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POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE FOR BRAZILIAN AGRICULTURE AND ADAPTIVE STRATEGIES FOR WHEAT, MAIZE AND SOYBEAN[1]

EFEITOS POTENCIAIS DE MUDANÇAS CLIMÁTICAS GLOBAIS NA AGRICULTURA BRASILEIRA E ESTUDOS DE ADAPTAÇÃO PARA TRIGO, MILHO E SOJA

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RESUMO

Utilizando-se os cenários climáticos gerados pelos modelos de equilíbrio atmosférico GISS, GFDL e UKMO, e os modelos de simulação CERES e SOYGRO, simulou-se o impacto do efeito estufa sobre a produção nacional de trigo, milho e soja, com base em dados climáticos diários de 13 locais (1951-1980). Todos os modelos GCMs projetam aumentos de temperatura, algumas mudanças de precipitação e menores efeitos na radiação solar. Em decorrência da elevação de temperatura, são projetados encurtamentos no ciclo e na produção de trigo e milho, sendo a soja menos afetada devido ao efeito benéfico da maior concentração de CO_2. Foram projetadas diminuições nas produções nacionais de trigo e milho de cerca 1.2 e 3.5 milhões ton, respectivamente, e aumentos de 2.8 milhões ton na produção nacional de soja. As regiões nordeste e central foram detectadas como mais vulneráveis ao efeito estufa, a primeira em relação a produção de milho e soja e a segunda em relação à produção de trigo. Novas cultivares e ajustamentos em práticas de manejo associadas à irrigação e fertilização nitrogenada podem compensar o efeito das modificações climáticas.

Palavras-chave: efeito estufa, agricultura, trigo, milho, soja e simulação.

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ABSTRACT

Wheat, maize and soybean production was simulated with CERES and SOYGRO crop growth models for 13 sites in Brazil, under climate change scenarios generated by GISS, GFDL and UKMO GCMs. Historical climate data were used as base scenarios, run with 330 and 555 ppm CO_2. All GCMs projected increases in temperature, some changes in precipitation and less effect in solar radiation. Global warming would reduce wheat and maize season length and yields, soybean being less affected due to CO_2 effect. National grain supply was projected to reduce near 1.2 and 3.5 million tons for wheat and maize, and to increase in 2.8 million tons for soybean. Vulnerable regions were detected, the Northeast for maize and soybean and the Central region for wheat. New cultivars and better crop management, associated to irrigation and nitrogen fertilization, could compensate for some climate changes.

Key words: greenhouse gases, global warming, agriculture, wheat, maize, soybean and simulation.

INTRODUCTION

The rising concentration of greenhouse gasses in the atmosphere may lead to increased global temperature (INTERGOVERNMENTAL... 1990). The study of the possible impacts of climate change on ecosystems and agriculture, is a relatively new area of research (SMITH & TIRPAK, 1989a; 1989b; 1989c). Potential impacts of global climate change in some regional agricultural systems, have been evaluated (GROTCH, 1987; RAMANATHAN, 1988; SCHLESINGER & MITCHEL, 1987; SCHLESINGER, 1988). Some studies in the US have used simulation crop growth models and climate change scenarios generated from General Circulation Models (GCMs), to analyse the possible impacts of global warming on selected crops (ROSENZWEIG, 1989a; 1989b; 1990; RITCHIE et al, 1989; CURRY et al, 1990). In Brazil, very few studies have been conducted in this area; some results have been presented by MOTA et al (1984) using statistical models.

In this study we analyze the possible impact of global climate change on wheat, maize and soybean production in Brazil using crop growth simulation models and climate change scenarios created with GCMs. These crops are, along with rice, the major crops in Brazil, covering around 25 million Has of cultivated land. In addition, this study analyzes possible adaptation strategies to minimize the impact of climate change on crop production.

METHODOLOGY

AGROECOLOGIC REGIONS AND SITES

Thirteen sites were selected for this study (Table 1). The location of the sites varies from 31 South to close to the equatorial line. The sites were selected based on previous agroclimatic studies (MOTA, 1989; MOTA & AGENDES, 1986; ALFONSI et al, 1981; QUEIROZ et al, 1979; MALUF et al, 1986). Nine sites are located in the most important agricultural regions: South and Central South; almost 99% of the wheat national production and more than 80% of the maize and soybean production are concentrated in these regions. The other sites were selected according to the availability of weather data to represent as much as possible other agroecologic zones.

CROP GROWTH SIMULATION MODELS

Crop growth models developed by IBSNAT (JONES et al, 1990) were selected for this simulation study: CERES-Wheat version 2.10 (GODWIN et al, 1989; RITCHIE & OTHER, 1985), CERES-Maize (JONES & KINIRY, 1986; RITCHIE et al, 1989) and SOYGRO-Soybean (JONES et al, 1988). The IBSNAT crop models simulate plant development and growth, as they integrate soil, plant, climate (daily max and min temperature, precipitation and solar radiation) and management factors (INTERNATIONAL... 1986; 1988). Strategy analysis are included in the Decision Support System (DSSAT) used in this work to integrate the annual simulations set for each aggregate input data and site, and to support decison under uncertainty (INTERNATIONAL... 1989). The IBSNAT crop models include an option to simulate the direct physiological effects of CO_2 atmospheric concentrations on plant photosynthesis and water use, based on experimental results (ROSE, 1989; CURRY et al, 1990; ALLEN, 1990). The photosynthetic enhancement at 555 ppm CO_2 used for wheat is 1.17, for soybean 1.21 and for maize 1.06.

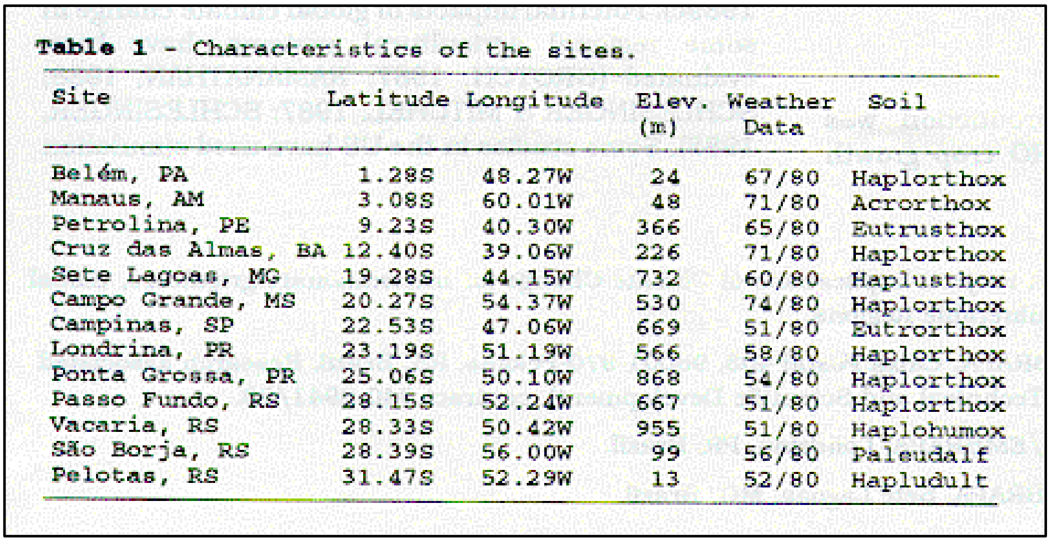

Table 1 - Characteristics of the sites.

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

SOILS

Soils were chosen to best represent the local soils of the sites selected. Soil data were obtained from regional soil survey studies (BRASIL, 1971; 1973; LARACH et al, 1984; OLIVEIRA et al, 1984; MOTHEI et al, 1979; SANTOS et al, 1983). The soil profile for Passo Fundo (calibration site) was generated with local data (see Table 2 for the representation of this soil with all data required by the simulation models).

BASELINE CLIMATE

The base climate is represented by the historical data available for each site during 1951-1980 (Table 1) and include daily maximum and minimum temperatures, precipitation and hours of sunshine. Daily solar radiation data were calculated using hours of sunshine and the results were compared to actual data when available.

Vacaria shows the lowest mean temperatures and has a significant seasonal temperature variation (see average data in Table 3). In contrast, Belém shows the highest temperatures with the smallest variation during the year. A broad variation in precipitation is observed among the sites: the highest precipitation occurs in the northern sites and the lowest in the Northeast. There is quite a variation in seasonal precipitation in some central sites, where the lowest monthly rainfall occurs during the winter (May-September). Solar radiation seasonal differences are observed more in the southern sites.

CROP MANAGEMENT

The cultivars, plant population, and planting date used as input for the crop growth models (INTERNATIONAL... 1986, 1988) are indicated in Table 4; the information was obtained from published crop management reports (QUEIROZ et al, 1979; MIYASAKA & MEDINA, 1981; VERNETTI, 1983; REUNIÃO, 1988a, 1988b, 1988c, 1989).

Although there are water deficits in some regions, practically all maize and soybean are cultivated without irrigation. For wheat irrigation is recommended in some regions, including Campinas, Campo Grande, and Sete Lagoas. In Campo Grande, wheat could be dryland, if planted at a different time.

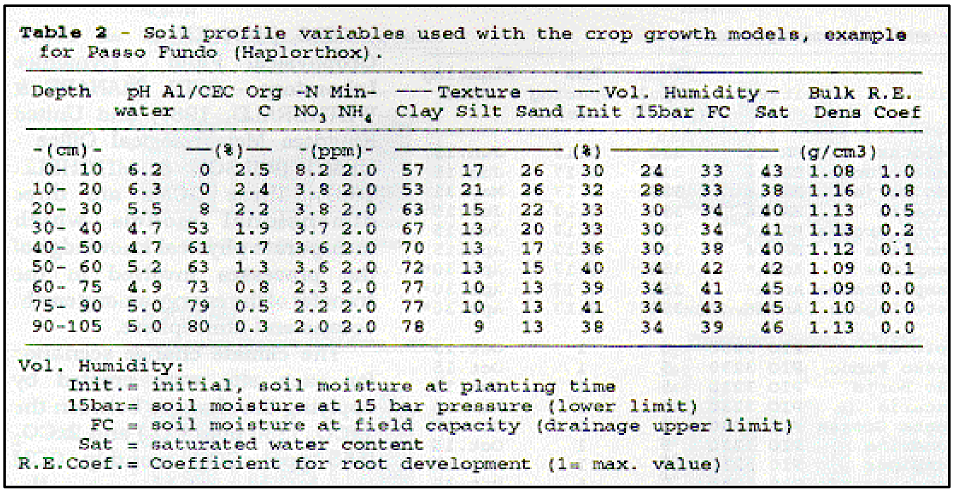

Table 2 - Soil profile variables used with the crop growth models, example for Passo Fundo (Haplorthox).

