European Journal of Agronomy 13 (2000) 179–189

European Journal of Agronomy

www.elsevier.com/locate/eja

Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations

Francesco N. Tubiello [a,*], Marcello Donatelli [b], C. Rosenzweig [a], Claudio O. Stockle [c]

[a] *NASA GISS and Columbia University, 2880 Broadway, New York, NY 10025, USA*
[b] *ISCI Bologna, Via di Corticella 133, 40128 Bologna, Italy*
[c] *Department of Biological Systems Engineering, WSU, Pullman, WA, USA*

Received 19 February 1999; received in revised form 13 September 1999; accepted 28 November 1999

Abstract

The potential effects of future climate change were investigated, corresponding to a doubling of atmospheric CO_2 from 350 to 700 ppm, on agricultural production of four different cropping systems at two Italian locations, Modena and Foggia. Climate change scenarios, derived from two general circulation models (GCMs), were used as weather input to a soil-plant growth simulator, CropSyst. This model was recently modified to include the effects of elevated CO_2 on crop photosynthesis and transpiration. Six different crops in total were simulated at the two Italian sites. At Modena, a 3-year maize–maize–wheat rotation and a 2-year soybean–barley–summer sorghum rotation were studied. At Foggia, a 2-year sunflower–wheat–fallow rotation, and a 2-year wheat–fallow–spring sorghum rotation were simulated. Results suggested that the combined effects of elevated atmospheric CO_2 and climate change at both sites would depress crop yields if current management practices were not modified. Specifically, predicted warmer air temperatures accelerated plant phenology, reducing dry matter accumulation and crop yields by 10–40%. By investigating adaptation strategies, it was found that a combination of early planting for spring–summer crops and the use of slower-maturing winter cereal cultivars succeeds in maintaining crop yields at current levels at both sites. For irrigated maize and soybean production at Modena, 60–90% more irrigation water was required under climate change to keep grain yields at current levels. This implies that adaptation to climate change may be limited for irrigated crops, depending on site-specific water availability.

Keywords: Cropping systems; Climate change; Elevated CO_2; Adaptation

1. Introduction

Atmospheric CO_2 concentration has risen by more than 30% since pre-industrial times, from equilibrium levels of about 280 ppm in 1880, to the currently observed levels of 365 ppm. This

* Corresponding author. Tel.: +1-212-6785585; fax: +1-212-6785552.
E-mail address: franci@giss.nasa.gov (F.N. Tubiello).

1161-0301/00/$ - see front matter
PII: S1161-0301(00)00073-3

increase is the direct result of human activities, primarily fossil fuel burning, cement production, and modified land-use patterns (IPCC, 1996).

Current anthropogenic CO_2 emissions into the atmosphere are about 8 GT C year^{-1}, with atmospheric levels increasing by almost 0.5% per year. If present emission patterns continue in the future, atmospheric CO_2 will be doubled by the end of the 21st century. Simulations with global climate models (GCMs) suggest that the projected increases in CO_2 — the major greenhouse gas after water vapour — will modify the global climate, by causing widespread rising of surface air temperatures; by altering precipitation patterns and the global hydrologic cycle; and by increasing the frequency of severe weather events, such as drought spells and flooding (IPCC, 1996).

Agricultural crop production is one of the key human sectors that might be significantly affected by changes in climate and rising atmospheric CO_2 concentrations, with consequences to global food supply (Rosenzweig and Hillel, 1998). Whereas elevated atmospheric CO_2 increases plant photosynthesis rates and thus crop yields (Kimball, 1983), GCM-predicted increases in temperature and related precipitation changes may also affect crop photosynthesis, plant development rates, as well as water and nutrient budgets in the field (Long, 1991). Ultimately, the net effects of increased CO_2 and climate change on crop yields will depend on local conditions. For example, warmer spring–summer air temperatures might be beneficial to crop yields at northern temperate latitudes, where the length of growing seasons could increase. However, increased temperatures would likely be negative in Mediterranean-type environments, where high summer temperature and water stresses already limit crop production (Rosenzweig and Tubiello, 1997).

The response of agricultural systems to future climate change also depends strongly on management practices, such as the type and levels of water and nutrient applications. It is well-known that water limitation tends to enhance the positive crop response to elevated CO_2, compared to well-watered conditions (Chaudhuri et al., 1990; Kimball et al., 1995). The contrary is true for nitrogen limitation: well-fertilised crops respond more positively to CO_2 than less fertilised ones (Sionit et al., 1981; Mitchell et al., 1993).

In cropping systems, a wide range of adaptations to climate change may exist, to maintain or even increase crop yields under future climate change compared to current conditions. After all, farmers are able to respond to changes in environmental conditions by choosing the most favourable crops, cultivars, and cropping systems. Assessment studies should indicate which strategies might have a better chance to succeed in the future, and which specific climate conditions might represent a threshold for adaptation. Such thresholds may identify points of 'no return', where management adaptation strategies would not succeed at maintaining crop yields at present levels.

