POTENTIAL EFFECTS OF GLOBAL CLIMATIC CHANGE ON THE PHENOLOGY AND YIELD OF MAIZE IN VENEZUELA *

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Abstract. Simulated impacts of global and regional climate change, induced by an enhanced greenhouse effect and by Amazonian deforestation, on the phenology and yield of two grain corn cultivars in Venezuela (CENIAP PB-8 and OBREGON) are reported. Three sites were selected: *Turén, Barinas* and *Yaritagua*, representing two important agricultural regions in the country. The CERES-Maize model, a mechanistic process-based model, in the *Decision Support System for Agrotechnology Transfer (DSSAT)* was used for the crop simulations. These simulations assume non-limiting nutrients, no pest damage and no damage from excess water; therefore, the results indicate only the difference between baseline and perturbed climatic conditions, when other conditions remain the same. Four greenhouse-induced global climate change scenarios, covering different sensitivity levels, and one deforestation-induced regional climate change scenario were used. The greenhouse scenarios assume increased air temperature, increased rainfall and decreased incoming solar radiation, as derived from atmospheric GCMs for doubled CO_2 conditions. The deforestation scenarios assume increased air temperature, increased incoming solar radiation and decreased rainfall, as predicted by coupled atmosphere-biosphere models for extensive deforestation of a portion of the Amazon basin. Two baseline climate years for each site were selected, one year with average precipitation and another with lower than average rainfall. Scenarios associated with the greenhouse effect cause a decrease in yield of both cultivars at all three sites, while the deforestation scenarios produce small changes. Sensitivity tests revealed the reasons for these responses. Increasing temperatures, especially daily maximum temperatures, reduce yield by reducing the duration of the phenological phases of both cultivars, as expected from CERES-Maize. The reduction of the duration of the kernel filling phase has the largest effect on yield. Increases of precipitation associated with greenhouse warming have no effects on yield, because these sites already have adequate precipitation; however, the crop model used here does not simulate potential negative effects of excess water, which could have important consequences in terms of soil erosion and nutrient leaching. Increases in solar radiation increased yields, according to the non-saturating light response of the photosynthesis rate of a C_4 plant like corn, compensating for reduced yields from increased temperatures in deforestation scenarios. In the greenhouse scenarios, reduced insolation (due to increased cloud cover) and increased temperatures combine to reduce yields; a combination of temperature increase with a reduction in solar radiation produces fewer and lighter kernels.

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1. Introduction

Many studies suggest that important changes in the climatic conditions of our planet will occur during the next century, caused by the increase in the atmospheric concentration of carbon dioxide, chlorofluorocarbons, methane, and other radiatively important trace gases which enhance the planet's natural greenhouse effect. The global temperature increase has been estimated to be as high as 0.3 °C per decade during the next century (Houghton *et al.*, 1990, 1992). It has also been suggested that global warming could have a significant impact on the intensity and variability of the hydrological cycle (Houghton *et al.*, 1990, 1992).

Projections are for smaller temperature increases at tropical latitudes than in middle and high latitudes. Nevertheless, the expected temperature increase in tropical regions (*e.g.* 2 to 4 °C) is larger than the current inter-annual ranges of temperature *e.g.* 1.4 to 1.6 °C) reported for several meteorological stations im important agricultural areas of the western alluvial plains of Venezuela (Maytín, 1990).

Another process that could induce climatic change is the deforestation of large areas in the intertropical regions. Shukla *et al.* (1990) estimated that deforesting a large part of the Amazon watershed could produce a temperature increase of 1.5 to 2.5 °C and a mean annual precipitation decrease of 400 to 800 mm, in the northern part of South America, including Venezuela.

In 1989 an inter-disciplinary group of Venezuelan scientists under auspices of the PAN-EARTH Project (Harwell, 1993) identified a set of potential problems associated with global climatic change and assigned high priority to the assessments of the effects of global climate change on the Venezuelan agricultural system (Acevedo *et al.*, 1989). At a subsequent PAN-EARTH workshop held in Maracay at the National Agricultural Research Institute (*Fondo Nacional de Investigaciones Agrícolas y Pecuarias, FONAIAP*), the CERES maize model was calibrated for the OBREGON cultivar (Hoogenboom *et al.*, 1989), a high yielding variety (FONAIAP, 1984) for which experimental data is abundant. In this workshop the potential use of this model to assess the impacts of global climate change on crop yield was preliminarily evaluated (Harwell and Acevedo, 1989).

As a continuation of these efforts, the work reported here details the impact of simulated climatic change, associated with the greenhouse effect and Amazonian deforestation, on the phenology and productivity of OBREGON and CENIAP PB-8, another high yielding variety (FONAIAP, 1984) grown in Venezuela.

