IMPACTS OF GLOBAL CLIMATE CHANGE ON MEDITERRANEAN AGRIGULTURE: CURRENT METHODOLOGIES AND FUTURE DIRECTIONS

An Introductory Essay

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Abstract. Current trends in Mediterranean agriculture reveal differences between the Northern and Southern Mediterranean countries as related to population growth, land and water use, and food supply and demand. The changes in temperature and precipitation predicted by general circulation models for the Mediterranean region will affect water availability and resource management, critically shaping the patterns of future crop production. Three companion papers analyze in detail future impacts of predicted climate change on wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) production in Spain, Greece, and Egypt, and test farm- level adaptation strategies such as early planting and cultivar change with the aid of dynamic crop models. Strategies to improve the assessment of the potential effects of future climate change on agricultural production are discussed.

Key words: climate change, mediterranean region, agriculture, cereal production, impact assessment.

1. Introduction

There is increasing evidence that anthropogenic activity is affecting the earth's climate on a global scale, since greenhouse gas emissions enhance the heat-trapping capacity of the atmosphere (IPCC, 1996). Deforestation and other land-use activities are critically modifying natural biogeochemical cycles (e.g., the carbon and nitrogen cycles), which also interact with the global climate. Projected increases in world population will likely maintain these human pressures on the global environment for decades.

Because of the complexity and natural variability of climate, it is extremely difficult to prove with certainty that human-induced climate change is already under way. Instead, scientists have used sophisticated computer models, known as general circulation models (GCMs), to show that the earth's future climate is likely to be characterized by a rise in mean surface temperatures in the range of 1.5–4.5°C (although anthropogenic sulfate aerosols in the troposphere could partially counter this warming trend), an increase in the frequency of extreme weather events like floods and droughts, and by substantial changes in the regional patterns of temperature and precipitation (IPCC, 1996).

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Although many uncertainties exist with respect to the spatial and temporal variations of these predictions, climate change clearly has the potential to affect human welfare and economic activity. The extent to which climate change will be mitigated by concurrent action by the contributing nations is also uncertain. There is thus a need to assess the risks of climate change to human society, so that adaptation strategies can be devised to help cope with future problems (Mendelsohn and Rosenberg, 1994). One important sector with strong links between climate and human activities is agriculture (Rosenzweig and Hillel, 1995).

The papers that follow this essay analyze the potential effects of climate change on cereal production in three Mediterranean countries: Egypt, Greece, and Spain, and discuss the potential for developing farm-level adaptation strategies (El-Shaer *et al.*, 1996; Kapetanaki and Rosenzweig, 1996; Iglesias and Minguez, 1996). The Mediterranean region is chosen for the analysis because of the importance of agriculture for domestic food production and generation of export income, and because climate change could significantly and differentially affect crop productivity throughout the area. This may tend to exacerbate existing problems related to land and water use in the region. Specifically, water availability is at present the most important factor limiting cereal yields in Mediterranean countries, due to pronounced seasonal precipitation gradients, generally poor soils with low water-holding capacities, and extensive water use for irrigation in competition with other sectors of the economy (Lindh, 1992; Baric and Gasparovic, 1992). Further constraints to crop water budgets and irrigation requirements due to climate change will determine which countries in this region will be able to maintain economically viable production.

We present herein the methodologies that are common to these studies and discuss future directions needed to improve modeling techniques for climate change impacts on agriculture.

2. Mediterranean Region and Climate

The Mediterranean region comprises the Mediterranean sea and its coastal area, and includes eighteen countries. It can be roughly located between 30°N–50°N latitude and 10°W–40°E longitude. Climatically, it is characterized by mild temperatures, winter-dominated rainfall, and dry summers (Wigley, 1992). The Mediterranean countries can be grouped according to similar climatological and socio-economic characteristics: northern basin countries (Spain, France, Monaco, Italy, Former Yugoslavia, Albania, Greece) and southern basin countries (Turkey, Cyprus, Syria, Lebanon, Israel, Egypt, Libya, Malta, Tunisia, Algeria, Morocco). With respect to climate, northern regions are relatively more temperate and humid, while southern regions are warmer and drier, with endemic water shortages due to the interaction of relatively low seasonal rainfall and high evapotranspiration rates.