There are many factors that determine the response of crops to changes in climate conditions and to elevated CO_2 concentration. Hence, computer simulations have been widely used to analyse crop responses and adaptation strategies to future climate change. Several authors have pioneered the use of GCM output within crop models, in order to assess climate change impacts on world agriculture (e.g. Rosenzweig and Parry, 1994; Wolf and Van Diepen, 1995).

The objective of this work was to study the effects of climate change and elevated CO_2 on crop production at two Italian locations, Modena and Foggia. Yield responses were analysed and potential management adaptation strategies across the north–south gradient spanned by these two sites were studied. The analyses focused on local cropping systems at the two sites. Such an approach is useful because, for any given climate, cropping systems — and not single crops — constitute the fundamental units controlling the movement of nutrients and the patterns of water use, upon which crop productivity and farm viability depend.

2. Material and methods

The output of two GCMs was used as weather input for a cropping system simulator, CropSyst, at the two sites. The GCMs used for this study were the GISS model, developed at the NASA Goddard Institute for Space Studies (Hansen et al., 1988); and the GFDL model, developed at the Princeton Geophysical Fluid Dynamics Laboratory (Manabe and Weatherland, 1987). Both models simulate atmospheric circulation and land-surface dynamics, with seasonal sea-surface temperatures specified as boundary conditions. Numerical resolution for both was $4° \times 5°$ latitude–longitude (corresponding to average linear dimensions for each model grid-box of about 500 km), with nine vertical atmospheric layers. The GCM simulation outputs employed for this study corresponded to 'doubled CO_2 equilibrium simulations'. In such experiments, the GCM is first run to equilibrium under current climatic conditions. Atmospheric CO_2 is then doubled instantaneously and the model is run again until a new equilibrium is reached. The climate sensitivity to CO_2 was similar for the two GCMs, i.e. both predicted an increase of roughly 4°C in global mean annual surface temperature for a doubling of atmospheric CO_2.

Doubled CO_2 equilibrium scenarios do not provide information about the timing of the projected climate change. Transient GCM scenarios, which simulate climate change as a function of time-dependent increases in CO_2 concentration, indicate that at current fossil fuel emission rates, the warming predicted with the equilibrium simulations could be realised by the end of the next century (IPCC, 1996).

2.1. Climate data and climate change scenarios

Observed meteorological data were collected at Modena (44.4 N, 10.55 E; years 1968–95) and Foggia (41.27 N, 15.34 E; 1952–91), representing complete time-series of daily maximum/minimum air temperature and precipitation. The weather generator ClimGen (Stockle et al., 1998; Stockle and Nelson, 1999a) was used to generate a 50-year 'baseline' climate scenario from the observed daily data. For the generation of precipitation and temperature, ClimGen follows a similar approach to that introduced by Richardson and Wright (1984). Precipitation occurrence (wet or dry day), determined by using a first order Markov chain, is the primary variable conditioning the maximum and minimum temperature. The temperature generation process is based on serial and cross-correlation (maximum temperature, minimum temperature, and solar radiation) 3×3 matrices whose coefficients are locally calibrated. ClimGen allows for the reduction of these matrices to a 2×2 dimension so as to generate temperature at locations where no radiation data are available. Observed solar radiation data at both sites were available for short periods of time (~ 4 years). The model of Donatelli and Campbell (1998), based on Bristow and Campbell (1984) and modified to improve the estimation of peak values of daily radiation, was used to estimate solar radiation from temperature for the remaining datasets.

'Climate change' (CC) scenarios were generated at each site using output of two atmospheric GCMs, using GCM data distributed by the US National Climate and Atmospheric Center (NCAR). Standard scenario generation methodologies were followed, as discussed in Rosenzweig and Tubiello (1997). First, climatic data relative to baseline and 'doubled-CO_2' GCM scenarios were downscaled to each of the study sites by linear interpolation, using the four grid points nearest to the study site. Second, differences of mean monthly temperature and ratios of mean monthly precipitation and solar radiation were calculated between 'doubled CO_2' and baseline GCM simulations. Third, calculated temperature differences, and precipitation and solar radiation ratios, were applied to the baseline observed climate files to generate the climate change scenarios. Tables 1 and 2 show values for observed climatic variables at both sites, along with the GCM-predicted changes in mean daily temperature and precipitation. Changes in solar radiation were smaller than those shown for the latter two variables, and were not included in the tables.

For each GCM, predictions at the two sites were rather similar, a probable result of the coarse model resolution. Predicted mean annual temperature was roughly 4°C higher at both sites. Mean annual precipitation increases were slightly above 10% in all cases, except for the GFDL prediction at Foggia, giving a 7% increase. Unlike the GISS model, which predicted precipitation increases for virtually all months at both sites, the GFDL model predicted up to 30% decrease in some spring and summer months.

