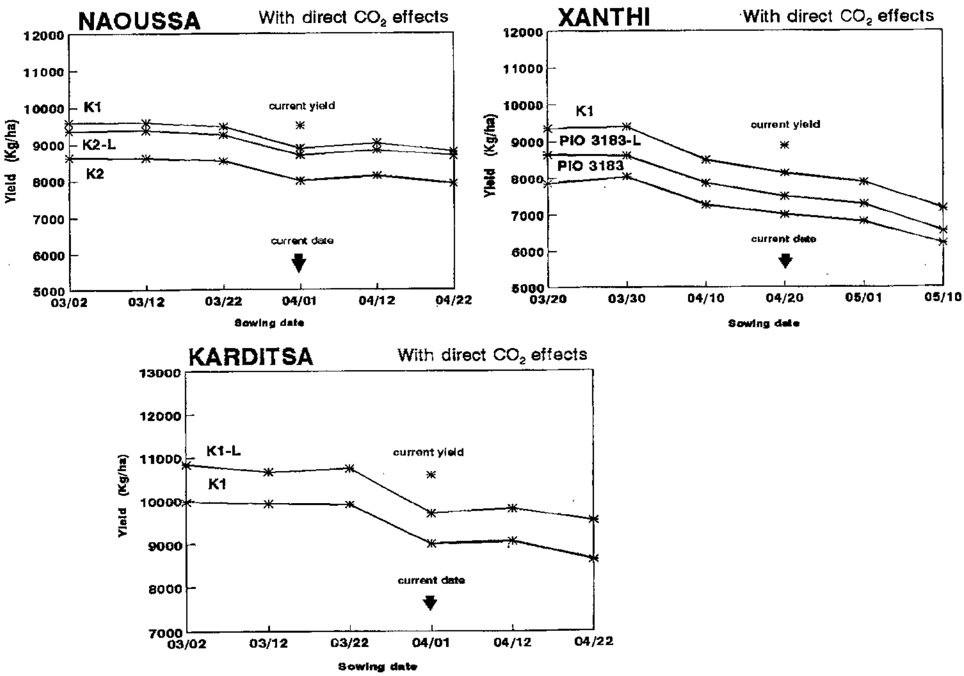


Figure 8. Sensitivity to changes in sowing dates and varieties of simulated maize yield for the UKMO scenario, with direct CO_2 effects. All sites.

that the introduction of these new varieties could help to partially counteract the negative effect of climate change at each of the three sites (Figure 8). The combined introduction of new varieties and earlier planting dates completely counterbalanced in our simulations the negative effects of climate change at the Karditsa site, but not entirely at the two northernmost sites.

A different strategy was then tested at the Xanti and Naoussa sites. Because of the predicted temperature increases in northern Greece (Table 2), it was possible to simulate a northward extension of the variety K1, presently restricted by temperature to central Greece. This variety has a higher potential grain filling rate than varieties currently sown in northern Greece (coefficient G3; see Table 1). Introduction of this variety at the two northern sites and earlier planting by 10 to 15 days completely counterbalanced the predicted negative effects of climate change on yields obtained with current varieties and current planting schedules (Figure 8).

Conclusions

The simulation results obtained from this study suggest that maize yield in central and northern Greece under present management practices may be reduced by climate change. Our study focused solely on the direct effects of climate change