Table 1. Changes in temperature and precipitation as predicted by several GCMs, for either equilibrium ($2 \times CO_2$) or transient scenarios (decade of 2020s). Values are mean annual averages over the entire Mediterranean Region.

GCM	Resolution[1]	Scenario	ΔT(°C)	ΔP(%)
GISS	4 × 5	$2 \times CO_2$	3.94	−2.8
GFDL	R-30	$2 \times CO_2$	4.11	4.0
UKMO	5 × 7.5	$2 \times CO_2$	6.59	7.9
GFDL 1%	R15	Transient	1.51	−1.5
UKMO-tr	T21	Transient	2.60	−7.3
MPI	T21	Transient	1.43	−2.9

[1]Expressed as either lat × long or as number of spectral waves used in the numerical schemes.
(Higher numbers have higher resolution).

Greenhouse warming is predicted to change the larger-scale characteristics of the Mediterranean climate, and therefore to affect temperature, precipitation, and water availability. Predictions of changes in temperature, precipitation, and solar radiation from three GCMs are used in the companion papers: the GISS model developed at the NASA-Goddard Institute for Space Studies (Hansen *et al.*, 1983); the GFDL model developed at the Geophysical Fluid Dynamics Laboratories (Manabe and Weatherland, 1987); and the UKMO model developed at the United Kingdom Meteorological Observatory (Wilson and Mitchell, 1987).

For the Mediterranean region these models predict mean annual temperature increases in the range of 3.5–5.5°C for a doubling of atmospheric CO_2 concentration, with mean annual precipitation changes less clearly defined. All three GCMs predict a widening of the current seasonal precipitation gradient, which is likely to cause further reductions in water availability during the crop growing season (Wigley, 1992).

Figures 1 and 2 show seasonal trends in temperature and precipitation change as predicted by the current standard version of the GISS $2 \times CO_2$ equilibrium model, running at a resolution of 4° × 5° (Hansen and Ruedy, Personal Communication, 1996). GCM transient runs suggest that such temperature increases could be realized by the middle of the next century (e.g.: GFDL, Manabe *et al.*, 1992; Max Planck Institute (MPI), Cubash *et al.*, 1992; UKMO, Murphy and Mitchell, 1995), if current fossil fuel emission rates continue unabated and the negative forcing of anthropogenic aerosols in the troposphere is not considered. Table 1 provides a summary of GCM predictions for the Mediterranean region for equilibrium and transient GCM simulations (decade of 2020s).