Atmospheric CO_2 concentrations were set at 350 ppm for the baseline simulations, and to 700 ppm for the climate change simulations. In GCM simulations for climate change, the forcing CO_2 concentrations are often referred to as 'effective' concentrations, describing the radiative effects of CO_2 alone, or of CO_2 plus a mix of other greenhouse gases. The two CO_2 values specified in the GCM simulations were used by the authors 'as is', to avoid uncertainty in defining future composition of other greenhouse gases. Lower CO_2 concentrations than used herein might also be consistent with the above GCM scenarios. The choices may tend to overestimate positive effects of CO_2 on crop growth and water use efficiency in the simulations.

Table 1
Baseline and climate change scenarios at Modena

Month	Baseline			GISS		GFDL	
	T_{max} (°C)	T_{min} (°C)	P (mm)	ΔT (Δ°C)	ΔP (ratio)	ΔT (Δ°C)	ΔP (ratio)
Jan	8.1	−2.4	37	3.8	1.19	3.9	1.29
Feb	9.9	−0.6	40	5.1	1.10	5.9	1.21
Mar	13.7	2.3	45	3.5	1.16	3.9	1.08
Apr	17.4	5.9	52	4.9	1.15	5.2	0.88
May	23.0	10.7	46	3.2	1.21	3.7	1.01
Jun	26.9	14.3	70	3.3	1.06	4.7	1.02
Jul	29.6	16.4	49	2.6	1.27	4.8	0.70
Aug	28.7	16.3	90	3.2	1.03	4.2	1.25
Sep	24.6	13.0	66	4.8	1.02	3.6	1.07
Oct	17.6	8.1	66	3.1	1.12	3.6	1.14
Nov	11.1	3.1	68	3.1	1.16	4.3	1.07
Dec	8.2	−1.0	40	4.6	1.13	3.9	1.08
Mean	18.2	7.2	669	3.8	1.13	4.3	1.07

Table 2
Baseline and climate change scenarios at Foggia

Month	Baseline			GISS		GFDL	
	T_{max} (°C)	T_{min} (°C)	P (mm)	ΔT (Δ°C)	ΔP (ratio)	ΔT (Δ°C)	ΔP (ratio)
Jan	12.0	3.6	57	3.5	1.14	3.7	1.23
Feb	12.2	2.9	34	4.6	0.95	5.3	1.19
Mar	15.0	4.1	48	3.9	1.12	3.7	1.00
Apr	18.5	6.6	45	5.4	1.12	4.4	0.74
May	23.7	10.8	45	3.8	1.15	3.7	1.21
Jun	27.4	14.5	29	3.3	1.04	4.6	0.63
Jul	30.9	17.5	31	2.9	1.39	4.7	1.09
Aug	29.9	17.5	47	3.7	0.97	3.9	1.53
Sep	26.4	14.8	56	4.6	0.98	3.7	0.85
Oct	21.1	10.8	62	3.5	1.25	3.3	1.07
Nov	15.4	6.7	70	3.7	1.22	3.2	1.04
Dec	12.5	4.4	57	3.4	1.11	4.0	1.25
Mean	20.4	9.5	581	3.9	1.12	4.0	1.07

Table 3
Rotation types, planting dates, temperature sum for phenological development from emergence until the indicated stage, as used in all baseline and climate change simulations

Rotation type	Planting date	Flowering (°C-days)	Maturity (°C-days)	Irrigation
Modena				
Maize	Apr. 10	920	1550	Yes
Wheat	Oct. 31	1000	1650	No
Barley	Nov. 3	1050	1650	No
Sorghum	Jul. 1	920	1680	Yes
Soybean	Apr. 15	820	1250	Yes
Wheat-adapted	Oct. 31	1150	1900	No
Barley-adapted	Nov. 3	1210	1900	No
Foggia				
Wheat	Nov. 15	1500	2200	No
Sunflower	Mar. 10	1200	1810	No
Spring sorghum	Apr. 25	850	1450	No
Wheat-adapted	Nov. 15	1770	2600	No

2.1.1. Crop model and equations for crop growth under elevated CO_2

Baseline and climate change scenarios were used as weather inputs into a crop simulator. CropSyst was used (Stockle et al., 1994; Stockle and Nelson, 1999b), a crop simulator that computes water and nitrogen movement through the soil-plant continuum, crop phenological development, dry matter accumulation and crop yield, and which allows for multi-year, sequential simulations of cropping systems. The performance of the model has been evaluated for diverse environments (e.g. Pala et al., 1996; Stockle et al., 1997; Pannkuk et al., 1998), including Northern and Central Italy (Donatelli et al., 1997).

CropSyst calculates dry matter accumulation as a function of daily intercepted solar radiation and daily crop transpiration, using constant coefficients of radiation-use efficiency, *RUE* (Monteith, 1981), and transpiration efficiency, *K* (Tanner and Sinclair, 1983). Modifications were introduced to CropSyst in order to account for the effects of atmospheric CO_2 concentration on plant growth and water use. These modifications are similar to those presented by Stockle et al. (1992), and are summarised in Table 4. For more information on CropSyst growth and water-use calculations, the reader is referred to Stockle et al. (1994) and Jara and Stockle (1999).