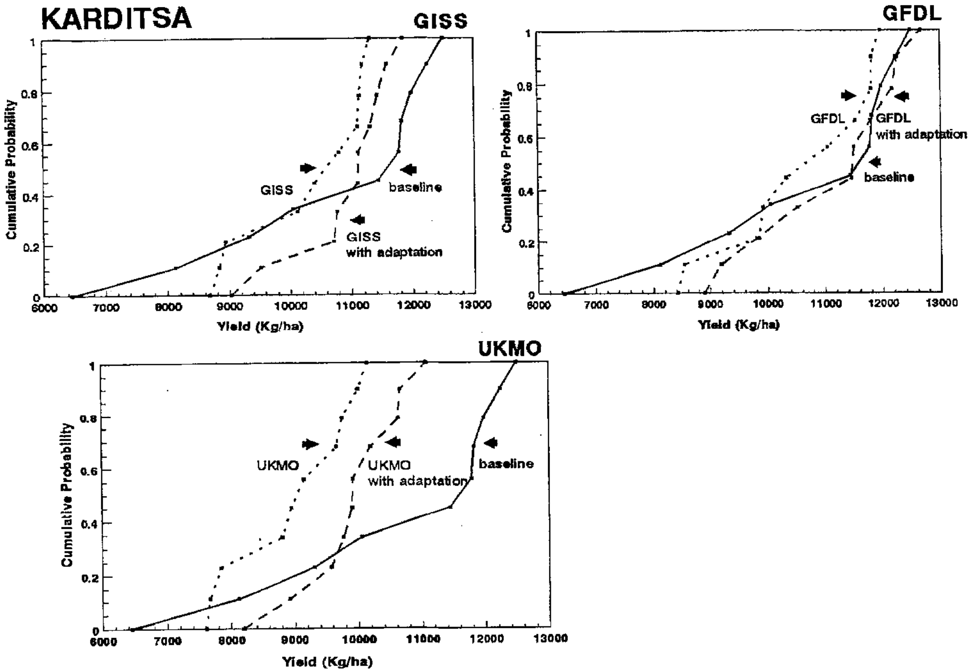


Figure 9. Cumulative probability of simulated maize yield for the present climate (baseline) and the GISS, GFDL, and UKMO climate change scenarios, without and with adaptation strategy (10 day earlier sowing under the current using variety K1) at Karditsa.

and elevated CO_2 on maize yields. Other factors, such regional economic trends and competition from other crops, that will also influence the future of Greek maize cultivation, were not analyzed.

The GCM scenarios resulted in yield reductions of up to 20%. Yield decreases were associated with higher temperatures that reduced the length of the growing period, particularly the grain filling-period. The simulated CO_2 effects only partially counterbalanced the negative effects of climate change at all three sites. Yield reductions were accompanied by significant decreases in irrigation requirements, with the largest decrease in irrigation requirements being more than 50%.

Most importantly, our results suggest that challenges to maize cultivation in Greece due to climate change may differ regionally. Adaptation strategies will need to be regionally devised as well. In the northern region, currently characterized by lower temperatures and higher precipitation, a northward extension of varieties currently sown in the central region of Greece, with higher kernel-filling rate, might be possible because of the predicted temperature increases. This cultivar change, coupled to earlier planting, appears likely to counterbalance the negative effects of climate change as predicted by three GCM scenarios. In the central region, with already high spring and summer temperatures in the current climate and related large irrigation requirements, adaptation might depend on future availability of new cultivars. Our simulations indicate that a change of present management practices (earlier planting date) and the introduction of a new cultivar, having longer duration of the kernel-filling period, appear capable of mitigating the negative effects of climate change.

Overall, the magnitude of yield changes and the potential for adaptive strategies predicted by our study indicate that climate change may present a moderate challenge for maize farmers in Greece.

The present study is a contribution to understanding the possible impacts of climate change on maize production in Greece. Future research will include more sites, management practices and varieties. In addition, potential changes in the frequency of extreme climate events, especially the occurrence of drought periods and competing demands for irrigation water need to be investigated. Finally, further research should consider the impact of climate change on the production of other major crops in Greece.

Acknowledgments

We thank Ana Iglesias, Rich Goldberg, Francesco Tubiello, Chris Shashkin, and three anonymous reviewers for their costructive help in preparing this paper.

References

Cock, B. and Allen Jr. L. H.: 1985. Crop responses to elevated carbon dioxide concentrations. In B. R. Strain and J. D.Cure (eds). *Direct Effects of Increasing Carbon Dioxide on Vegetation.* U.S. Department of Energy. DOE/ER–0238. Washington, D.C. pp. 33–97.

Basci, Z., Thornton, P. K. and Dent, J. B.: 1991. Impacts of Future Climate Change on Hungarian Crop Production: An Application of Crop Growth Simulation Models. *Agr. Syst.* **37**, 435–450.

Hansen, J., Russel, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., and Travis, L.: 1983. Efficient three dimensional global models for climate studies: Models I and II. *Monthly Weather Review* **111(4)**, 609–662.

Hansen, J., Fung, I., Lacis, A., Rind, D., Russel, G., Lebedeff, S., Ruedy, R., and Stone, P.: 1988. Global climate changes as forecast by the GISS 3-D model. *Journal of Geophysical Research* **93**, 9341–9364.

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT).: 1989. *Decision Support System for Agrothechnology Transfer Version 2.1 (DSSAT 2.1).* Dept. of Agronomy and Soil Science. College of tropical Agriculture and Human Resources. University of Hawaii. Honolulu.

IPCC. Climate Change, 1995: Impacts, Adaptations and Mitigations of Climate Change: Scientific-Technical Analyses, 1996. R. T. Watson, M. C. Zinyowera, R. H. Moss (Eds), Cambridge University Press, Cambridge, 890 pp.