These assessments evaluated the potential effects from specific regional scenarios of climate change developed at another PAN-EARTH workshop held in cooperation with the *Center for Advanced Studies of the Tropical Climate (CEACT)* in Mérida (Harwell and Acevedo, 1990; Robock *et al.*, 1993).

Maize is a staple crop of traditional consumption in Venezuela. This cereal has the largest total production and area under cultivation in Venezuela. For example, in 1990 production reached approximately one million tons from a total cultivated area of 4.62×10^5 hectares (MAC, 1991). Maize is also one of the crops for which the climatic range is best known and for which biophysical models have been most developed, facilitating the type of evaluation proposed.

2. Description of Sites

Three localities were selected to analyze the impact of climate change on maize production in Venezuela: *Turén* (9°15′ N, 69°06′ W, and 275 m in elevation); *Barinas* (8°36′ N, 70°12′ W, and 189 m in elevation); and *Yaritagua* (10°05′ N, 69°07′ W, and 375 m in elevation) (Figure 1). Although this selection is not representative of the entirety of Venezuela, these three sites are located in two of the most important agricultural regions: the *Western Plains* (Turén and Barinas) and the *Upper Valleys* in the transition zone between the Andes Mountain Range and the Coastal Mountain Range (Yaritagua).

The climate in all three localities is seasonal, with defined wet and dry seasons, associated with migration of the Intertropical Convergence Zone (ITCZ). The annual precipitation is concentrated in the wet season (80–90%) when most of the maize is grown. Like other tropical areas, monthly rainfall occurs as a few intense events. Generally, the wet season begins in April–May and ends in October–November. In Yaritagua, five months (November–March) comprise the dry season (monthly rainfall less than 50 mm), contrasting with Barinas and Turén where only four months (December–March) comprise the dry season. The climate in Yaritagua is subject to coastal influences and therefore a smaller range of seasonal and interannual temperature variation is observed. Table I summarizes some climate characteristics of the three sites.

The soil type for the Turén site is siliceous, coarse loamy, of the Haplustolls Order, and has a good natural fertility, even though compaction problems between 0.1 and 0.15 m of depth limit the root penetration and productivity in some sectors (Comerma, 1989).

Soils in the Barinas site correspond to the Alfisols Order, showing low natural fertility but good physical conditions, implying good agricultural use potential when its characteristic chemical limitations are corrected (Hetier *et al.*, 1989).

Soils in Yaritagua are clay of the Ultisols Order, and characterized by a medium natural fertility and a moderate moisture deficiency (Comerma, 1989).

3. Crop Model

The CERES-Maize model version 2.10 (Ritchie *et al.*, 1989a), as included in the *Decision Support System for Agrotechnology Transfer (DSSAT)* (IBSNAT, 1990), was used to simulate the phenology and yield of the selected cultivars under different scenarios of climate change. The CERES-Maize model (Jones and Kiniry, 1986) is designed to predict phenology and yield of different varieties for different climate and soil conditions and various management practices. It is a process-based model which includes development of growth stages, development of vegetative

SITE	LAT.	LONG.	ALT. m.a.s.l.
BARINAS	08°36'N	70°12'W	189
TUREN	09°15'N	69°06'W	215
YARITAGUA	10°05'N	69°09'W	312

Fig. 1. Geographical location and elevation of selected study sites.

and reproductive units, growth of leaves and stems, biomass production and partitioning, and other processes including the dynamics of nitrogen. The model does not simulate the effects of weeds, diseases, insects, excessive rainfall and catastrophic events.

Selecting the CERES-Maize model for this study allows a comparative analysis of the results to those obtained for other regions where this model has been used

TABLE I

Climate characteristics of the three selected sites.

Sites	Barinas [a]	Turén [b]	Yaritagua [b]
Period	1976–86	1971–81	1971–81
Mean annual temperature (°C)	27.0	27.1	25.9
Coeff. of variation (°C)	2.2	2.2	1.0
Mean daily min. temperature (°C)	22.5	21.5	21.0
Coeff. of variation (°C)	2.2	1.3	1.1
Mean daily max. temperature (°C)	31.5	32.8	30.9
Coeff. of variation (°C)	2.4	1.0	1.2
Mean annual precipitation (mm)	1640	1535	970
Coeff. of variation (mm)	14.3	15.2	13.2
Mean annual solar radiation ($W \cdot m^{-2}$)	182.9	216.0	208.3
Coeff. of variation ($W \cdot m^{-2}$)	4.65	13.00	2.55
Mean number rainy days/year	141	148	87
Mean number rainy days/dry season	14	12	14