Depth	pH water	Al/CEC	Org C	Min-N NO_3	Min-N NH_4	Texture Clay	Texture Silt	Texture Sand	Vol. Humidity Init	Vol. Humidity 15bar	Vol. Humidity FC	Vol. Humidity Sat	Bulk Dens	R.E. Coef
-(cm)-		(%)	(%)	-(ppm)-	-(ppm)-	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(g/cm3)	
0- 10	6.2	0	2.5	8.2	2.0	57	17	26	30	24	33	43	1.08	1.0
10- 20	6.3	0	2.4	3.8	2.0	53	21	26	32	28	33	38	1.16	0.8
20- 30	5.5	8	2.2	3.8	2.0	63	15	22	33	30	34	40	1.13	0.5
30- 40	4.7	53	1.9	3.7	2.0	67	13	20	33	30	34	41	1.13	0.2
40- 50	4.7	61	1.7	3.6	2.0	70	13	17	36	30	38	40	1.12	0.1
50- 60	5.2	63	1.3	3.6	2.0	72	13	15	40	34	42	42	1.09	0.1
60- 75	4.9	73	0.8	2.3	2.0	77	10	13	39	34	41	45	1.09	0.0
75- 90	5.0	79	0.5	2.2	2.0	77	10	13	41	34	43	45	1.10	0.0
90-105	5.0	80	0.3	2.0	2.0	78	9	13	38	34	39	46	1.13	0.0

Vol. Humidity:

Init.= initial, soil moisture at planting time

15bar= soil moisture at 15 bar pressure (lower limit)

FC = soil moisture at field capacity (drainage upper limit)

Sat = saturated water content

R.E.Coef.= Coefficient for root development (1= max. value)

CALIBRATION AND VALIDATION OF THE CROP MODELS

CERES-Wheat

The local wheat cultivar BR 14 was chosen for most dryland sites and its genetic coefficients were determined using experimental field data. The cultivar Anza, with the original genetic coefficients included in the DSSAT data base, was selected for the irrigation sites. The model was validated in Passo Fundo with data from several field experiments with a satisfactory agreement between observed and estimated grain yields (SIQUEIRA, 1991). In Brazil the CERES model has also been validated for wheat in São Paulo, South region (ANUNCIAÇÃO & LIU, 1991).

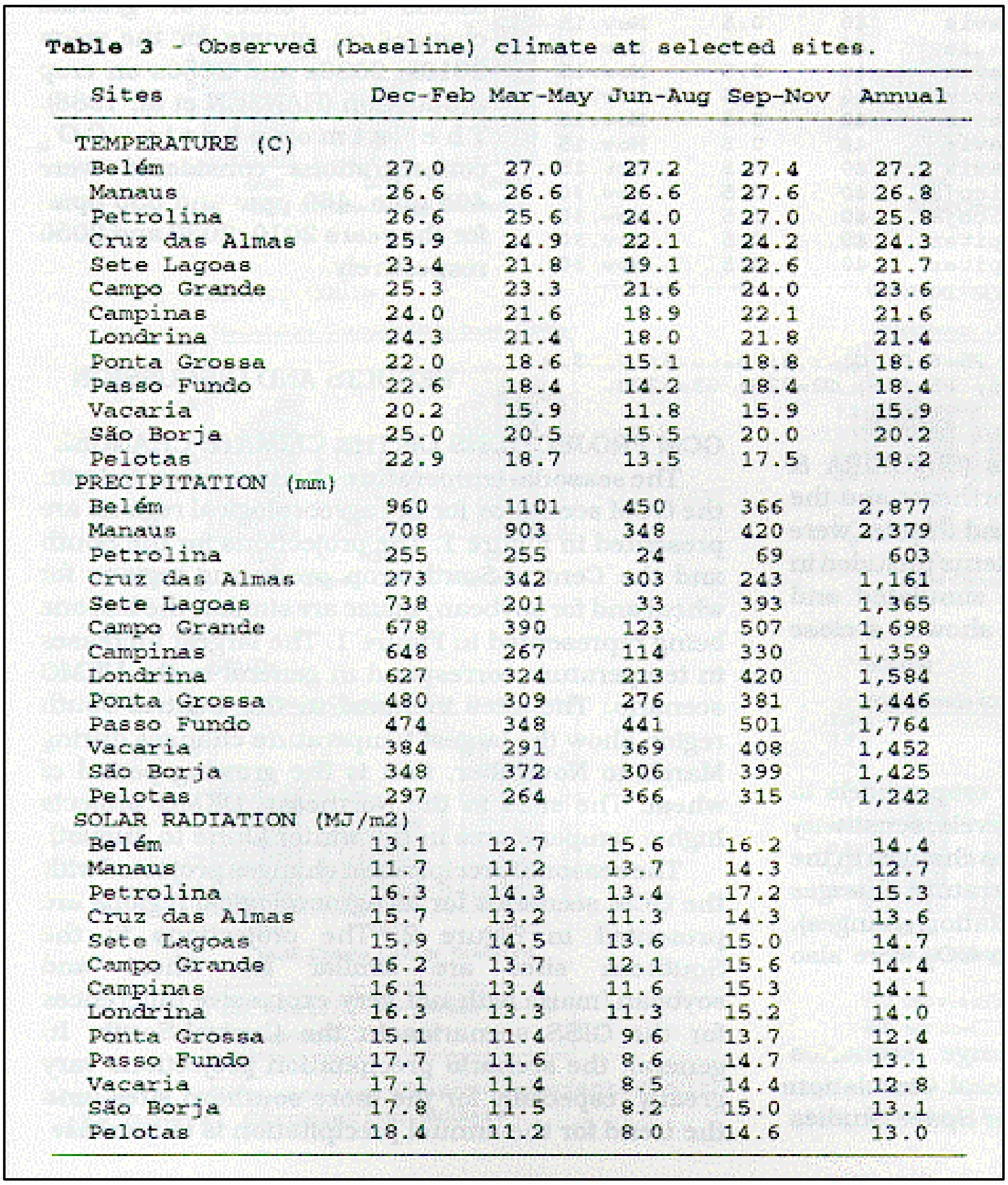

Table 3 - Observed (baseline) climate at selected sites.

Sites	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
TEMPERATURE (C)					
Belém	27.0	27.0	27.2	27.4	27.2
Manaus	26.6	26.6	26.6	27.6	26.8
Petrolina	26.6	25.6	24.0	27.0	25.8
Cruz das Almas	25.9	24.9	22.1	24.2	24.3
Sete Lagoas	23.4	21.8	19.1	22.6	21.7
Campo Grande	25.3	23.3	21.6	24.0	23.6
Campinas	24.0	21.6	18.9	22.1	21.6
Londrina	24.3	21.4	18.0	21.8	21.4
Ponta Grossa	22.0	18.6	15.1	18.8	18.6
Passo Fundo	22.6	18.4	14.2	18.4	18.4
Vacaria	20.2	15.9	11.8	15.9	15.9
São Borja	25.0	20.5	15.5	20.0	20.2
Pelotas	22.9	18.7	13.5	17.5	18.2
PRECIPITATION (mm)					
Belém	960	1101	450	366	2,877
Manaus	708	903	348	420	2,379
Petrolina	255	255	24	69	603
Cruz das Almas	273	342	303	243	1,161
Sete Lagoas	738	201	33	393	1,365
Campo Grande	678	390	123	507	1,698
Campinas	648	267	114	330	1,359
Londrina	627	324	213	420	1,584
Ponta Grossa	480	309	276	381	1,446
Passo Fundo	474	348	441	501	1,764
Vacaria	384	291	369	408	1,452
São Borja	348	372	306	399	1,425
Pelotas	297	264	366	315	1,242
SOLAR RADIATION (MJ/m2)					
Belém	13.1	12.7	15.6	16.2	14.4
Manaus	11.7	11.2	13.7	14.3	12.7
Petrolina	16.3	14.3	13.4	17.2	15.3
Cruz das Almas	15.7	13.2	11.3	14.3	13.6
Sete Lagoas	15.9	14.5	13.6	15.0	14.7
Campo Grande	16.2	13.7	12.1	15.6	14.4
Campinas	16.1	13.4	11.6	15.3	14.1
Londrina	16.3	13.3	11.3	15.2	14.0
Ponta Grossa	15.1	11.4	9.6	13.7	12.4
Passo Fundo	17.7	11.6	8.6	14.7	13.1
Vacaria	17.1	11.4	8.5	14.4	12.8
São Borja	17.8	11.5	8.2	15.0	13.1
Pelotas	18.4	11.2	8.0	14.6	13.0

CERES-Maize

The genetic coefficients for the local cultivar used on the South and Central-South regions (PIO 3230) were determined by running the crop model comparing data from a field experiment conducted by

MATZENAUER et al (1988) in Taquari, involving irrigation, nitrogen and population levels. Satisfatory agreement was found between observed and simulated yield data (data not published). For the other regions, cultivar Suwan 1, with the original genetic coefficients included in the DSSAT data base, was used, since the simulated results were in agreement with regional observed crop parameters.

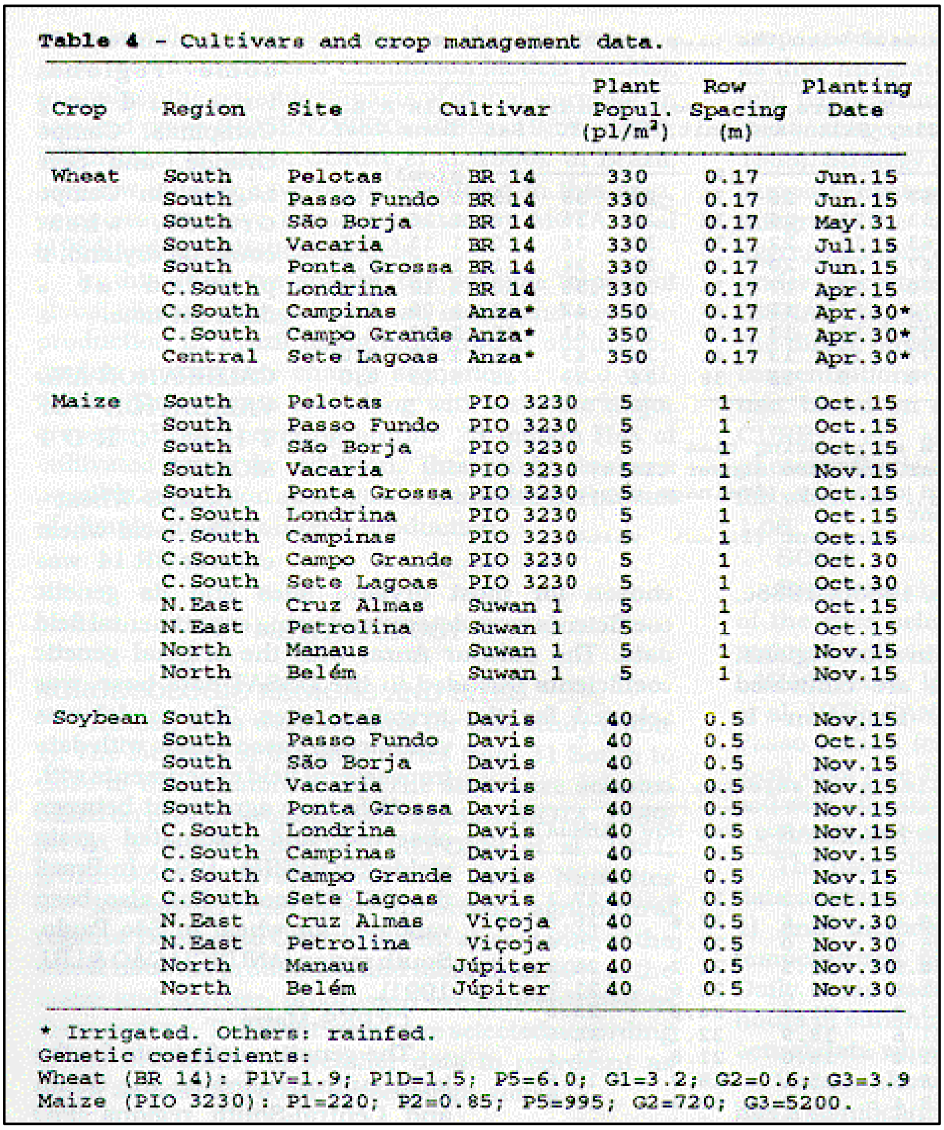

Table 4 - Cultivars and crop management data.