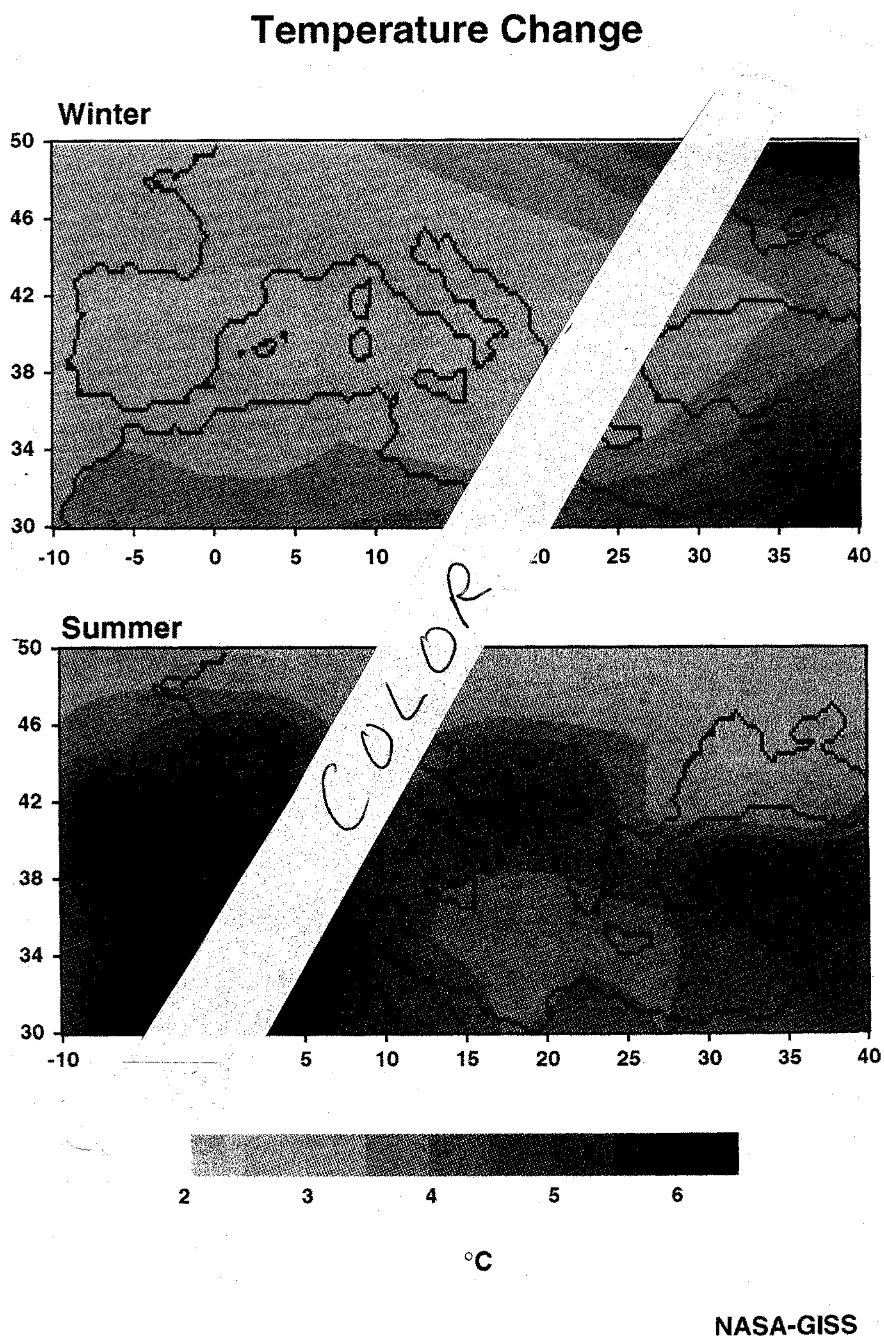

Figure 1. Seasonal mean temperature change for the Mediterranean region corresponding to a doubling of CO_2, as predicted by the GISS GCM. (1a) Winter (December, January, February); (1b) Summer (June, July, August).