[a] Barinas data from: Data records of the Meteorology and Hydrology Department of the Ministry of the Environment and Natural Resources (MARNR).
[b] Turén and Yaritagua data from: Benacchio (1983).

for assessments of potential impacts of global climate change; e.g., the U.S.A. Great Lakes region (Ritchie *et al.*, 1989c), the U.S.A. Central and Southern Great Plains region (Rosenzweig, 1989, 1990) and the Southeastern U.S.A. (Peart *et al.*, 1989). See also Smith and Tirpak (1989, Chapter 6) and Adams *et al.* (1990) for summaries of these assessments.

Selection of CERES-Maize also facilitates the simulations due to its previous use by FONAIAP in Venezuela (Comerma, 1986, 1989); when validating for field experiments conducted in the country, phenology and yield have shown a reasonable relation to experimental data (see Figure 2). CERES-Maize has also been used for other South American conditions; for example, in Brazil Liu *et al.* (1989) analyzed phenological and yield predictions for the DINA 10 variety and Bowen *et al.* (1993) evaluated the nitrogen dynamics after green manure application for the CARGILL 111 variety. Selection of CERES-Maize also facilitates continuing assessments due to the IBSNAT efforts to develop further capabilities for climate change impact assessment within DSSAT (Hoogenboom *et al.*, 1993).

The following minimum data set is needed to run the model v 2.10 as implemented in DSSAT (IBSNAT, 1988):

(a) *management practices*: sowing date and depth, cultivation density, irrigation and fertilization;

(b) *daily climatic records*: solar radiation, precipitation, maximum and minimum air temperatures;

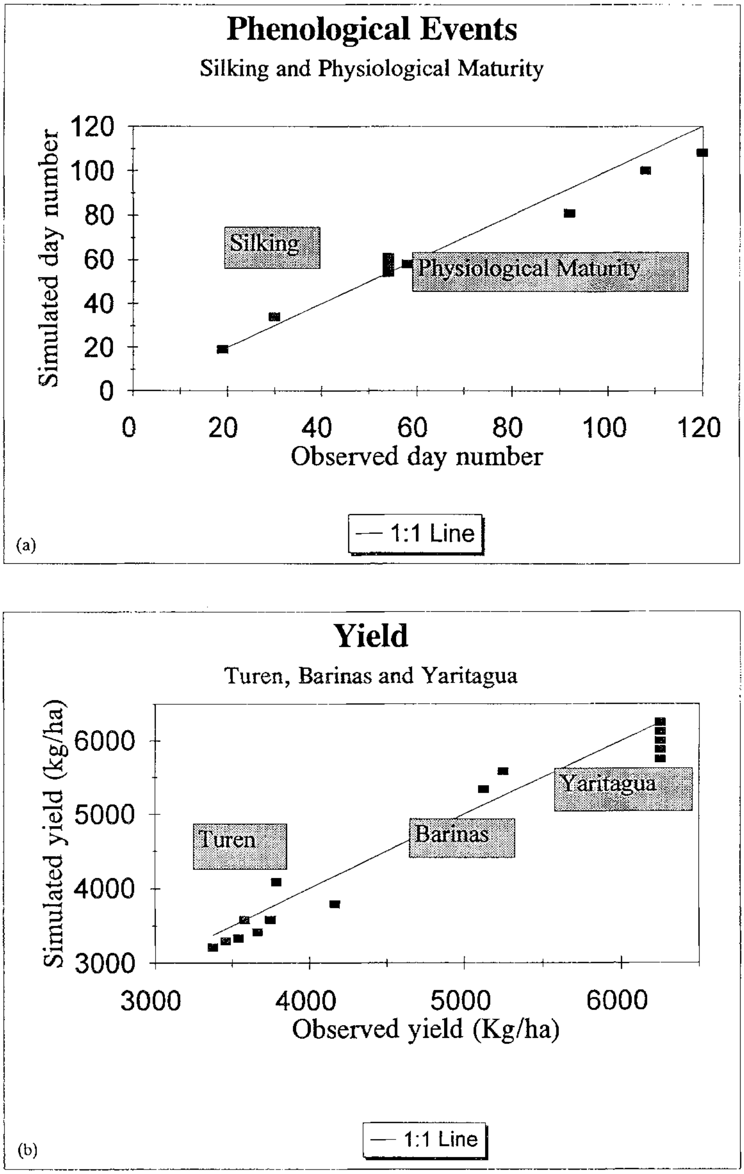

Fig. 2. Validation results for the CERES-Maize model with experimental data from Venezuela. (a) Time to silking and time to physiological maturity. (b) Rainfed yield in three selected sites. Results for Turén and Yaritagua are from Comerma (1986), and for Barinas are from Zuvia (personal communication).