Crop	Region	Site	Cultivar	Plant Popul. (pl/m^2)	Row Spacing (m)	Planting Date
Wheat	South	Pelotas	BR 14	330	0.17	Jun.15
	South	Passo Fundo	BR 14	330	0.17	Jun.15
	South	São Borja	BR 14	330	0.17	May.31
	South	Vacaria	BR 14	330	0.17	Jul.15
	South	Ponta Grossa	BR 14	330	0.17	Jun.15
	C.South	Londrina	BR 14	330	0.17	Apr.15
	C.South	Campinas	Anza*	350	0.17	Apr.30*
	C.South	Campo Grande	Anza*	350	0.17	Apr.30*
	Central	Sete Lagoas	Anza*	350	0.17	Apr.30*
Maize	South	Pelotas	PIO 3230	5	1	Oct.15
	South	Passo Fundo	PIO 3230	5	1	Oct.15
	South	São Borja	PIO 3230	5	1	Oct.15
	South	Vacaria	PIO 3230	5	1	Nov.15
	South	Ponta Grossa	PIO 3230	5	1	Oct.15
	C.South	Londrina	PIO 3230	5	1	Oct.15
	C.South	Campinas	PIO 3230	5	1	Oct.15
	C.South	Campo Grande	PIO 3230	5	1	Oct.30
	C.South	Sete Lagoas	PIO 3230	5	1	Oct.30
	N.East	Cruz Almas	Suwan 1	5	1	Oct.15
	N.East	Petrolina	Suwan 1	5	1	Oct.15
	North	Manaus	Suwan 1	5	1	Nov.15
	North	Belém	Suwan 1	5	1	Nov.15
Soybean	South	Pelotas	Davis	40	0.5	Nov.15
	South	Passo Fundo	Davis	40	0.5	Oct.15
	South	São Borja	Davis	40	0.5	Nov.15
	South	Vacaria	Davis	40	0.5	Nov.15
	South	Ponta Grossa	Davis	40	0.5	Nov.15
	C.South	Londrina	Davis	40	0.5	Nov.15
	C.South	Campinas	Davis	40	0.5	Nov.15
	C.South	Campo Grande	Davis	40	0.5	Nov.15
	C.South	Sete Lagoas	Davis	40	0.5	Oct.15
	N.East	Cruz Almas	Viçoja	40	0.5	Nov.30
	N.East	Petrolina	Viçoja	40	0.5	Nov.30
	North	Manaus	Júpiter	40	0.5	Nov.30
	North	Belém	Júpiter	40	0.5	Nov.30

* Irrigated. Others: rainfed.
Genetic coeficients:
Wheat (BR 14): P1V=1.9; P1D=1.5; P5=6.0; G1=3.2; G2=0.6; G3=3.9
Maize (PIO 3230): P1=220; P2=0.85; P5=995; G2=720; G3=5200.

SOYGRO-Soybean

The genetic coefficients of the cultivar Davis were calibrated using data from a field experiment conducted in Passo Fundo in 1989 and the model was validated with data from several field experiments (SIQUEIRA & BERG, 1991). For the sites in the Northeast and the North regions, the cultivars Viçoja and Júpiter were used, with the original genetic coefficients included in the DSSAT data base. In Belém, simulated and observed yields and anthesis dates showed a close relationship.

CLIMATE CHANGE SCENARIOS

Sensitivity scenarios

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

General Circulation models

This study used climate change scenarios generated by three equilibrium General Circulation Models (GCMs): Goddard Institute for Space Studies - GISS (HANSEN et al, 1983), Geophysical Fluid Dynamics Laboratory - GFDL (MANABE & WETHERALD, 1987) and United Kingdom Meteorological Office - UKMO (WILSON & MITCHELL, 1987). These GCMs are three dimensional models which incorporate physical knowledge of the processes involved in the transfer of the energy among earth, oceans and atmosphere.

The climate change scenarios for each site were created by applying the changes between the $1xCO_2$ (330 ppm CO_2) and $2xCO_2$ (555 ppm CO_2) monthly GCM simulated variables to the corresponding daily baseline climate variables.

GISS Transient scenarios

The GISS Transient scenarios were also used in this study, to assess the effect of gradual changes on climate for the years 2010s, 2030s and 2050s on crop production (HANSEN et al, 1988). The atmospheric CO_2 concentrations considered were 405 ppm, 460 ppm and 530 ppm, for the years 2010, 2030 and 2050 respectively.

RESULTS AND DISCUSSION

GCM PROJECTIONS OF THE CLIMATE CHANGES

The seasonal temperature changes projected with the GCM scenarios for the agroecological regions are presented in Figure 1. The projections for the South and the Central-South crop producing regions for wheat and for soybean/maize are similar, the last one being represented in Figure 1. The largest increases in temperature correspond in general to the UKMO scenario. The sites included in the Central-South region show the largest temperature changes during March to November, that is the growing period of wheat. The sites in the Northeast, UKMO projects higher temperatures in the winter (June to August).

The seasonal precipitation changes projected with the GCM scenarios for all agroecological regions are presented in Figure 2. The projections in the Southern sites are similar for wheat and soybean/maize with not very expressive differences for the GISS scenarios in the Central-South. In general, the scenario precipitation projections vary greatly, especially for the more southern sites, and the trend for the annual precipitation is to increase compared to the current (observed) climate. The GFDL scenario projects the largest precipitation increases for sites in the South from September to November, and also from March to May for sites in the Central-South. The precipitation projected by the GFDL and UKMO scenarios for December for most of the Southern sites, is lower than the current precipitation, meaning more of a change of drought problems for the summer crops. Annually, lower increases in precipitation are projected for the sites in the Northeast and the North regions; the UKMO scenario projects decreases of about 10 to 15% for these regions; the precipitation reductions projected by the UKMO scenario during the summer (December to February) and winter (June to August) might represent an additional stress for the crops in the northern sites, especially considering the current low water supply in the winter (see Table 3).

Differences in solar radiation between baseline and climate change scenarios are not very expressive (data not shown).

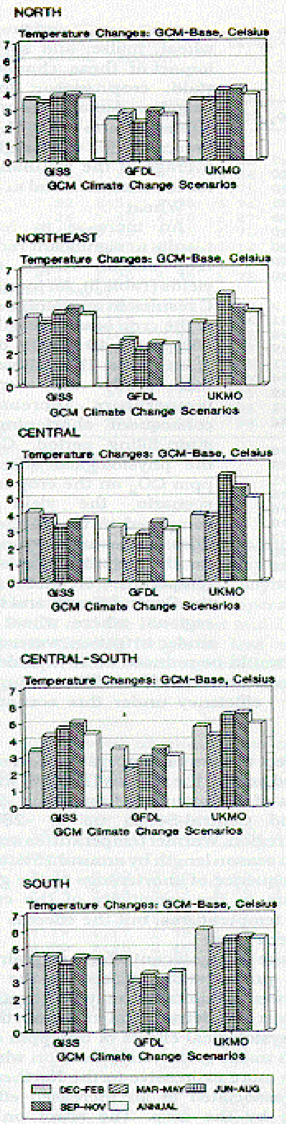

Figure 1 - Temperature changes projected with the General Circulation Models.

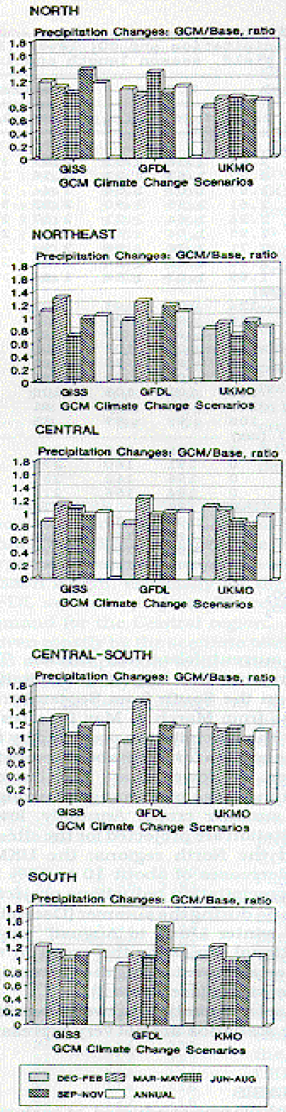

Figure 2 - Precipitation changes projected with the General Circulation Models.

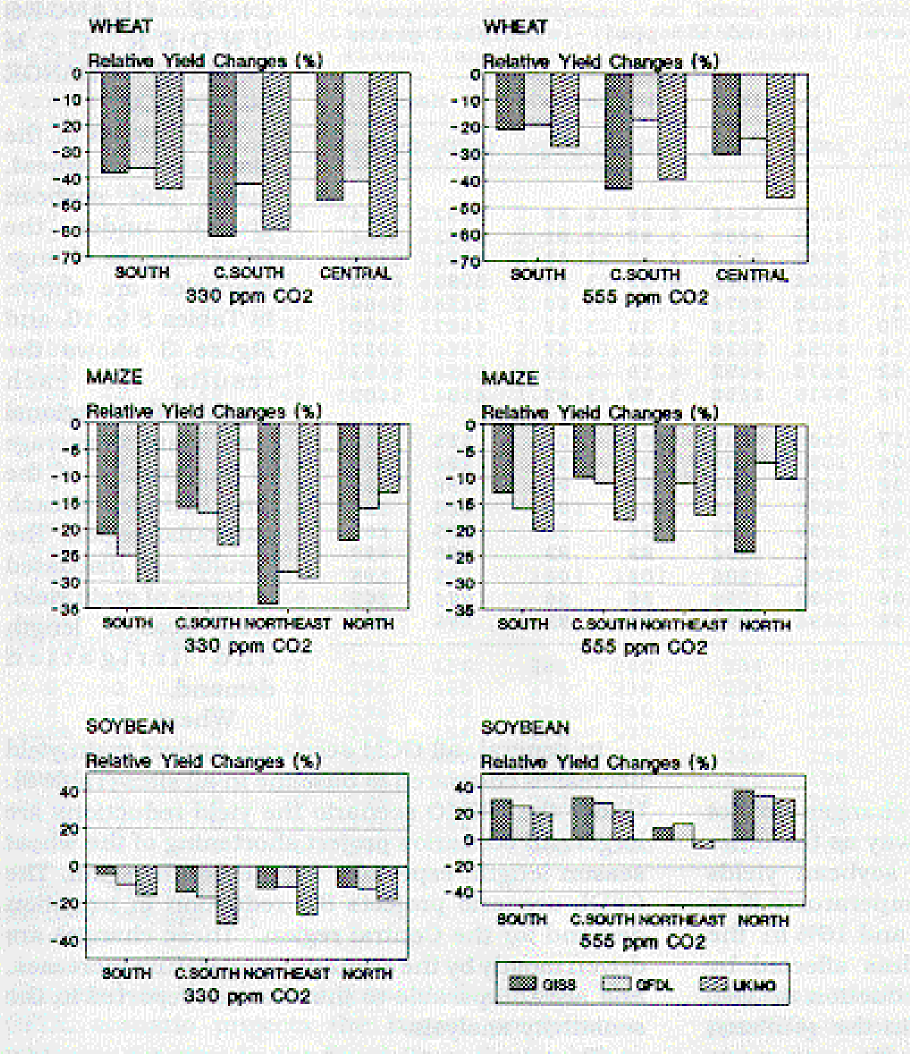

Figure 3 - Wheat , maize, and soybean grain yield projected with GCMs (330 and 555 ppm CO_2).