For selecting values of *Gratio*, a coefficient used to increase daily crop RUE (Table 4), one differentiated between C3 (wheat, barley, sunflower, and soybean) and C4 crops (maize and sorghum), but assumed the same response for crops within each of the two classes. For a doubling of atmospheric CO_2 from 350 to 700 ppm, potential crop growth was specified to increase by 25% for C3 crops, and by 10% for C4 crops.

2.2. Cropping systems simulations

At Modena, a 3-year maize–maize–wheat rotation and a 2-year soybean–barley–summer sorghum rotation, and at Foggia, a 2-year sunflower–wheat–fallow and a 2-year sunflower–wheat–fallow rotation were simulated (Table 3). CropSyst had been previously validated for the two sites by using meteorological and agronomic data observed in crop rotations similar to those simulated in this work (Donatelli et al., 1997).

Optimal nitrogen fertilisation was assumed for all crops. Irrigation water was applied automatically (for maize, soybean, and sorghum at Modena), based on maximum soil moisture depletion of 50% plant available water in the upper 0.7 m of the soil profile. Irrigation water is readily available in Modena for spring–summer crops such as sorghum, soybean and maize. In Foggia, no irrigation was simulated, as water at this location is used preferentially to grow better-yielding, and more valuable vegetable crops, such as tomatoes.

2.3. Adaptation strategies

In addition to the baseline and climate change scenarios, crop simulations were performed for a 'Climate Change plus Adaptation' scenario at each site, based on the same weather inputs as the climate change scenario, but with different cropping practices.

One did not seek to maximise rotation yields under the future scenarios, but rather to investigate the effects of simple adaptation solutions, largely available to the farmer even today. These adaptation strategies, tested in previous assessments of climate change and agriculture (Rosenberg, 1993; Rosenzweig and Parry, 1994), include earlier planting of spring crops and adoption of slow maturing winter crop cultivars.

Early planting of spring crops helps to avoid plant drought and heat stress during the hotter and drier summer months predicted under climate change. Slower-maturing winter cultivars are needed to counterbalance the reduction of potential crop yield due to accelerated phenological development in a warmer climate.

For the adaptation scenarios, planting of spring-sown crops (maize, sunflower, and sorghum) was anticipated by 2 weeks with respect to the baseline case. This choice roughly corresponded to having similar air temperatures at planting for both the climate change and the baseline simulations. 'New' adapted genotypes were used for simulating winter cereals like wheat and barley. Total required temperature sum to maturity was increased by 20%, while the duration of vegetative and grain-filling periods were maintained in similar proportions to those defined in the original cultivars (Table 3). With this choice, the life-cycle of the adapted crop, under the warmer temperatures of the climate change scenarios, was comparable in length to that of the cultivars used for the baseline simulations.

Table 4
Equations for calculation of biomass production at given CO_2 concentrations in CropSyst[a]

Biomass production	$B = \text{Min}\ (\varepsilon \text{IPAR}, KT)$
Effective transpiration efficiency	$K = k/\text{VPD}$
CO_2 dependence of ε	$\varepsilon = \text{Gratio}^* \varepsilon_0$
CO_2 dependence of k	$k = \text{Gratio}^* k_0/F$
CO_2 dependence of r	$r = r_0^*([CO_2]/350)/\text{Gratio}$
CO_2 dependence of F	$F = (\delta + \gamma(r_0 + r_a)/r_a)/(\delta + \gamma(r + r_a)/r_a)$

[a] K = canopy water-use efficiency; IPAR = intercepted photosynthetically-active radiation; ε_0 = crop radiation-use efficiency at reference CO_2 concentration (350 ppm); ε = crop radiation-use efficiency at specified CO_2 concentration, $[CO_2]$; k_0 = crop water-use efficiency at reference CO_2 concentration; k = crop water-use efficiency at specified CO_2 concentration; T = crop transpiration at specified CO_2 concentration; VPD = air vapour pressure deficit; Gratio = ratio of potential growth at specified to reference CO_2 concentration; F = ratio of transpiration at specified to reference CO_2 concentration; r_0 = canopy resistance to water-vapour transfer at reference CO_2 concentration; r = canopy resistance to water-vapour transfer at specified CO_2 concentration; r_a = aerodynamic resistance to water-vapour transfer; δ = slope of the saturation vapor pressure function of temperature; γ = psychrometric constant.