(c) *soil horizon characteristics*: depth, texture, moist bulk density, organic material content, pH, field capacity and wilting point, albedo, type of drainage, permeability and root growth limitations;

(d) *genetic characteristics*: summarized into five genetic coefficients:

- *duration of the juvenile phase* (P_1): accumulated degree-days (base 8 °C) during the non-reproductive phase (juvenile) of the cultivars;
- *sensitivity to photoperiod* (P_2): coefficient (in 1/hour) to represent changes in development rate as a function of day-length;
- *duration of kernel filling period* (P_5): accumulated degree-days (base 8 °C) in the linear phase of filling;
- *maximum number of kernels per plant* (G_2): obtained at optimum temperature with no water or nutrient stress.
- *maximum rate of kernel filling* (G_3): in mg. day^{-1} per kernel, also obtained at optimum temperature with no water or nutrient stress.

The following data were used for the selected sites:

Soils: for Barinas, soil data were taken from Hetier *et al.* (1989), except field capacity, saturation, and wilting point, which were taken from Maytín (1991); for Yaritagua and Turén, soil data were provided by FONAIAP (unpublished data), except field capacity, saturation, and lower limit, for which DSSAT estimates were used (Ritchie *et al.*, 1987, 1989b).

Management practices: the sowing dates for each site in these simulations were varied from May to June, depending on the availability of soil water. In all sites, cultivation density and sowing depth was 5 plants m^{-2} and 50 mm, respectively. Nitrogen was assumed not to be limited and therefore not simulated. The validation of the CERES-Maize model prediction with respect to nitrogen has not produced good results in Venezuela to date (Delgado, 1988). Moreover, most studies concerning the evaluation of the impact of climatic change using this model assumed that nitrogen is not limited (e.g. Rosenzweig, 1989, 1990; Ritchie *et al.*, 1989c; Peart *et al.*, 1989). The consideration of nitrogen deficiency could be very important for the assessment of potential impacts of climatic change in the country, due to the possibility of enhancing nitrogen leaching due to increased rainfall, and will be addressed in a subsequent paper.

Genetic coefficients: the values that have been used for the selected cultivars are those developed at FONAIAP (Table II).

Climate: baseline historic climatic records from stations operated by FONAIAP and by the *Ministry for the Environment and Renewable Natural Resources (MARNR), Department of Hydrology and Meteorology* were used. These climatic records were subsequently modified according to the scenarios of climate change as described in the following section.

4. Climatic Change Scenarios

The main tool used to predict global climate change, atmospheric general circulation models (GCMs), simulate on a much coarser horizontal resolution than is needed to make regional and local predictions in an heterogeneous region such as Venezuela. The scenarios used in this study are based on those developed at the

TABLE II
Genetic coefficients of PB-8 and OBREGON cultivars (from Marrero, 1987)

Coefficient	PB-8	OBREGON
P1 degree-days	300	276
P2 1/hour	0.5	0.8
P5 degree-days	900	850
G2 kernels/plant	400	515
G3 mg/day	7.0	6.8

PAN-EARTH/CEACT Workshop on *Variability of Climate and Climatic Change in Venezuela and the Caribbean Region* (Harwell and Acevedo, 1990), and described by Robock *et al.* (1993).

At this scenario workshop GCM simulations of the current climate ($1 \times CO_2$) using the United Kingdom Meteorological Office (UKMO; Wilson and Mitchell, 1987; with resolution 5° latitude × 7.5° longitude), the Oregon State University (OSU; Schlesinger and Zhao, 1989; with resolution 4° latitude × 5° longitude), the Goddard Institute for Space Studies (GISS; Hansen *et al.*, 1984; with resolution 7.83° latitude × 10° longitude), and the Geophysical Fluid Dynamics Laboratory (GFDL; Wetherald and Manabe, 1986; R15 with resolution 4.44° latitude × 7.5° longitude) were compared with observed temperature and precipitation in nine 1° latitude × 1° longitude cells. Four months, January, April, July and October were used for this comparative analysis (Andressen, 1989; Robock *et al.*, 1993). The GCM results available for this analysis were generated by atmospheric low resolution models. The uncertainties associated with the use of low resolution GCMs and the need for using coupled ocean-atmosphere models have been emphasized in many papers (see Houghton *et al.*, 1990).