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted at each site, to evaluate the effect of step changes in temperature, precipitation, and CO_2 atmospheric concentration on crop physiology and production of wheat, maize, and soybean. The impact of these changes in grain yield, crop season length and irrigation demand are presented in Tables 5 to 7. The results presented for each region are an average of the simulation results for the sites included in the region.

Wheat

An increase in temperature results in significant reductions in crop season length and grain yields (Table 5). An increment of +4 C results in an average shortening of the crop season length by about 15% and a 40 to 50% decrease in grain yields. The cultivars used in this study are sensitive to temperature increases, with consequent shortenings in the grain filling period. Considering the physiological effects of 555 ppm CO_2 on the crop in the +4 C scenario, the yield increases compared to the +4 C alone, but does not completely compensate for the negative effects of higher temperature on wheat yields. For the Central-South and the Central regions, where wheat is grown under irrigation, water demand for irrigation would be reduced in 15% under the 555 ppm CO_2 concentration (Table 5), meaning increased water use efficiency under this scenario (ROSE, 1989).

Maize

The effect of warmer temperatures on maize grain yield varied among the regions (Table 6) with average reductions of 22%, ranging from about -20% in the South and Central-South up to -28% in the Northeast region. Warmer temperatures would reduce maize crop season length by around 15%, on average, as a consequence of shortenings in the grain filling period, due to the sensitivity of the cultivars to increased temperatures, but the effect is greater for the southern sites.

There are no significant effects on grain yield with increased precipitation, except in the Northeast region. Lower precipitation may be beneficial in the North region and detrimental in the Northeast.

The physiological effects of 555 ppm of CO_2 are smaller on maize grain yields than on wheat. These effects are more expressive in the Northeast region, probably associated to an increased efficiency in water use by the crop. The effect on irrigation demand was not tested considering the dryland crop management adopted for maize in all production regions.

Soybean

Temperature and precipitation changes do not alter soybean growth in the same way as the other two crops (Table 7). In average, soybean yields reduces near 12% under warmer temperatures (6 to 8% in the South and the Northeast and 16% in the other regions). Season length is less affected by increased temperatures (average reduction of 1%), and the greater effect is observed in the southern regions.

Table 5 - Sensitivity of the CERES-Wheat model to changes in temperature, precipitation and CO_2 level (330 and 555 ppm) - simulated grain yield, season length and irrigation demand.

Prec Diff (%)	Temp Diff (C)	South		C.South		Central		Mean	
		$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$
GRAIN YIELD (T/Ha)									
0	+0	2.30	2.66	2.36	2.91	2.93	3.36	2.53	2.98
0	+2	1.88	2.27	1.63	2.22	2.18	2.71	1.90	2.40
0	+4	1.47	1.87	1.03	1.54	1.44	2.00	1.31	1.80
+20%	0	2.26	2.61	2.35	2.90	2.93	3.34	2.51	2.95
+20%	+2	1.86	2.24	1.64	2.21	2.17	2.70	1.89	2.39
+20%	+4	1.46	1.85	1.04	1.54	1.44	2.00	1.31	1.80
-20%	0	2.32	2.71	2.36	2.96	2.94	3.32	2.53	3.00
-20%	+2	1.89	2.30	1.63	2.24	2.18	2.67	1.90	2.40
-20%	+4	1.48	1.89	1.03	1.54	1.44	1.97	1.32	1.80
SEASON LENGTH (Days)									
0	0	124	124	103	103	100	100	109	109
0	+2	116	116	95	95	91	91	101	101
0	+4	108	108	89	89	85	85	94	94
+20%	0	124	124	103	103	100	100	109	109
+20%	+2	116	116	95	95	91	91	101	101
+20%	+4	108	108	89	89	85	85	94	94
-20%	0	124	124	103	103	100	100	109	109
-20%	+2	116	116	95	95	91	91	101	101
-20%	+4	108	108	89	89	85	85	94	94
IRRIGATION DEMAND (mm)									
0	0	0	0	186	156	281	240	234	198
0	+2	0	0	191	160	275	236	233	198
0	+4	0	0	196	162	281	240	238	201
+20%	0	0	0	184	156	276	237	230	196
+20%	+2	0	0	188	159	273	233	230	196
+20%	+4	0	0	194	159	276	239	235	198
-20%	0	0	0	189	161	282	243	236	202
-20%	+2	0	0	195	164	275	237	235	200
-20%	+4	0	0	202	169	280	240	241	204

$1xCO_2$ = 330 ppm CO_2
$2xCO_2$ = 555 ppm CO_2

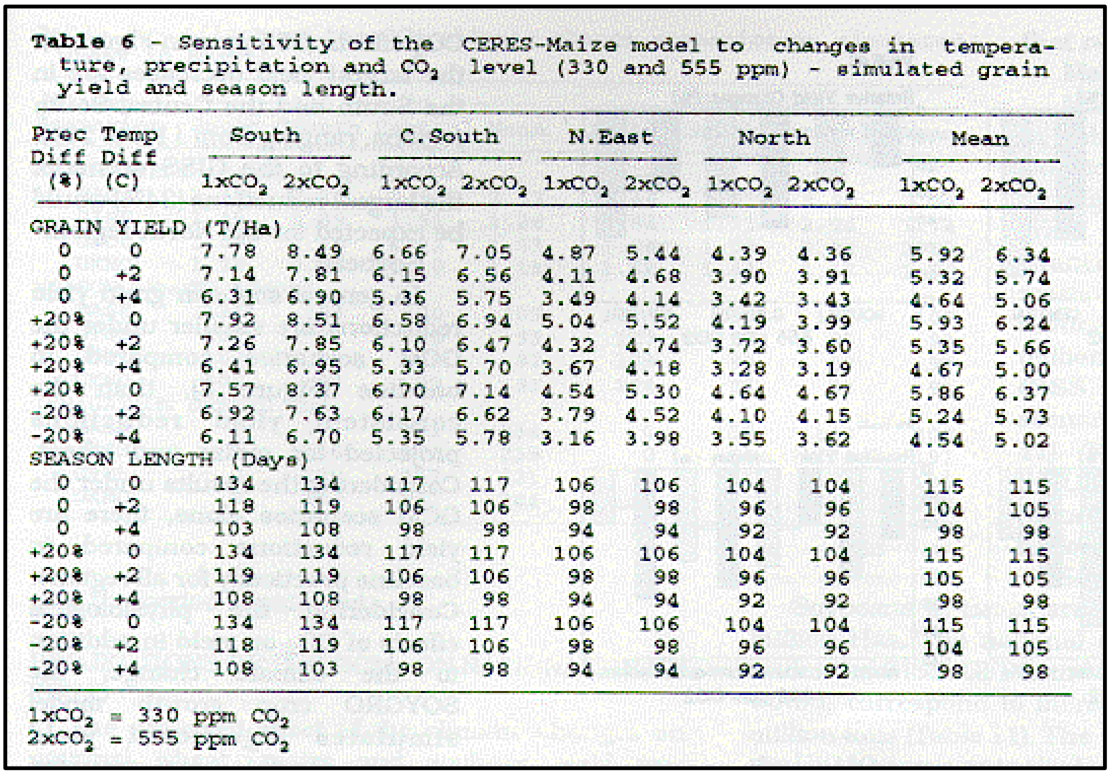

Table 6 - Sensitivity of the CERES-Maize model to changes in temperature, precipitation and CO_2 level (330 and 555 ppm) - simulated grain yield and season length.

Prec Diff (%)	Temp Diff (C)	South		C.South		N.East		North		Mean	
		$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$
GRAIN YIELD (T/Ha)											
0	0	7.78	8.49	6.66	7.05	4.87	5.44	4.39	4.36	5.92	6.34
0	+2	7.14	7.81	6.15	6.56	4.11	4.68	3.90	3.91	5.32	5.74
0	+4	6.31	6.90	5.36	5.75	3.49	4.14	3.42	3.43	4.64	5.06
+20%	0	7.92	8.51	6.58	6.94	5.04	5.52	4.19	3.99	5.93	6.24
+20%	+2	7.26	7.85	6.10	6.47	4.32	4.74	3.72	3.60	5.35	5.66
+20%	+4	6.41	6.95	5.33	5.70	3.67	4.18	3.28	3.19	4.67	5.00
+20%	0	7.57	8.37	6.70	7.14	4.54	5.30	4.64	4.67	5.86	6.37
-20%	+2	6.92	7.63	6.17	6.62	3.79	4.52	4.10	4.15	5.24	5.73
-20%	+4	6.11	6.70	5.35	5.78	3.16	3.98	3.55	3.62	4.54	5.02
SEASON LENGTH (Days)											
0	0	134	134	117	117	106	106	104	104	115	115
0	+2	118	119	106	106	98	98	96	96	104	105
0	+4	103	108	98	98	94	94	92	92	98	98
+20%	0	134	134	117	117	106	106	104	104	115	115
+20%	+2	119	119	106	106	98	98	96	96	105	105
+20%	+4	108	108	98	98	94	94	92	92	98	98
-20%	0	134	134	117	117	106	106	104	104	115	115
-20%	+2	118	119	106	106	98	98	96	96	104	105
-20%	+4	108	103	98	98	94	94	92	92	98	98

$1xCO_2$ = 330 ppm CO_2
$2xCO_2$ = 555 ppm CO_2

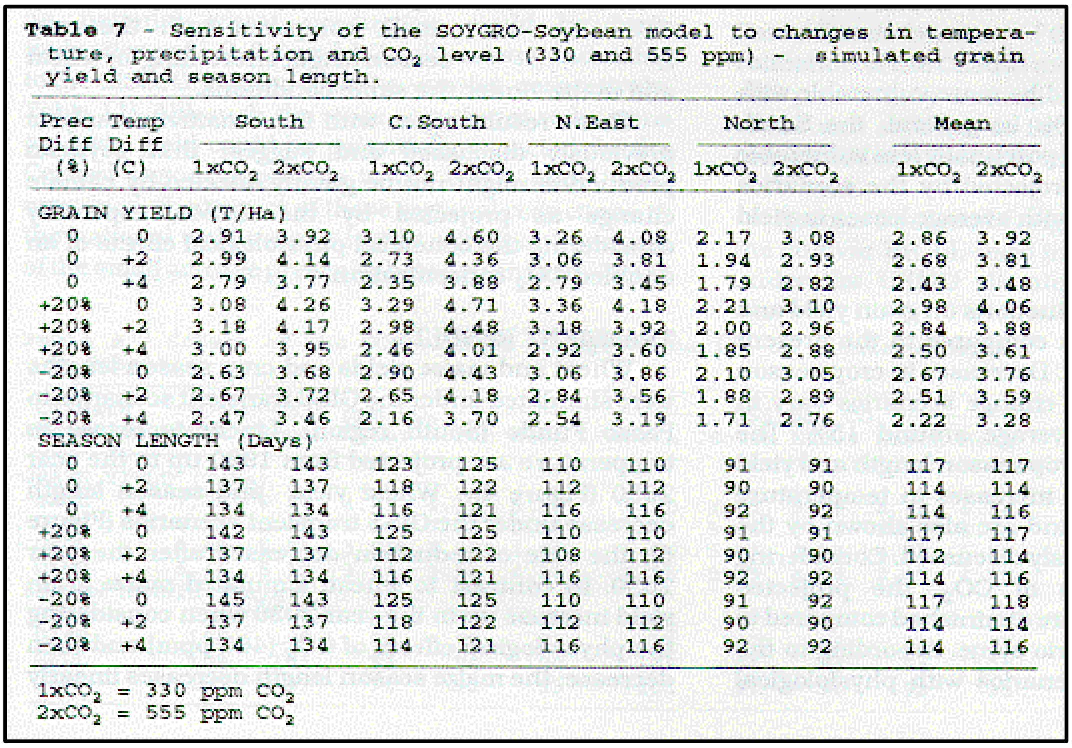

Table 7 - Sensitivity of the SOYGRO-Soybean model to changes in temperature, precipitation and CO_2 level (330 and 555 ppm) - simulated grain yield and season length.