3. Results and discussion

3.1. Baseline simulations

Baseline simulation results show the differences in climate and typical management practices between Modena, a site characterised by a temperate, continental climate, and Foggia, having a Mediterranean climate with low summer precipitation. Wheat yields were, on average, 60% higher in Modena (5.0 t DM ha^{-1}) than in Foggia (3.3 t DM ha^{-1}), due mostly to more favourable water regimes and, to a smaller extent, slightly longer growing periods (Tables 5 and 6). The ratios of actual versus potential cumulative evapotranspiration was 0.70 in Modena, compared to 0.61 in Foggia. Sorghum yields were similar at the

Table 5
Yield (grain dry weight), actual cumulative evapotranspiration (AET), precipitation during the growth period (P), irrigation (Irr), and duration from crop emergence till maturity for different scenarios at Modena[a]

	Duration (days)	Yield (t ha^{-1})	AET (mm)	P (mm)	Irr (mm)
Wheat					
BASE[b]	212 ± 5	5.2 ± 0.7	308 ± 59	368 ± 99	
CC_G	185 ± 6	4.4 ± 1.0	217 ± 56	342 ± 105	
CC_P	185 ± 6	4.9 ± 1.0	241 ± 55	322 ± 100	
CC+A_G	202 ± 6	4.9 ± 0.6	305 ± 61	379 ± 115	
CC+A_P	202 ± 6	5.2 ± 0.6	320 ± 61	347 ± 106	
Barley					
BASE	203 ± 7	4.6 ± 0.6	301 ± 24	392 ± 102	
CC_G	179 ± 5	3.1 ± 0.6	229 ± 31	384 ± 114	
CC_P	179 ± 5	3.3 ± 1.1	249 ± 34	360 ± 112	
CC+A_G	197 ± 5	4.9 ± 0.4	285 ± 24	423 ± 113	
CC+A_P	197 ± 5	5.1 ± 0.5	300 ± 27	388 ± 109	
Sorghum					
BASE	81 ± 5	3.1 ± 0.4	164 ± 54	214 ± 114	7 ± 21
CC_G	77 ± 2	1.6 ± 0.3	128 ± 39	196 ± 106	40 ± 23
CC_P	67 ± 1	1.3 ± 0.2	111 ± 39	187 ± 108	40 ± 22
CC+A_G	94 ± 3	3.5 ± 0.3	213 ± 42	253 ± 130	53 ± 29
CC+A_P	93 ± 3	3.1 ± 0.3	199 ± 43	243 ± 119	53 ± 31
Maize					
BASE	114 ± 5	9.2 ± 0.9	415 ± 32	299 ± 87	67 ± 35
CC_G	98 ± 4	7.6 ± 1.0	347 ± 33	244 ± 88	28 ± 30
CC_P	93 ± 4	7.0 ± 1.0	340 ± 38	183 ± 71	35 ± 30
CC+A_G	129 ± 5	8.4 ± 0.7	429 ± 27	342 ± 95	97 ± 42
CC+A_P	121 ± 4	7.6 ± 0.8	421 ± 31	289 ± 88	107 ± 41
Soybean					
BASE	121 ± 6	2.4 ± 0.3	401 ± 49	285 ± 103	69 ± 50
CC_G	111 ± 4	1.7 ± 0.3	362 ± 34	274 ± 104	35 ± 30
CC_P	110 ± 3	1.6 ± 0.2	369 ± 29	226 ± 100	44 ± 27
CC+A_G	124 ± 4	2.7 ± 0.3	430 ± 31	351 ± 121	133 ± 59
CC+A_P	122 ± 3	2.7 ± 0.3	476 ± 39	316 ± 115	180 ± 50

[a] Mean of 50 years and S.D.s.
[b] Simulation symbols: BASE: results from baseline simulations; CC_G: results from climate change simulations, GISS model; CC_P: results from climate change simulations, GFDL model; CC+A: results from climate change simulations, with adaptation.

two sites, although the use of irrigation in Modena resulted in more stable yields (coefficient of variation, CV = 13%) compared to rain-fed sorghum in Foggia, with twice as high CV coefficients. Spring–summer crops like sorghum, sunflower, maize, and soybean received more precipitation in Modena than in Foggia.

3.2. Climate change without adaptation

Effects of climate change and elevated CO_2 on crop yields were similar for both GCM climate change scenarios, but strongly different among crop type and location (Tables 5 and 6). Without adaptation of management and genotype, the negative effects on crop yields of warmer temperatures in the changed climate were stronger than the positive effects of elevated CO_2. As shown in Fig. 1, wheat and maize yields at Modena decreased by 5–15%, soybean and barley yields decreased by more than 20%, and sorghum yields decreased by more than 50%. In Foggia, where wheat crops already suffered from severe water stress under baseline conditions, wheat yields de-

Table 6
Yield (grain dry weight), actual cumulative evapotranspiration (AET), precipitation during the growth period (P), and duration from crop emergence till maturity for different scenarios at Foggia[a]