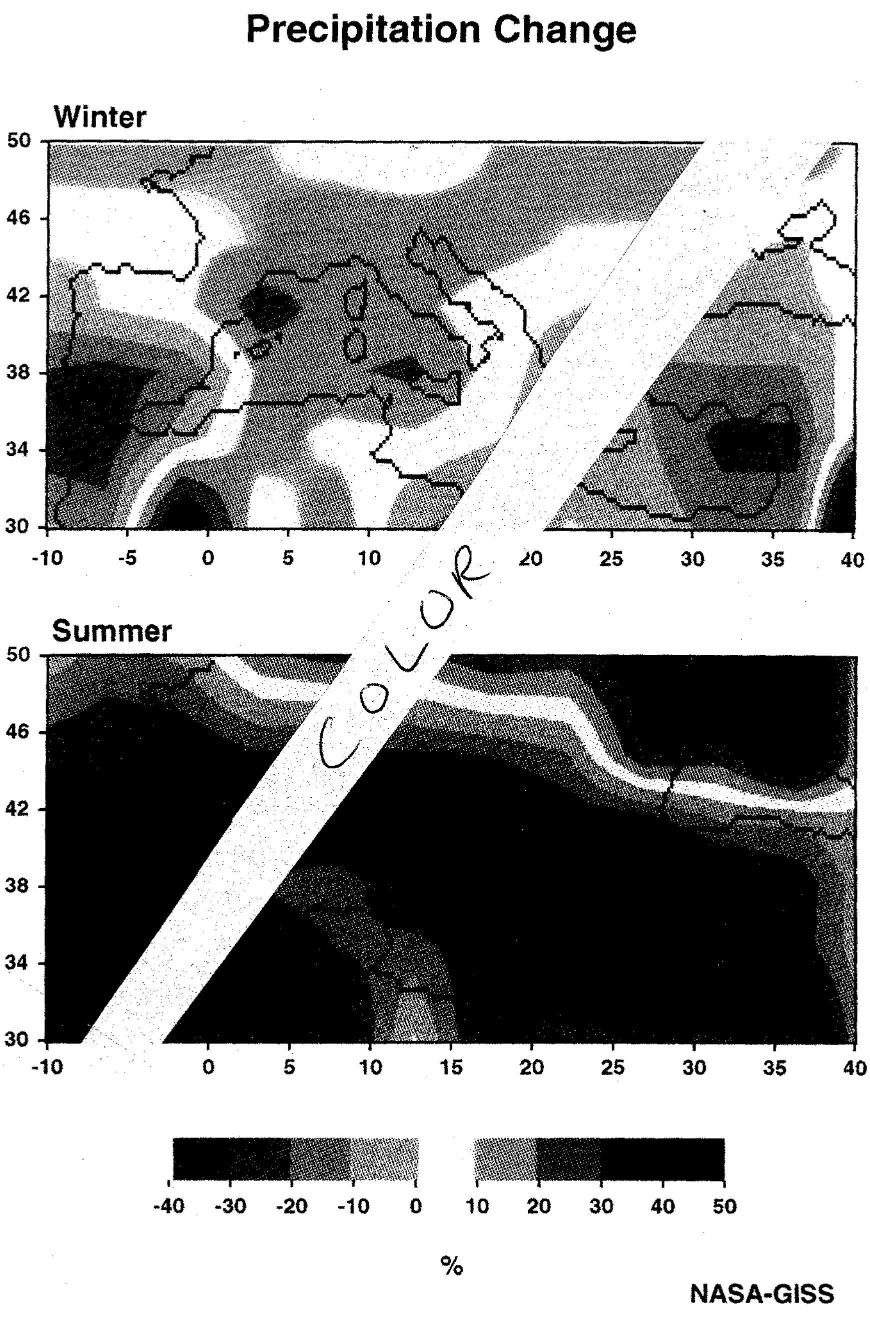

Figure 2. Seasonal mean precipitation change for the Mediterranean region corresponding to a doubling of CO_2, as predicted by the GISS GCM. (2a) Winter (December, January, February); (2b) Summer (June, July, August).

Table 2. Population, annual cereal production and consumption, 1961–1994.

Year	Region	Population 10^6	Production 10^6 ton†	Consumption 10^6 ton	Yield ton ha^{-1}	Prod/capita kg $person^{-1}$
1961	North	157.4	55.4	59.3	1.8	364
	South	106.5	24.3	27.4	1.1	253
1994	North	192.2	104	86.2	4.3	542
	South	200.0	53.0	75.7	1.8	240
Δ(94–61)	North	+22%	+89%	+46%	139%	+49%
	South	+87%	+121%	+176%	64%	−5%

†Metric tonne
Source: FAO Production Yearbook, 1961–1992; ERS-NASS, US Department of Agriculture, 1992 and 1994.

3. Mediterranean Agriculture and Climate Change

Mediterranean agriculture accounts for virtually all olive oil produced worldwide, 60 percent of wine production, 45 percent of grape production, 25 percent of dried nuts (mostly almonds, chestnuts, and walnuts); 20 percent of citrus production, and about 12 percent of total cereal production (FAO Production Yearbook, 1993). There is a marked difference in levels of production between northern and southern basin countries, only partly due to climate, and increasingly determined by differences in population growth, land use, and water availability. These factors will continue to affect Mediterranean agriculture in the next century (Le Houreau, 1992), so that impacts due to climate change must be weighed relative to such other projected changes. Cereal production, occupying more than 40 percent of all arable land and supplying about 75 percent of the region's internal demand for grain, may be particularly at risk of significant climate-induced effects.