Prec Diff (%)	Temp Diff (C)	South		C.South		N.East		North		Mean	
		$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$
GRAIN YIELD (T/Ha)											
0	0	2.91	3.92	3.10	4.60	3.26	4.08	2.17	3.08	2.86	3.92
0	+2	2.99	4.14	2.73	4.36	3.06	3.81	1.94	2.93	2.68	3.81
0	+4	2.79	3.77	2.35	3.88	2.79	3.45	1.79	2.82	2.43	3.48
+20%	0	3.08	4.26	3.29	4.71	3.36	4.18	2.21	3.10	2.98	4.06
+20%	+2	3.18	4.17	2.98	4.48	3.18	3.92	2.00	2.96	2.84	3.88
+20%	+4	3.00	3.95	2.46	4.01	2.92	3.60	1.85	2.88	2.50	3.61
-20%	0	2.63	3.68	2.90	4.43	3.06	3.86	2.10	3.05	2.67	3.76
-20%	+2	2.67	3.72	2.65	4.18	2.84	3.56	1.88	2.89	2.51	3.59
-20%	+4	2.47	3.46	2.16	3.70	2.54	3.19	1.71	2.76	2.22	3.28
SEASON LENGTH (Days)											
0	0	143	143	123	125	110	110	91	91	117	117
0	+2	137	137	118	122	112	112	90	90	114	114
0	+4	134	134	116	121	116	116	92	92	114	116
+20%	0	142	143	125	125	110	110	91	91	117	117
+20%	+2	137	137	112	122	108	112	90	90	112	114
+20%	+4	134	134	116	121	116	116	92	92	114	116
-20%	0	145	143	125	125	110	110	91	92	117	118
-20%	+2	137	137	118	122	112	112	90	90	114	114
-20%	+4	134	134	114	121	116	116	92	92	114	116

$1xCO_2$ = 330 ppm CO_2
$2xCO_2$ = 555 ppm CO_2

CROP CHANGES UNDER GCM CLIMATE CHANGE SCENARIOS

The results of the simulation of wheat, maize and soybean growth under the GCM climate change scenarios are shown in Tables 8 to 10, and Figure 3 shows the results for each region; the regional results are an average of the results of the sites included in each particular region. The results are discussed in terms of grain yield, crop season length and irrigation demand.

Wheat

In general, all GCM scenarios project grain yield decreases compared to baseline in all sites (Table 8). Under the UKMO scenario the yield reductions are larger. All scenarios project shortening of the wheat season length, especially for the South region. The GFDL scenario projects 8% reduction in irrigation demand for the Central region. These changes are driven mostly by the scenario temperature increases, and are comparable to the changes reported in the sensitivity analysis.

The percent change in wheat grain yields, projected for the different climate scenarios, for each region, are illustrated in Figure 3. Considering the physiological effects of CO_2 (555 ppm in Figure 3), the negative effect of the climate change alone is partially diminished. Wheat yields in the Central region are potentially the most vulnerable to future climate changes under the GFDL and the UKMO scenarios (yield reductions of 24 and 46%, respectively). Under the GISS scenario, the Central-South region could be more vulnerable with losses projected near 43%. In general, the South region could be considered potentially less vulnerable to the climate changes projected by the scenarios considered in this study, with average losses in yield projected to be 22%.

Maize

All scenarios project reductions on grain yield and crop season length, when compared to the present climate (Table 9, Figure 3). Decreases in crop season length under the climate change scenarios vary in each region, but they average around 15%. The climate change effect on crop season length and yield are a consequence of the increases in temperature projected by the GCMs, and are also shown by the sensitivity studies previously discussed. Considering the physiological effects of CO_2, the projected reductions on grain yield are diminished compared to the climate change scenario alone. According to the GFDL and the UKMO scenarios with physiological CO_2 effects (555 ppm in Figure 3), the largest yield decreases are in the South and the Central-South regions, ranging from 11% to 20%. According to the GISS scenario, the largest reductions (24%) would be expected for the North region.

Soybean

In general soybean grain yield reductions are smaller under the GCM scenarios compared to baseline (Figure 3), than the consistent yield reductions projected for maize and wheat. Considering the results under the GCM scenarios alone, there are yield reductions compared to baseline practically for all regions. Considering the physiological effects of CO_2 on yield in addition to the climate change, the

SOYGRO crop growth model simulates significant yield increases. In this case, projected average gains in soybean yield average 22% compared to baseline (330 ppm CO_2, Table 10). The results are consistent in all regions, except the Northeast where yields decreased or the increases were under 15% (Figure 3). A small shortening in crop season length is simulated under all GCM scenarios for the sites in the South and the Central-South regions, but this effect is very small, compared with the crop season length shortening for wheat and maize under the same conditions.

These results agree with the sensitivity analysis previously discussed and suggest that soybean production might not be greatly affected by climate change as projected by the GCMs, especially considering the beneficial physiological effects of an doubled CO_2 concentration.

TRANSIENT RESULTS

Wheat and maize yields and crop season lengths were simulated under the GISS transient scenarios in Passo Fundo (South region). Linear increases in temperature are projected from 1990 up to the year 2050 (Figure 4). Wheat yield and season length decrease under the GISS transient scenarios (Figure 5); the rate of reduction decreases after the year 2030. In contrast to wheat, simulated maize grain yield increase up to the year 2030 when considering the physiological effects of CO_2 (460 ppm) and then decrease; the maize season length decreases linearly over the period considered.

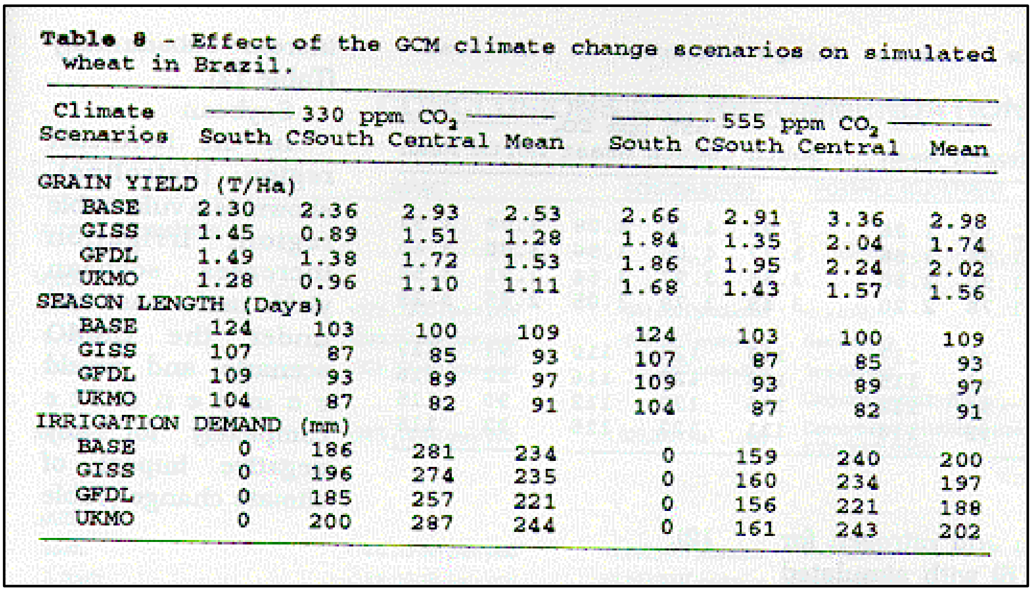

Table 8 - Effect of the GCM climate change scenarios on simulated wheat in Brazil.

Climate Scenarios	330 ppm CO_2 South	330 ppm CO_2 CSouth	330 ppm CO_2 Central	330 ppm CO_2 Mean	555 ppm CO_2 South	555 ppm CO_2 CSouth	555 ppm CO_2 Central	555 ppm CO_2 Mean
GRAIN YIELD (T/Ha)								
BASE	2.30	2.36	2.93	2.53	2.66	2.91	3.36	2.98
GISS	1.45	0.89	1.51	1.28	1.84	1.35	2.04	1.74
GFDL	1.49	1.38	1.72	1.53	1.86	1.95	2.24	2.02
UKMO	1.28	0.96	1.10	1.11	1.68	1.43	1.57	1.56
SEASON LENGTH (Days)								
BASE	124	103	100	109	124	103	100	109
GISS	107	87	85	93	107	87	85	93
GFDL	109	93	89	97	109	93	89	97
UKMO	104	87	82	91	104	87	82	91
IRRIGATION DEMAND (mm)								
BASE	0	186	281	234	0	159	240	200
GISS	0	196	274	235	0	160	234	197
GFDL	0	185	257	221	0	156	221	188
UKMO	0	200	287	244	0	161	243	202

PROJECTIONS OF THE GCMs ON NATIONAL GRAIN YIELD

The projected effect of the climatic changes on national wheat, maize and soybean yield was estimated aggregating the regional results weighted according to cultivated area. All results reported consider the beneficial physiological CO_2 effects on crop yield. In this study the crop management, technology and distribution of cultivated land are assumed to remain constant.

Wheat

Wheat is grown in 3.6 million Has in Brazil. Considering the changes in regional wheat yield under the GCM scenarios, and the contribution of these regions to the national wheat area, we estimate that the possible impact of climate change scenarios on national wheat production could be large (reductions of 1.2, 0.6 and 1.2 million tons, according to the GISS, GFDL and UKMO scenarios, respectively, Table 11). Although the more significant reductions on grain yield could be potentially expected for the Central region, according to the GFDL and UKMO scenarios, the impact of these regional reductions in the national yield are not highly significant because of the small acreage presently being cultivated (1%) in that region.

Maize

Maize in Brazil is cultivated in about 22 million Has. Considering the cultivated area by region and the changes in grain yield under the climate chance scenarios, the national maize production could be reduced 2.3, 2.4 and 3.5 million tons, according to the GISS, GFDL and UKMO scenarios, respectively (Table 11). The projected values with the UKMO model represent 16% reduction on the present national maize yields.

Soybean

Soybeans in Brazil are cultivated in about 15.6 million Has. The national estimated yield changes under the GISS, GFDL and UKMO climate scenarios would correspond to increases of 4.1, 3.6 and 2.8 million tons (Table 11). The 6% yield decrease under the UKMO scenario in the Northeast region, does not have a large impact in the national yields since that region only contributes about 1% of the total soybean cultivated land in this country.