	Duration (days)	Yield (t ha^{-1})	AET (mm)	P (mm)
Wheat				
BASE	193 ± 6	3.5 ± 0.5	288 ± 39	340 ± 102
CC_G	167 ± 6	1.7 ± 0.4	212 ± 23	341 ± 114
CC_P	167 ± 6	1.5 ± 0.4	207 ± 26	335 ± 112
CC+A_G	177 ± 6	2.6 ± 0.3	282 ± 27	358 ± 113
CC+A_P	176 ± 6	2.6 ± 0.4	276 ± 39	352 ± 109
Sorghum				
BASE	106 ± 5	2.9 ± 0.9	317 ± 54	149 ± 56
CC_G	98 ± 3	2.5 ± 0.5	309 ± 39	149 ± 49
CC_P	97 ± 3	1.9 ± 0.4	270 ± 39	121 ± 46
CC+A_G	102 ± 4	3.1 ± 0.7	340 ± 42	167 ± 49
CC+A_P	102 ± 4	2.3 ± 0.5	306 ± 43	125 ± 39
Sunflower				
BASE	117 ± 5	1.6 ± 0.5	337 ± 59	190 ± 56
CC_G	103 ± 3	1.6 ± 0.5	333 ± 56	186 ± 57
CC_P	104 ± 3	1.5 ± 0.5	305 ± 55	143 ± 49
CC+A_G	109 ± 3	1.9 ± 0.5	352 ± 61	212 ± 60
CC+A_P	110 ± 3	1.8 ± 0.5	326 ± 61	169 ± 51

[a] Mean of 50 years and S.D.s. Simulation symbols are the same as in Table 5.

creased with climate change by 30–50% (Fig. 2). Sorghum yields decreased by 10–30%, whereas sunflower yields did not change.

Sunflower yields were similar at Foggia for both climate change scenarios, despite pronounced differences in precipitation predictions with the two GCMs during spring and summer (Table 2). This was likely an effect of the August–March fallow period, which preceded sunflower planting in the simulations. The replenishment of the soil–water profile in the fallow period buffered differences in precipitation between the two climate change scenarios during crop growth, from mid-March to mid-July. Similar results were not found for sorghum, perhaps due to the later planting compared to the sunflower crop, which translated into higher temperature and water stresses, and thus created higher crop vulnerability to precipitation regimes.

The decreases in crop yields under climate change were largely caused by shortened growth periods, due to accelerated phenology under increased air temperatures. All crops matured 2–4 weeks earlier compared to the baseline climate. Shorter growth periods resulted in less irrigation water was used at Modena for sorghum, maize, and soybean (Table 5 and Fig. 3). CV of yield, a measure of farming risk, increased significantly with climate change for all crops and both sites, with the largest increase in CV (60%) for wheat.

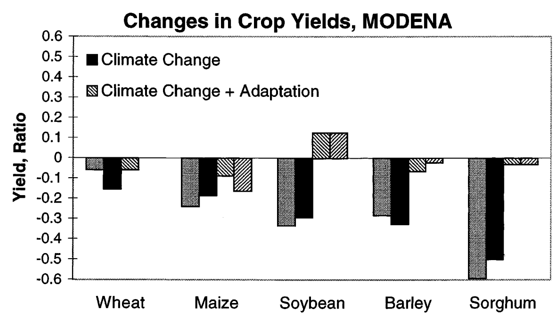

Fig. 1. Changes in crop yields at Modena, as simulated with CropSyst. Graph shows the ratio of climate change scenarios, with and without adaptation, to baseline yields. Within each category (with and without adaption), results from both GISS (left) and GFDL (right) climate scenarios are shown

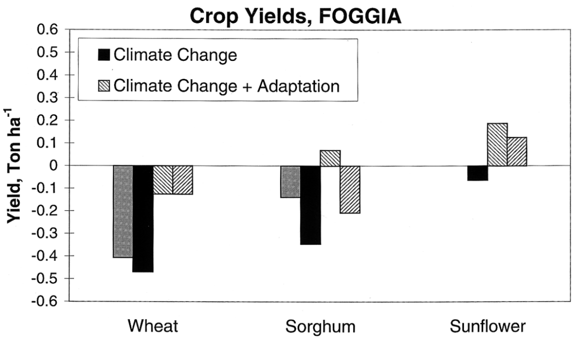

Fig. 2. Changes in crop yields at Foggia, as simulated with CropSyst. Graph shows the ratio of climate change scenarios, with and without adaptation, to baseline yields. Within each category (with and without adaption), results from both GISS (left) and GFDL (right) climate scenarios are shown.

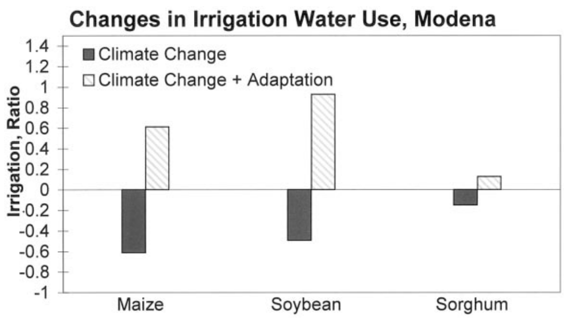

Fig. 3. Changes in irrigation water use at Modena, expressed as ratios of climate change scenarios, with and without adaptation, to baseline irrigation. Values have been averaged for the two general circulation model (GCM) simulations.