Total population in the Mediterranean region has increased by 50 percent in the last thirty years, and is approximately 400 million today (Table 2). Over this period, population growth rates were four times higher in the southern basin (3.2% y^{-1}) than in the northern countries (0.8% y^{-1}), with the gap in growth rates currently widening. Although cereal production increased by a factor of two in both Mediterranean regions since 1961, production per capita increased by 50 percent in the northern basin, while it decreased by 5 percent in the south. Thirty years ago, both northern and southern Mediterranean countries satisfied about 90 percent of their internal demand for food. Today, the northern basin is self-sufficient, while southern Mediterranean countries produce less than 60 percent of their food. The ratio of imports to consumption in the south has increased four-fold (FAO Production Yearbook, 1961–1993).

During the same period, cropland decreased in the north by about 20 percent as production intensified, along with a 10 percent increase in forested areas. The reverse happened in the southern basin, where land used for agriculture increased by 10 percent at the expense of shrublands and other marginal lands. Irrigated agriculture has grown more than ten-fold in the north since 1961, but only by 40 percent in the south, where crops and soils now largely exist in a regime of marginal water supply (FAO Production Yearbook, 1961–1993). More than a third of irrigated land in the southern basin is in Egypt, where, as discussed by El-Shaer *et al.* (1996), special problems arise due to salinization, water logging, and salt-water intrusion.

If the current trends in population growth, land transformation, and water use persist, southern cereal production may be increasingly unable to satisfy internal food demand, while soil quality and water availability may continue to deteriorate (Le Houreau, 1992). Water management could also become a problem in semi-arid areas of the northern basin, especially in parts of Spain, Greece, and southern Italy. Climate change could further modify this trend. Predicted regional changes in temperature, precipitation, and evapotranspiration will further constrain agricultural production by affecting water budgets. Although negative impacts could be reduced if irrigation is applied, this depends on the availability of local water supplies in the changing climate.

Warmer and drier climates, and expanding growing seasons (allowing for early planting of cold-sensitive crops) could benefit olive and citrus production by extending their cultivation range northward (Morettini, 1972). On the other hand, cereal crops requiring periods of vernalization such as winter wheat, grown in northern basin countries, could be negatively affected and their productivity reduced. Overall production might be negatively affected by an increase in the frequency of extreme high temperature events, which can cause heat stress and plant sterility (Mearns *et al.*, 1992; Paulsen, 1994).

The impacts of climate change could be mitigated and possibly counterbalanced by the physiological effects of carbon dioxide on crop growth. Crop response to increasing atmospheric CO_2 alone tends to be positive, with an average increase in yields of about 30 percent for doubled- CO_2 conditions (Kimball, 1983). This response however depends significantly on a variety of limiting factors, mainly water and nutrient levels (Lawlor and Mitchell, 1991). Because it is difficult to estimate the combined effects of climate change and elevated CO_2 on crop growth from current field and growth chamber experiments, computer crop models are generally used for predictions.

A number of climate change assessment studies have been conducted in Mediterranean countries. Using the dynamic crop models CERES-Wheat (Ritchie, 1985) and CERES-Maize (Jones and Kiniry, 1986; Ritchie, 1989), together with output from three GCM doubled-CO_2 equilibrium scenarios, Delecolle *et al.* (1995) calculated that winter wheat yields in France would not be decreased in temperate and Mediterranean sites where irrigation is not limiting. Iglesias and Minguez (1995), using the same models, projected negative impacts of climate change in arid areas of Spain, when irrigation is often not sufficient. Similar negative results were obtained for rainfed maize crops in southern Italy and the coast of Spain (Wolf and Van Diepen, 1995). Bindi *et al.* (1993) calculated that temperature increases and precipitation changes would generally lower yields of winter wheat in Northern and Central Italy, although their models did not include physiological effects of CO_2. Eid (1994) suggested that, despite CO_2 enhancement of crop growth, climate change would severely reduce Egyptian maize and wheat yields.