ADAPTIVE STUDIES

Wheat and maize development and yield are affected by the climate changes projected by the GCM scenarios studied and the changes are larger under the UKMO scenario. This part of the study aims to detect possible alternatives that would compensate for the negative impact of the climate changes on wheat and maize. The simulation was carried out in Passo Fundo because of the careful calibration and validation of the CERES model at that site. Additional and preliminary strategies were also simulated for maize and soybean in Petrolina (Northeast region), considered a vulnerable region to climate change.

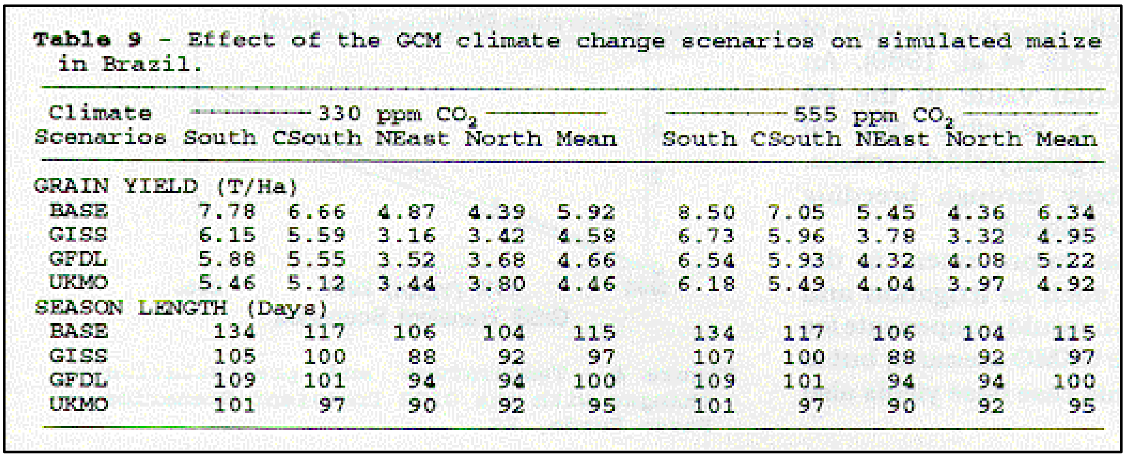

Table 9 - Effect of the GCM climate change scenarios on simulated maize in Brazil.

Climate Scenarios	330 ppm CO_2 South	CSouth	NEast	North	Mean	555 ppm CO_2 South	CSouth	NEast	North	Mean
GRAIN YIELD (T/Ha)										
BASE	7.78	6.66	4.87	4.39	5.92	8.50	7.05	5.45	4.36	6.34
GISS	6.15	5.59	3.16	3.42	4.58	6.73	5.96	3.78	3.32	4.95
GFDL	5.88	5.55	3.52	3.68	4.66	6.54	5.93	4.32	4.08	5.22
UKMO	5.46	5.12	3.44	3.80	4.46	6.18	5.49	4.04	3.97	4.92
SEASON LENGTH (Days)										
BASE	134	117	106	104	115	134	117	106	104	115
GISS	105	100	88	92	97	107	100	88	92	97
GFDL	109	101	94	94	100	109	101	94	94	100
UKMO	101	97	90	92	95	101	97	90	92	95

Wheat

Results from modifying the genetic coefficients of the cultivar BR 14, used in most simulation studies, under the UKMO climate scenario, are shown in Figure 6. The modified coefficients are related to responses in the changes in temperature: P1V refers to response to vernalization and P5 corresponds to the duration of the grain filling period, also very responsive to changes in temperature (GODWIN et al, 1989). Crop management alternatives, combining irrigation and nitrogen for maximum yield (N off in Figure 6) with simulated cultivars, adapted to warmer temperatures are considered as possible adaptation strategies under the climate change conditions. The strategy with the genetic coefficient values of 8 for P5, and 2.5 for P1V, with irrigation and no nitrogen stress, would result in values for grain yield and crop season length close to the estimated for the baseline climate. The actual values of P5 and P 1V correspond, respectively, to 6 and 1.9 and the value of 8 for P5 is beyond the range found in the IBSNAT database (GODWIN et al, 1989). Aggregating irrigation, nitrogen for maximum yield, and a P1V coefficient value of 2.5 that represents a feasible situation, would approximate actual yields in 90%.

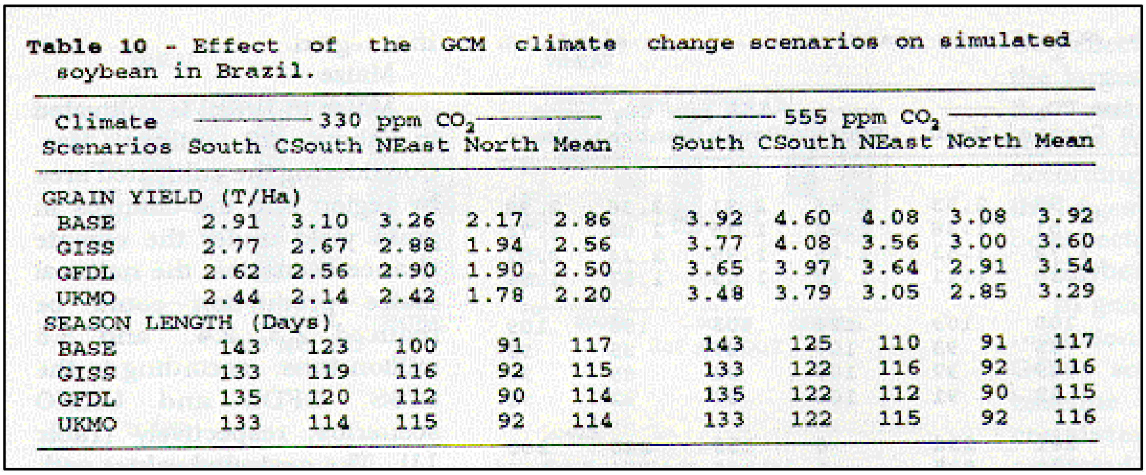

Table 10 - Effect of the GCM climate change scenarios on simulated soybean in Brazil.

Climate Scenarios	330 ppm CO_2 South	CSouth	NEast	North	Mean	555 ppm CO_2 South	CSouth	NEast	North	Mean
GRAIN YIELD (T/Ha)										
BASE	2.91	3.10	3.26	2.17	2.86	3.92	4.60	4.08	3.08	3.92
GISS	2.77	2.67	2.88	1.94	2.56	3.77	4.08	3.56	3.00	3.60
GFDL	2.62	2.56	2.90	1.90	2.50	3.65	3.97	3.64	2.91	3.54
UKMO	2.44	2.14	2.42	1.78	2.20	3.48	3.79	3.05	2.85	3.29
SEASON LENGTH (Days)										
BASE	143	123	100	91	117	143	125	110	91	117
GISS	133	119	116	92	115	133	122	116	92	116
GFDL	135	120	112	90	114	135	122	112	90	115
UKMO	133	114	115	92	114	133	122	115	92	116

Modern cultivars with high yield potential also could compensate for the decrease in the total grain supply, as shown in Figure 7, comparing data for cultivar BR 23, in relation to the cultivar BR 14 used for most regions.

Maize

The changes on crop management tested (irrigation and changes in planting date) do not compensate for the maize yield decrease under the UKMO scenario in Passo Fundo, South region (Table 12). The development of a hypothetical new cultivar with different P5 "genetic coefficient" would improve maize yield production under the climate change scenarios (Table 12). The P5 coefficient is associated with the characteristic of the cultivar to respond to the warmer temperatures, reflecting the duration of the grain filling period (RITCHIE et al, 1989). An increase of 20% of the actual value of the P5 coefficient would present a possible way of compensating for the projected grain yield decreases. The feasibility of this strategy through breeding programs should be further explored.

In Petrolina (Northeast) an improvement in the crop management practices such as irrigation and increased nitrogen fertilization, could compensate for the yield decreases under the UKMO scenario; but is important to notice that in this case base yields also increase substantially (Table 12).

Soybean

In the Northeast region (Petrolina), shown as a vulnerable region, irrigation increases soybean yields under base and under the UKMO scenario and would compensate completely for any negative impact of climate change (Table 12).

SOME LIMITATIONS OF THE STUDY

The crop models have not been validated in all regions considered in the study. Technology and land use are considered constant. The direct physiological effects of CO_2 on crop development and yield may be different than the simulated ones

The General Circulation Models do not include variability that might represent a very important factor for crop production, especially in the more vulnerable regions. The resolution of the Climate Change Scenarios as created in this study, is low. Some climatic differences observed in the southern sites, were not apparent in the climate change scenarios.

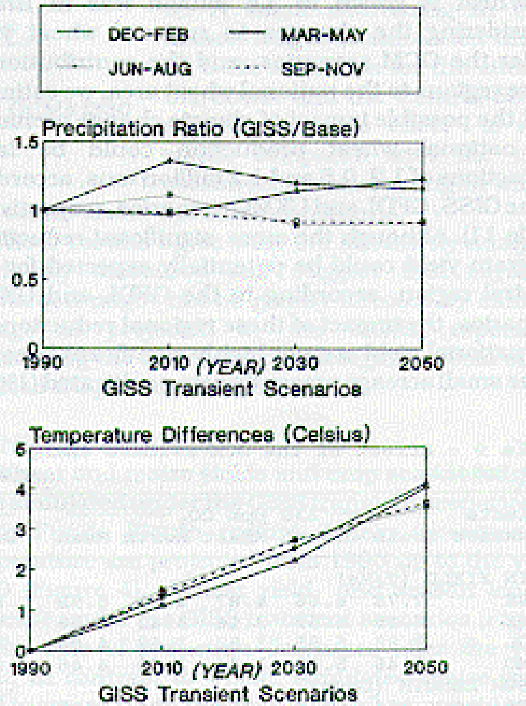

Figure 4 - Temperature and precipitation changes with the GISS Transient Scenarios, Passo Fundo, RS.

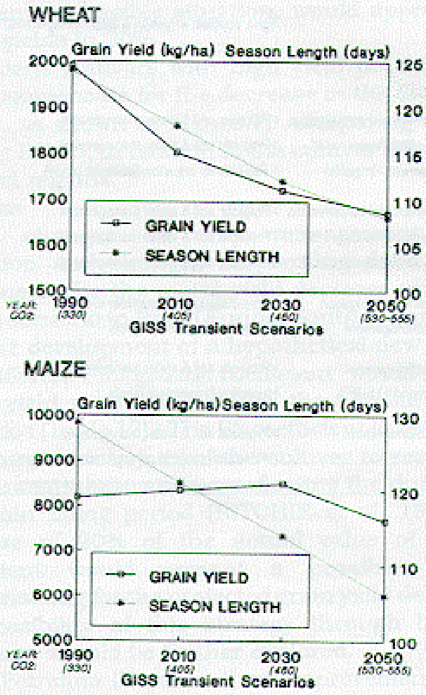

Figure 5 - Wheat and maize grain yield and season length with the GISS Transient Scenarios.