3.3. Climate change with adaptation

For the climate change scenarios with adaptation, yields for all crops were similar to those in the baseline climate, apart from maize, which were 13% lower than baseline yields (Table 5). For winter cereal crops like barley and wheat, the growth period duration of the adapted cultivars was, despite the warmer temperatures in the changed climate, only slightly smaller than that of the present varieties in the baseline climate.

For maize and soybean, the longer growth duration in the scenarios with adaptation, combined with the high evaporative demand during the summer, increased irrigation use by 60–90%, and by 15% for sorghum (Fig. 3). Thus irrigation-use efficiency, defined as seed dry matter yield produced per irrigation water used (g DM l^{-1}), significantly decreased with climate change.

3.4. Limitations and uncertainties of modeling study

GCM predictions of climate change are not very reliable at small regional scales. Nonetheless, they are based on detailed descriptions of the major physical processes controlling climate, and provide coherent physical realizations of possible future changes in climate (Tubiello, 1997). In the growth simulations, however, one only considered predicted changes in mean temperature, precipitation, and solar radiation, maintaining their daily and interannual variability at present values. Had a larger variability of temperature and precipitation been included under climate change, as current studies indicate, the study might have resulted in more negative effects of climate change on simulated crop yields (Mearns et al., 1992).

Secondly, it is possible that the equations used in this model to predict the effects of elevated CO_2 on crop yield, based on the concept of radiation-use efficiency and performed in daily time-steps, are too simplistic to provide realistic predictions of yield. Some authors have argued that mechanistic feedbacks between photosynthetic rates and leaf stomatal conductance must be resolved, and that to this end smaller computing time-steps are necessary (Grant et al., 1999). Others have used simple photosynthetic equations in a daily time-step crop model to reproduce observed yield under elevated CO_2 in the field (Tubiello et al., 1999).

In general, crop response to CO_2 in the field may be small compared to model predictions, usually parameterised with results from controlled experiments. Factors limiting crop response may include plant adaptation to CO_2, source-sink relationships, pest-crop interactions, and site-specific characteristics such as soil structure, stoniness, salinity, etc. (e.g. Patterson and Flint, 1990). If these factors were incorporated in the simulation study, model predictions of crop response to elevated CO_2 and climate change might have predicted more negative effects of climate change on crop yields.

4. Conclusions

Results from this study show that the negative effects of climate change in the coming century on existing cropping systems in Italy may be strong, but that they could be attenuated by using simple adaptation strategies involving both management and breeding techniques. The first adaptation is to advance the sowing date of spring-sown crops. The effectiveness of this strategy, however, depends on the level of solar radiation in spring, which quickly decreases early in the year at northern latitudes, eventually becoming limiting to vegetative crop growth. Second, for winter-sown cereals (in this case wheat and barley), the yield of adapted, slower-maturing cultivars in a changed climate remained identical to yields of current cultivars in the baseline climate. Such positive effects of adapted cultivars may be significantly reduced by the onset of pest infestations, more likely under the longer crop exposure to warm temperatures, and which were not included in the simulations.

Results show that, despite the success in maintaining yields at baseline levels using adaptation, irrigation-use efficiency may strongly decrease under future climate change, due to the increased evaporative demands linked to higher temperatures. In the 'climate change with adaptation' simulations, 60–90% more irrigation water was required to maintain grain yields at current levels for maize and soybean.

These findings suggest that assessments of agricultural production should consider not only levels of crop yield, but should also include the trade-offs between crop production and resource availability, which influence farmer decision-making and profitability.

Acknowledgements

We thank two anonymous reviewers for several comments and suggestions, which improved the clarity and quality of this work. Francesco Tubiello and Cynthia Rosenzweig wish to acknowledge the Italian Ministry of the Environment for funding that made this study possible. Partial support for Marcello Donatelli was provided by the PANDA project of the Italian Ministry of Agriculture and Forestry. Francesco Tubiello was also sponsored in part by a grant from the Earth Institute of Columbia University.

References

Bristow, K., Campbell, G.S., 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agric. For. Meteorol. 31, 159–166.

Chaudhuri, U.N., Kirkam, M.B., Kanemasu, E.T., 1990. Root growth of winter wheat under elevated carbon dioxide and drought. Crop Sci. 30, 853–857.

Donatelli, M., Campbell, G.S., 1998. A simple model to estimate global solar radiation. Proceedings of the 5th ESA Congress, Nitra, Slovak Republic, pp. 133–134.

Donatelli, M., Stockle, C.O., Ceotto, E., Rinaldi, M., 1997. Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy. Eur. J. Agron. 6, 35–45.

Grant, R.F., Wall, G.W., Kimball, B.A., Frumau, K.F.A., Pinter, P.J., Hunsaker, D.J., LaMorte, R.L., 1999. Crop water relations under different CO_2 and irrigation: testing of ecosys with the free air CO_2 enrichment (FACE) experiment. Agric. For. Metereol. 95, 27–51.

Hansen, J., Fung, I., Rind, D., Lebedeff, S., Ruedy, R., Russel, G., 1988. Global climate changes as forecast by the Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res. 93 (D8), 9341–9364.