Iglesias and Minguez (1996), Kapetanaki and Rosenzweig (1996), and El-Shaer *et al.* (1996), herein analyze the interactions of climate change, elevated CO_2, and wheat and maize growth through sensitivity tests, GCM scenarios and adaptation studies in Spain, Greece and Egypt, where cereal production is highly intensive. Their contribution to climate change impact assessment lies in their attention to current and future water management problems, providing a detailed analysis of crop water use and local irrigation practices. These papers suggest that, even in the presence of a large water supply (like in the case of the Nile in Egypt), and some reduction in total crop water use, mainly due to the shortening of growing periods, predicted future climatic conditions are likely to increase plant water stress and reduce crop yields at most study sites in the Mediterranean Basin.

4. Current Methodologies and Future Directions

The three papers follow a methodology that has been developed for the assessment of the potential impacts of climate change on agricultural production around the world (see for example: Rosenzweig *et al.*, 1995; Rosenberg, 1993). This methodology consists of coupling dynamic crop growth models, designed to predict plant development and yield as a function of weather, soil, and management input variables, to predictors of climate change for sites within a given region. While the majority of the assessment studies to date have used climate projections from GCMs, others have used past climate events, like the 1930s drought in the American Great Plains, as analogs of future change (e.g., Easterling *et al.*, 1992; Rosenzweig and Hillel, 1993).

Regardless of the climate scenario methodology used, such impact studies have been developed along similar lines:

(1) Definition of the area of study and analysis of current climate and agricultural practices;
(2) Crop model calibration and evaluation;
(3) Development of climate change scenarios;
(4) Analyses of yield changes under changed climatic conditions; and,
(5) Development and analysis of adaptation strategies.

Projections of crop productivity from such studies are often used in economic analyses (e.g., Rosenzweig and Parry, 1994; Adams *et al.*, 1990). Methodological differences among these impact studies involve the generation of the climate scenarios, the crop models used, and the calibration and evaluation techniques.

The Intergovernmental Panel on Climate Change (IPCC Technical Guidelines, 1994) endorses the discussed modeling approach as one of several for the assessment of climate change impacts on agriculture. It is useful for such impact studies to be extended geographically in the framework of approved guidelines, in order to build a comparative understanding of likely effects on agricultural production throughout the world, and for more comprehensive results to be available for integrated assessment studies. At the same time, crop model development and applications must continue in order to enhance our ability to predict the impacts of climate change and CO_2, and to test the effects of adaptation strategies on future crop production.

Several authors have underlined the difficulty of interpreting the findings of climate change assessment studies due to lack of detailed data needed to validate GCM current climate depiction, and to the difficulty in evaluating sector-specific models under conditions other than current (e.g.: Skiles, 1995; Hanninen, 1995). To this end, the crop modeling community should devote greater attention to the development, calibration and validation of the crop models used at each site and/or region of study.

First, it is essential that crop models be shown to reproduce current yields with as great an accuracy as possible. Attention should be given not only to mean values of yield, but to reproducing interannual variability as well (Katz and Brown, 1992; Semenov and Porter, 1995). Data from agricultural research stations should be used extensively. Where available, time-series of regional (for example, at the county level) production should also be used, and statistics produced showing the goodness of fit (or lack thereof) between modeled and observed data. The three companion papers assess regional change from multiple representative sites in their respective study areas. This choice allows for crop model validation at each site through the use of well-defined local data for weather, soil type, cultivars, management practices, historical yield, and crop phenology. Calibration and validation at the regional scale is more difficult due to the spatial heterogeneity of the input parameters. This is a key issue in the development of future impact assessment studies (see, for example, Elliot and Cole, 1989; Riebsame *et al.*, 1994; Parton *et al.*, 1994).