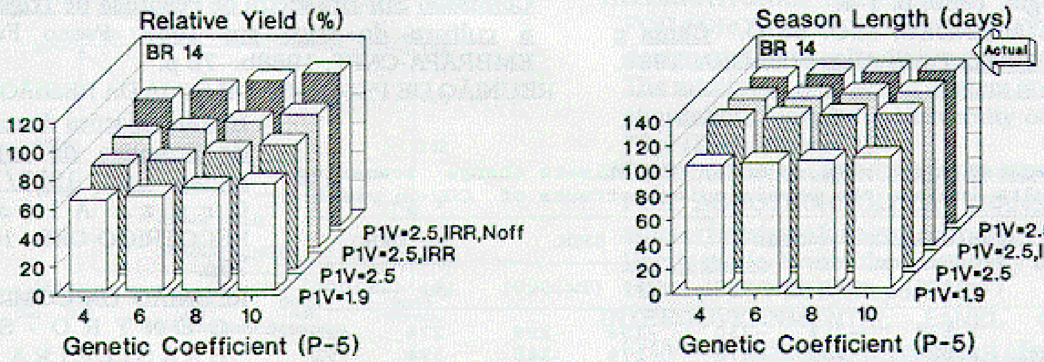

Figure 6 - Adaptation studies for wheat in Passo Fundo with UKMO 555 ppm CO_2 scenario: genetic coefficients and crop management.

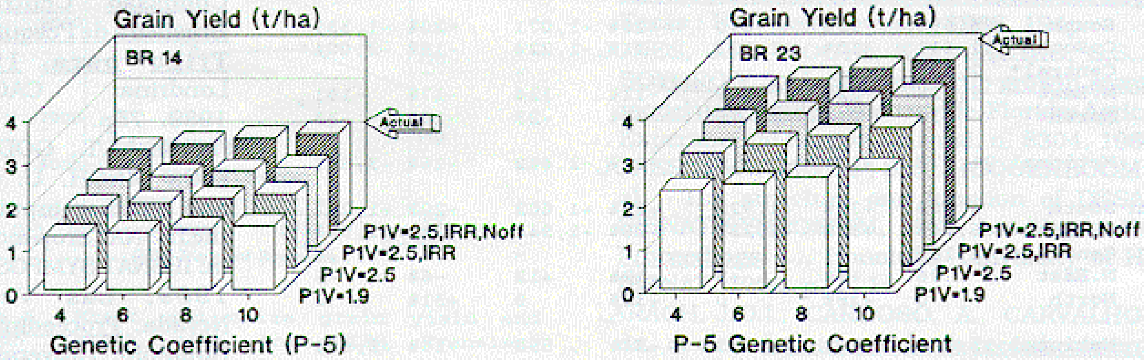

Figure 7 - Adaptation studies for wheat in Passo Fundo with UKMO 555 ppm CO_2 scenario: cultivars with different yield potential and crop management.

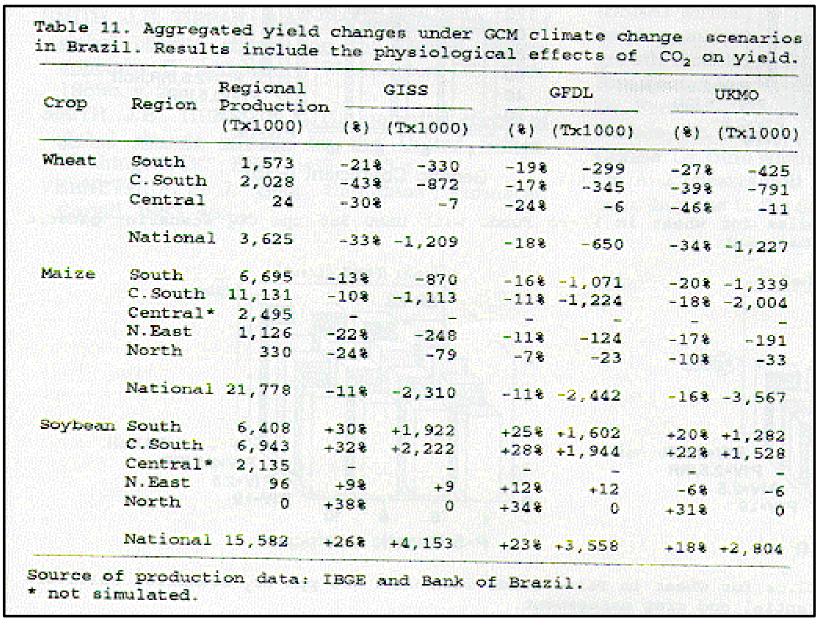

Table 11. Aggregated yield changes under GCM climate change scenarios in Brazil. Results include the physiological effects of CO_2 on yield.

Crop	Region	Regional Production	GISS		GFDL		UKMO	
		(Tx1000)	(%)	(Tx1000)	(%)	(Tx1000)	(%)	(Tx1000)
Wheat	South	1,573	-21%	-330	-19%	-299	-27%	-425
	C.South	2,028	-43%	-872	-17%	-345	-39%	-791
	Central	24	-30%	-7	-24%	-6	-46%	-11
	National	3,625	-33%	-1,209	-18%	-650	-34%	-1,227
Maize	South	6,695	-13%	-870	-16%	-1,071	-20%	-1,339
	C.South	11,131	-10%	-1,113	-11%	-1,224	-18%	-2,004
	Central*	2,495	-	-	-	-	-	-
	N.East	1,126	-22%	-248	-11%	-124	-17%	-191
	North	330	-24%	-79	-7%	-23	-10%	-33
	National	21,778	-11%	-2,310	-11%	-2,442	-16%	-3,567
Soybean	South	6,408	+30%	+1,922	+25%	+1,602	+20%	+1,282
	C.South	6,943	+32%	+2,222	+28%	+1,944	+22%	+1,528
	Central*	2,135	-	-	-	-	-	-
	N.East	96	+9%	+9	+12%	+12	-6%	-6
	North	0	+38%	0	+34%	0	+31%	0
	National	15,582	+26%	+4,153	+23%	+3,558	+18%	+2,804

Source of production data: IBGE and Bank of Brazil.
* not simulated.

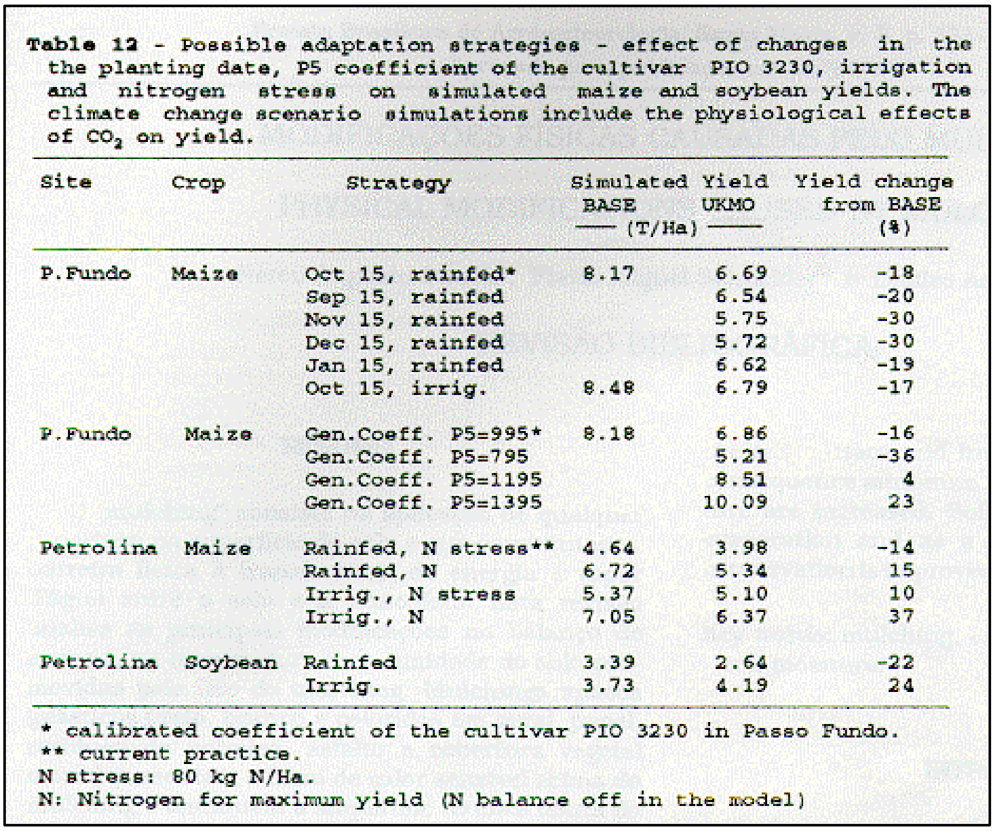

Table 12 - Possible adaptation strategies - effect of changes in the the planting date, P5 coefficient of the cultivar PIO 3230, irrigation and nitrogen stress on simulated maize and soybean yields. The climate change scenario simulations include the physiological effects of CO_2 on yield.

Site	Crop	Strategy	Simulated Yield BASE	UKMO	Yield change from BASE
			(T/Ha)		(%)
P.Fundo	Maize	Oct 15, rainfed*	8.17	6.69	-18
		Sep 15, rainfed		6.54	-20
		Nov 15, rainfed		5.75	-30
		Dec 15, rainfed		5.72	-30
		Jan 15, rainfed		6.62	-19
		Oct 15, irrig.	8.48	6.79	-17
P.Fundo	Maize	Gen.Coeff. P5=995*	8.18	6.86	-16
		Gen.Coeff. P5=795		5.21	-36
		Gen.Coeff. P5=1195		8.51	4
		Gen.Coeff. P5=1395		10.09	23
Petrolina	Maize	Rainfed, N stress**	4.64	3.98	-14
		Rainfed, N	6.72	5.34	15
		Irrig., N stress	5.37	5.10	10
		Irrig., N	7.05	6.37	37
Petrolina	Soybean	Rainfed	3.39	2.64	-22
		Irrig.	3.73	4.19	24

* calibrated coefficient of the cultivar PIO 3230 in Passo Fundo.
** current practice.
N stress: 80 kg N/Ha.
N: Nitrogen for maximum yield (N balance off in the model)

REFERENCES

ALFONSI, R.R., PEDRO Jr., M.J., CAMARGO, A.P. de Zoneamento agroclimático da soja no Brasil. In: MIYSAKA, S., MEDINA, J. C., A soja no Brasil. São Paulo: Banco do Estado de São Paulo / FINEP / NDCT / Ministério da Agricultura/Ministério da Indústria e Comércio/Cooperativa Agrícola de Cotia, 1981. p. 184-187.

ALLEN Jr., L.H. Plant responses to rising carbon dioxide and potential interactions with air pollutants. Journal of Environmental Quality, v. 19, p. 15-34, 1990.

ANUNCIAÇÃO, Y.M.T. da, LIU, W.T. Estimativa da produtividade do trigo em campo experimental, utilizando o modelo fisiológico CERES trigo em campo experimental. In: CONGRESSO BRASILEIRO DE AGROMETEOROLOGIA, 7, 1991, Viçosa, MG. Resumos...,Viçosa: Universidade Federal de Viçosa, 1991. 314 p. p. 22-25.

BRASIL Levantamento de reconhecimento dos solos do sul do Estado do Mato Grosso. Rio de Janeiro: Ministério da Agricultura. Departamento Nacional de Pesquisa Agropecuária. Divisão de Pesquisa Pedológica. 1971. 839 p. (Tech. Bull. 18).