IPCC, Climate Change 1995: The science of Climate Change, 1996. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Cambridge University Press, Cambridge, p. 572.

Jara, J., Stockle, C.O., 1999. Simulation of corn water uptake using models with different levels of process detail. Agron. J. 91, 256–265.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observation. Agron. J. 75, 779–786.

Kimball, B.A., Pinter, P.J. Jr, Garcia, R.L., LaMorte, R.L., Wall, G.W., Hunsaker, D.J., Wechsung, G., Wechsung, F., Kartschall, T., 1995. Productivity and water use of wheat under free-air CO_2 enrichment. Global Change Biol. 1, 429–442.

Long, S.P., 1991. Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentrations: has its importance been underestimated? Plant Cell Env. 14 (8), 729–739.

Manabe, S., Weatherland, R.B., 1987. The effects of doubling the CO_2 concentration on the climate of a general circulation model. J. Atmos. Sci. 44, 1211–1235.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1992. Effects of changes in interannual climatic variability on CERES-

Wheat yields: sensitivity and $2 \times CO_2$ general circulation model studies. Agric. For. Meteorol. 62, 159–189.
Mitchell, R.A.C., Mitchell, V.J., Driscoll, S.P., Franklin, J., Lawlor, D.W., 1993. Effects of increased CO_2 concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. Plant Cell Env. 16, 521–529.
Monteith, J.L., 1981. Climatic variations and the growth of crops. J. R. Met. Soc. 107, 749–774.
Patterson, D.T., Flint, E.P., 1990. Implications of increasing carbon dioxide and climate change for plant communities and competition in natural and managed ecosystems. In: Kimball, B.A., Rosenberg, N.J., Allen, L.H. Jr (Eds.), Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. ASA Special Publication 53, Madison, Wisonsin, pp. 83–111.
Pala, M., Stockle, C.O., Harris, H.C., 1996. Simulation of durum wheat (triticum durum) growth under differential water and nitrogen regimes in a mediterranean type of environment using CropSyst. Agric. Syst. 51, 47–163.
Pannkuk, C.D., Stockle, C.O., Papendick, R.I., 1998. Validation of CropSyst for winter and spring wheat under different tillage and residue management practices in a wheat-fallow region. Agric. Syst. 57, 121–134.
Richardson, C.W., Wright, D.A,1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture, Agricultural Research Service, ARS-8, p. 83.
Rosenberg, N.J., 1993. Towards an integrated assessment of climate change: the MINK study. Clim. Change 24, 1–175.
Rosenzweig, C., Hillel, D., 1998. Climate Change and the Global Harvest. Oxford University Press, Oxford, UK.
Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. Nature 367, 133–138.
Rosenzweig, C., Tubiello, F.N., 1997. Impacts of future climate change on Mediterranean agriculture: current methodologies and future directions. Mitig. Adapt. Strategies Clim. Change 1, 219–232.
Sionit, N., Mortensen, D.A., Strain, B.R., Hellmers, H., 1981. Growth response of wheat to CO_2 enrichment and different levels of mineral nutrition. Agron. J. 73, 1023–1027.
Stockle, C.O., Nelson, R., 1999. ClimGen, a weather generator program. Biological Systems Engineering Dept., Washington State University, Pullman, Washington, USA.
Stockle, C.O., Nelson, R., 1999. CropSyst, a cropping systems simulation model. Biological Systems Engineering Dept., Washington State University, Pullman, Washington, USA.
Stockle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A., 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I. Modification of the EPIC model for climate change analysis. Agric. Syst. 38, 225–238.
Stockle, C.O., Martin, S., Campbell, G.S., 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agric. Syst. 46, 335–359.
Stockle, C.O., Cabelguenne, M., Debaeke, P., 1997. Validation of CropSyst for water management at a site in southern France using submodels of different complexity. Eur. J. Agron. 7, 89–98.
Stockle, C.O., Bellocchi, G., Nelson, R., 1998. Evaluation of the weather generator ClimGen for several world locations. Seventh International Congress for Computer Technology in Agriculture, Florence, Italy, 15–18 November, 1998.
Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. Am. Soc. Agron. Crop Sci. Soc. and Soil Sci. Soc. Am., Madison, WI, USA, p. 154.
Tubiello, F.N., 1997. Global climate models. 3-D representations of the earth's climate system. In: Cross, B. (Ed.), World Directory of Environmental Testing, Monitoring and Treatment 1997/98. James&James, London, UK, pp. 110–114.
Tubiello, F.N., Rosenzweig, C., Kimball, B.A., Pinter, P.J. Jr, Wall, G.W., Hunsaker, D.J., Lamorte, R.L., Garcia, R.L., 1999. Testing CERES-Wheat with FACE data: CO_2 and water interactions. Agron. J. 91, 1856–1865.
Wolf, J., Van Diepen, C.A., 1995. Effects of climate change on grain maize yield potential in the European Community. Clim. Change 29 (3), 299–331.