Jones, C. A. and Kiniry, J. R.: 1986. *CERES-Maize: A simulation Model of Maize Growth and Development.* Texas A&M Press. College station.

Jones, H. G.: 1992. *Plants and Microclimate. A Quantitative Approach to Environmental Plant Physiology,* Second Edition, Cambridge University Press, Cambridge, U.K.

Manabe., S. and Wetherland R.T.: 1987. Large-scale changes in soil wetness induced by an increase in CO_2, *Journal of Atmospheric Science*, **44** 1211–1235.

Maytin, E. C., Achevedo, M. F., Jaimez, R., Andressem, R., Harwell, M. A., Robock, A., and Azocar, A.: 1995. Potential effects of Global Climate Change on the Phenology and Yield of Maize in Venezuela. *Climatic Change* **29**, 189–211.

Mearns, L. O. and Rosenzweig, C.: 1996. Formulation of climate change scenarios incorporating changes in daily climate variability and application to crop models, in: *Assessing Climate Change: The story of the Model Evaluation Consortium for Climate Assessment.* Chap. 15. Howe, W., and Henderson-Sellers, A. (Eds.). Academic Publishers, in press.

National Agricultural Research Foundation. (NAGREF): 1995. *Meteorological data files* Pomology Institute at Naoussa Greece, unpublished.

Parry, M. L., Carter,T. R., and Konijn, N. T.(eds).: 1988. The Impact of Climatic Variation on Agriculture. Vol. 1. *Assessments in Cool Temperate and Cold Regions.* Vol. 2. *Assessments in Semi-arid Regions.* Kluwer. Dordrecht. Netherlands.

Peart, R. M., Jones, J. W., Curry, R. B., Boote K., and Allen. Jr., L. H.: 1989. Impact of climate change on crop yield in the southeastern U.S.A. In J. B. Smith and D. A. Tirpak (eds). *The Potential Effects of Global Climate Change on the United States.* Report to Congress. U.S. Environmental Protection Agency. EPA–230–05–89–050. Appendix C. Washington, D.C.

Ritchie, J. T., Singh, U., Godwin, D., and Hunt, L.: 1989. *A User's Guide to CERES-Maize* v.2.10. International Fertilizer Development Center. Muscle Shoals.

Rosenberg, N. J., and Crosson, P. R.: 1991. Processes for Identifying Regional Influences of and Responses to Increasing Atmospheric CO_2 and Climate Change: The MINK Project. An Overview. *Resources for the Future.* Dept. of Energy. DOE/RL/01830t-H5. Washington, D.C. 35 pp.

Rosenzweig, C.: 1990. Crop response to Climate Change in Southern Great Plains: A simulation study. *Prof. Geog.* **42**, 20–39.

Rosenzweig, C., and Parry, M. L.: 1994. Potential Impact of climate change on world food supply. *Nature* **367**, 133–138.

Rosenzweig, C., and Iglesias, A. (eds).: 1994. *Implications of Climate Change for International Agriculture: Crop modeling study.* USEPA. Washington DC.

Rosenzweig, C., Allen, Jr., L. H., Harper, L. A., Hollinger, S. E., and. Jones, J. W. (eds).: 1995. *Climate Change and Agriculture: Analysis of Potential International Impacts.* ASA Special Publication No 59, Madison, WI.

Rosenzweig, C. and Tubiello, F. N.: 1996. Effects of Changes in Minimum and Maximum Temperature on Wheat Yields in the Central U.S.: A Simulation Study. *Agric. For. Meteorol.*, in press.

Tobacco Research Organization (TRO.).: 1995. *Meteorological data files.* Dept. of Tobacco Research Organization Greece, unpublished.

Tsuji, G. Y., Uehara, G., and Balas, S.(eds).: 1994. Decision Support System for Agrotechnology Transfer Version 3.0 (DSSAT V3.0). *International Benchmark Sites Network for Agrotechnology Transfer Project (IBSNAT).* University of Hawaii, Honolulu, Hawaii.

Wilson, C. A., and Mitchell, J. F. B.: 1987. A Doubled CO_2 Climate Sensitivity Experiment with a Global Climate Model Including a Simple Ocean. *J. Geophys. Res.* **92**, 315–343.

Wolf, J., and Van Dieppen, C. A.: 1995. Effects of Climate Change on Grain Maize Yield Potential in the European Community. *Climatic Change* **29**, 299–331.