BRASIL. Levantamento de Reconhecimento dos solos do Estado do Rio Grande do Sul. Recife: Ministério da Agricultura. Departamento Nacional de Pesquisa Agropecuária. Divisão de Pesquisa Pedológica. 1973. 431p. (Tech. Bull. 30).

CURRY, R.B., PEART, R.M., JONES, J.W., et al Simulation as a tool for analyzing crop response to climate change. American Society of Agricultural Engineers, v. 33, n. 3, p. 981-990. 1990.

GODWIN, D., RITCHIE, J., SINGH, U. et al A user's guide to CERES wheat - V2.10. Muscle Shoals, ALA, USA. Michigan State University / IFDC / IBSNAT, 1989. 86 p.

GROTCH, S.L. Regionally Intercomparing GCM Predictions with Historical Climate Data. Livermore, CA: Lawrence Livermore National Lab., 1987, 156p.

HANSEN, J.,FUNG, I., LACIS, A., et al Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. Journal of Geophysical Research, v. 93, p. 9341-9364, 1988.

HANSEN, J., RUSSEL, G., RIND, D., et al Efficient three-dimensional global models for climate studies: models I and II. Monthly Weather Review, v. 3, n. 4, p. 609-662, 1993.

INTERNATIONAL BENCHMARK SITES NETWORK FOR AGROTECHNOLOGY TRANSFER Decision support system for agrotechnology transfer (DSSAT): Documentation for IBSNAT crop model and output files, version 1.0. Honolulu: University of Hawaii, 1986. 55p. (Tech. Report 5).

INTERNATIONAL BENCHMARK SITES NETWORK FOR AGROTECHNOLOGY TRANSFER Experimental design and data collection procedures for IBSNAT. The minimum data set for system analysis and crop simulation. Honolulu: University of Hawaii, 1988. 73p. (Tech. Report 1).

INTERNATIONAL BENCHMARK SITES NETWORK FOR AGROTECHNOLOGY TRANSFER Decision support systems for agrotechnology transfer, v .2.1: User's guide. Honolulu: University of Hawaii-IGBP, 1990. p. 201-251. (Report 12)

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. Scientific assessment of climate change. IPCC Working Group I. WMO/UNEP, 1990. 365p.

JONES, C.A., KINIRY, J.R. CERES-Maize: a simulation model of maize growth and development. Texas : University Press, 1986. 194p.

JONES, J.W., BOOTE, K.J., JAGTAG, S.S., et al SOYGRO V.5.41: Soybean crop growth simulation model user's guide. Gainesville, Florida: Agriculture Experimental Station Journal, n. 8304, 1988.

JONES, J.W., JAGTAP, S.S., HOOGENBOOM, G. et al The structure and function of DSSAT. In: IBSNAT SYMPOSIUM, 1989, Las Vegas, Nevada. Proceedings: ..., Honolulu: University of Hawaii, IBSNAT, 1990. p. 1- 14.

LARACH, J.O.I., CARDOSO, A., CARVALHO, A.P. de, et al Levantamento de reconhecimento dos solos do Estado do Paraná. Curitiba: EMBRAPA-SNCLS/ SUDESUL/IAPAR, 1984. (Tech. Bull. 27)

LIU, W.T.H.; BOTNER, D.M.; SAKAMOTO, C.M. Application of CERES- Maize Model to yield prediction of a Brazilian maize hybrid. Agricultural and Forest Meterorology, v. 45, p. 299-312, 1989.

MALUF, J.R.T., MATZENAUER, R., WESTPHALEN, S.L., et al Zoneamento agroclimático da cultura do milho (Zea mays, L.) para o Estado do Rio Grande do Sul. Agronomia Sulriograndense, v. 22, n. 2, p. 261-285, 1986.

MANABE, S., WETHERALD, R.T. Large-scale changes in soil wetness induced by an increase in carbon dioxide. Journal of Atmospheric Science, v. 44, p. 1211-1235, 1987.

MATZENAUER, R., PONS, A.L., MALUF, J.R.T. et al Efeito da irrigação e densidade de plantas na cultura do milho. I rendimento de grãos e componentes de rendimento. In: REUNIÃO TÉCNICA ANUAL DO MILHO, 33, 1988, Porto Alegre, RS. Anais ..., Porto Alegre: Secretaria da Agricultura e Abastecimento/IPAGRO, 1988, p. 91-100.

MIYASAKA, S., MEDINA, J.C. A soja no Brasil. Campinas: Banco do Brasil/ FINEP/MA/MIC/ITAL, 1981. 1062p.

MOTA, F.S. da. Clima, tecnologia e produtividade do trigo no Brasil. In:---. Agrometeorologia do trigo no Brasil. Campinas: Sociedade Brasileira de Agrometeorologia, 1989. p. 1-4.

MOTA, F.S. da, AGENDES, M.O. de O. Clima e agricultura no Brasil. Porto Alegre : SAGRA, 1986. 151p.

MOTA, F.S. da, BERNY, Z.B., AGENDES, M.O.de O. Perspectivas climáticas da agricultura até o ano 2000, no sul do Brasil, sob uma provável ação do efeito estufa. Pelotas : EMBRAPA- DDT, 1984. 70p. (EMBRAPA-UEPAE de Pelotas, Doc. 11)

MOTHEI, E.P., AMARAL, J.A.M. do, SANTOS, R.D. dos. Levantamento de reconhecimento detalhado e aptidão agrícola dos solos da área do Centro Nacional de Pesquisa de Gado de Corte, Mato Grosso do Sul. Rio de Janeiro: EMBRAPA-SNLCS, 1979. 225 p. (Tech. Bull. 59)

OLIVEIRA, J.B. de, MENK, J.R.F. Latossolos roxos do Estado de São Paulo. Campinas: Instituto Agronômico, 1984. (Tech. Bull. 82).

QUEIROZ, E.F., NEUMAIER, N., TORRES, E. Ecologia e manejo da cultura. In: EMBRAPA/Centro Nacional de Pesquisa de Soja. Ecologia, manejo e adubação da soja. Londrina, EMBRAPA/CNPSO 1979, p. 63-91. (EMBRAPA-CNPSO. Tech. Bull. 2)

RAMANATHAN, V. The greenhouse theory of climate change: a test by an inadvertent global experiment. Science, v. 240, p. 293-299, 1988.

REUNIÃO DA COMISSÃO CENTRO-BRASILEIRA DE PESQUISA DE TRIGO. Recomendações da Comissão Centro-Brasileira de Pesquisa de Trigo para o ano de 1988. São Paulo: CAC-CC, 1988a. 58 p.

REUNIÃO DA COMISSÃO SUL-BRASILEIRA DE PESQUISA DE TRIGO. Recomendações da Comissão Sul-Brasileira de Pesquisa de Trigo para a cultura do trigo em 1988. Passo Fundo: EMBRAPA-CNPT, 1988b. 76 p.

REUNIÃO DE PESQUISA DE SOJA DA REGIÃO SUL. Recomendações da reunião de pesquisa de soja da região Sul, 1987/1988. Cruz Alta : FECOTRIGO-CEP, 1988c. 75p.

REUNIÃO DA COMISSÃO CENTRO-SUL BRASILEIRA DE PESQUISA DE TRIGO. Recomendações da Comissão Centro-Sul Brasileira de Pesquisa de Trigo para 1989. Londrina: CAC-CC, 1989. 75p.

RITCHIE, J.T., GODWIN, D.C., SINGH, U. Soil and weather inputs for the IBSNAT crop models. In: IBSNAT SYMPOSIUM, 1989, Las Vegas, Nevada. Proceedings ..., Honolulu: University of Hawaii, IBSNAT, 1990. p. 31-45.

RITCHIE, J.T.., OTTER, S. Description and performance of CERES-Wheat: A user-oriented wheat yield model. In: WILLIS, W.O., (ed.) ARS Wheat Yield Project. Washington: Department of Agriculture/Agricultural Research Service/ARS-38, 1985. p. 159-175.

RITCHIE, J., SINGH, U., GODWIN, G., et al A user's guide to CERES maize, V.2.10. Muscle Shoals, ALA: IFDC/Michigan State University 0/IBSNAT, 1989. 86 p.

ROSE, E. Direct (physiological) effects of increasing CO2 on crop plants and their interactions with indirect (climatic) effects. In: SMITH, J.B., TIRPAK, D.A. (eds.). The potential effects of global climate change on the United States: appendix C-agriculture. Washington DC: EPA, 1989, v. 2, p. 7.1-7.37.

ROSENZWEIG, C. Climate change and CO2 effects on wheat and corn in the Great Plains. In: CONFERENCE ON AGRICULTURE AND FOREST METEOROLOGY, 19, 1989a. Proceedings ..., Charleston, South Carolina: Amer. Met. Soc., Boston, Mass, 1989. p. 7-110.

ROSENZWEIG, C. Potential effects of climate change on agricultural production in the great plains - a simulation study. In: SMITH, I.B., TIRPAK, D.A. (eds.). The potential effects of global climate change on the United States: appendix C-agriculture. Washington DC : EPA, 1989b, v. 2, p. 3.1-3.4.

ROSENZWEIG, C. Crop responses to climate changes to the Southern Great Plains: A simulation study. Professional Geographer, v. 42, n. 1, p. 20-37, 1990.

SANTOS, P.C.T. dos, VIEIRA, L.S., VIEIRA, M. de N.F. et al Os solos da Faculdade de Ciências Agrárias do Pará. Belém: Faculdade de Ciências Agrárias do Pará, 1983. 60 p. (Inform, 5)

SCHLESINGER, M.E. Model projections of the climatic changes induced by increased atmospheric CO2. In: SYMPOSIUM ON CLIMATE AND GEOCIENCES. Holand: Dordrecht, Reidel Publ. Co., 1988 (in press).

SCHLESINGER, M.E., MITCHEL, J.F.B. Model projections of the equilibrium climate response to increased carbon dioxide. Review of Geoghaphy, v. 25, p. 760-798, 1987.

SIQUEIRA, O.J.F. de. Avanços na informática, aplicados às relações solo-planta-clima: Exemplo, utilizando o sistema de suporte de decisão "DSSAT"-Nitrogênio x Trigo. In: REUNIÃO NACIONAL DE PESQUISA DE TRIGO, 16, 1991. Resumos ..., Dourados: EMBRAPA/ UEPAE, 1991. 203 p.

SIQUEIRA, O.J.F. de, BERG, M. Van Den. Validação do modelo de simulação SOYGRO-Soja - Passo Fundo, RS. In: Soja: resultados de pesquisa 1990-1991. Passo Fundo: EMBRAPA/CNPT, 1991. p. 139-144. (Doc. 3)

SMITH, J.B., TIRPAK, D.A. The potential effects of global climate change on the United States: appendix C -agriculture. Washington DC: EPA, 1989a, v. 1.

SMITH, J.B. TIRPAK, D.A. The potential effects of global climate change on the United States: appendix C -agriculture. Washington DC: EPA, 1989b, v. 2.

SMITH, J.B., TIRPAK, D.A. The potential effects of global climate change on the United States. Washington DC : EPA, 1989c, 413 p.

VERNETTI, F. de J. Soja. Campinas : Fundação Cargill, 1983. 463 p.

WILSON, C.A., MITCHELL, J.F.B. A doubled CO2 climate sensitivityexperiment with a global climate model including a simple ocean. Journal Geophysical Research, v. 92, p. 315-343. 1987.

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