Expanding the analysis from site to regional scale is necessary in order to include feedbacks among other sectors important to agriculture, such as regional water resources and economics. Only then will it be possible to assess the full impact of those adaptation strategies intended to minimize the negative effects of climate change over entire regions. Regional predictions involve not only computationally expensive manipulations of several interacting layers of data, as done in geographic information systems (e.g., Matthews *et al.*, 1994; Engels and Jones, 1995), but also involve the choice of the proper spatial scales necessary to resolve essential information on soils variability, land-use patterns, and crop management (Cushman *et al.*, 1988). Serious constraints to scale resolution are imposed by the coarseness of

GCM-generated output to be used in regional studies and by the lack of appropriate regional datasets, although current research efforts and the use of earth-observing satellites have been improving data availability significantly.

The second methodological improvement needed is greater attention to sensitivity tests and the development of response surfaces. Climate change scenarios derived from GCMs should be accompanied by crop sensitivity studies, in order to better understand how several climate variables interact to affect final yields. Researchers should focus on producing and analyzing yield-response surfaces to given changes of temperature, precipitation, and solar radiation at one site or region, under current and elevated CO_2 conditions, and under different management practices. This procedure will allow researchers to define critical thresholds for crop damage and create reduced-form models, simplifying the analysis of the impacts of different climate change scenarios on crop yields. An example of this technique is given in Kapetanaki and Rosenzweig (1996), where maize yields and water use under current climate conditions in Greece are compared to those computed by separately varying over a given range minimum and maximum temperatures, solar radiation, and precipitation. These sensitivity runs are then compared to simulations where daily mean temperature and precipitation for a long-term period (at least ten years of observed weather in these studies) are changed according to a given GCM scenario, with and without CO_2 effects on biomass production. A necessary refinement to this approach is the analysis of model sensitivity to interannual climate variability, in order to include effects of changed interannual and daily distribution of temperature and precipitation on long-term mean yields (Mearns *et al.*, 1992 and 1996).

Third, the crop models should be continuously improved, in particular with regard to those functions describing CO_2 and temperature effects on crop photosynthesis and transpiration. The CERES family of models used in the three companion papers follow a simplified approach to modeling crop response to elevated CO_2, multiplying biomass production by a numerical factor derived from the literature. Other models include more detailed computations of leaf and canopy photosynthesis (e.g., a modified version of CERES-Wheat, Tubiello *et al.*, 1995; ARCWHEAT, Mitchell *et al.*, 1996). The magnitude and even the direction of climate change impacts on agricultural yields, and the interactions with limiting factors related to nutrient and water supply, are highly dependent on these functions.

The Mediterranean studies included with this essay each investigate farm-level adaptation strategies to the projected climate change. Crop yield and water use are the two variables analyzed. The negative effects of climate change calculated in these studies are mainly due to temperature effects on phenology and increased daily water use. Adaptation strategies tested were early planting (to avoid heat stress during late summer) and faster-maturing varieties (to minimize irrigation requirements over the growing season). These are simple strategies that could easily be implemented, whose effects on crop yields can be qualitatively investigated without the need to model regional feedbacks. The farm-level approach clearly shows that the efficacy of these strategies is site-dependent, even within a given country. Iglesias and Minguez (1996) calculate that early sowing could reduce the negative effects of climate change on maize yields in northern Spain, but not in the southern regions. Kapetanaki and Rosenzweig (1996) show that adaptation techniques may vary by region: early sowing could be effective in central Greece, while cultivars with a greater grain-filling rate would be preferable in northern regions. El-Shaer *et al.* (1996) project that neither adaptation strategy would counterbalance the negative impacts of climate change in Egypt.

Finally, the three companion studies demonstrate the importance of collaboration between local scientists and experts in climate change impact studies. Local scientists know the agricultural systems intimately, an invaluable aid to proper crop model validation and evaluation of results. Collaborative studies expand the cadre of scientists informed about the climate change issue and are capacity-building. Because climate change imposes a long time frame on the analysis, the assessment of adaptation and mitigation strategies must incorporate a long-term perspective, a *sine qua non* for responsible sustainable development.

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