The UKMO GCM was selected as the basis to generate the greenhouse gas-induced $2 \times CO_2$ climate change scenarios, because it was demonstrated to provide reasonable simulations of both the magnitude and pattern of precipitation for Venezuela under normal climatic conditions, whereas the other models, OSU, GISS, and GFDL, did not (Andressen, 1989, 1990; Robock *et al.*, 1993). However, inter-annual variability of regional climate also had to be considered through expert judgment to generate plausible scenarios, as discussed in Robock *et al.* (1993).

Since UKMO is the most sensitive of the GCMs to $2 \times CO_2$, with a 5.2 °C global average temperature increase, its temperature results are used for the upper range of the scenarios. To take into account the uncertainty associated with this high climate sensitivity of the UKMO, three types of greenhouse $2 \times CO_2$ scenarios were derived: high, medium and low. These greenhouse climate change scenarios assume that solar radiation decreases and that the increase in daily minimum temperature

TABLE III

Climate change scenarios (adapted from Robock *et al.*, 1993)

	Greenhouse scenarios				Deforestation scenarios	
Climate sensitivity	Low	Medium		High		
Scenario number	GH1	GH2	GH3	GH4	DEF1	DEF2
Change in daily max. temp. (°C)	+1	+2	+2	+3	+1	+1
Change in daily min. temp. (°C)	+2	+3	+3	+4	+1	+1
Change in precip. (%)	0	0	+20	+40	–25	–25
Change in radiation (5) for days with perturbed precip.	0	0	–20	–40	+10	+10
Change in radiation (5) for days with unperturbed precip.	0	0	–10	–20	+10	+10
Initial soil water content	FC	FC	FC	FC	FC	40% of PWE

Note: FC = Field capacity,
PWE = potential water extractable by cultivar.

is larger than the increase in the daily maximum temperature. It is also assumed that for a GCM prediction of increased precipitation, the number of rainfall events increases, but not their intensity, since in Venezuela – like in other tropical areas – only a few rain events account for most of the total monthly precipitation (Riehl, 1979). To account for the potential increase of the frequency and intensity of severe tropical storms and hurricanes due to increased sea surface temperature, a scenario prescribing the addition of a day with rainfall of 500 mm in September or October was included (Robock *et al.*, 1993). For the assessments reported in this paper the hurricane scenario is not used because the CERES Maize model does not simulate the consequences of catastrophic events or of excess rainfall. Also, for the work reported in this paper the medium sensitivity category is further divided into two different scenarios, one with a prescribed precipitation increase and another with no change in precipitation, because the CERES Maize model simulates soil water content values below field capacity.

For deforestation of the Amazon basin the results of Shukla *et al.* (1990) using a high resolution (1.8° latitude × 2.8° longitude) GCM were used to derive two deforestation scenarios. These two scenarios do not differ in the temperature and precipitation values, but are prescribed according to soil water content at planting day.

Therefore, a total of four greenhouse 2 × CO_2 scenarios and two deforestation scenarios were used for the wet season (Table III).

Precipitation increases in the greenhouse scenarios were constructed by adding precipitation days to the historical climate series (baseline or control), adjoining these new rainy days to those occurring in the record. As observed in the climatic data sets for Barinas, Turén and Yaritagua, isolated rainy days are less frequent than sequences of several rainy days. Consequently, the procedure used is as follows: If the proposed monthly precipitation change is greater than or equal to the amount of precipitation on the rainiest day of a given month, then the rainfall value of the rainiest day is added to a day with no historical rainfall and adjacent to a rainy day sequence selected at random. This extra rainy day is located at the beginning or the end of the sequence, according to an alternate selection. This addition of rainy days is continued in order to distribute the remaining precipitation change, until the total amount to be changed for the month is added. If the monthly precipitation change is less than the rainiest day of the month, then only one rainy day is added to the climatic baseline data. This method makes the total changes in rainfall in a month consistent with the daily rainfall patterns.

For those days with increased rainfall, daily solar radiation was decreased in proportion to the percent change in precipitation. For the remaining days, radiation was decreased proportionally to half the increase in monthly precipitation. This takes into account that in a future warmer climate, even those days without rainfall may be cloudier than at present (Robock *et al.*, 1993).

For the greenhouse scenarios, the initial soil water content was assumed to be at field capacity, because the expected increase in precipitation would increase water availability in the soil. For the deforestation scenario, two values for initial water content were used: Field capacity (DEF1) and 40% of the potential water extractable by the cultivar (DEF2). This lower value was selected to explore the consequences of restricted water availability in a drier regional climate induced by the Amazon deforestation. However, local deforestation at the three study sites is not an ongoing process and therefore the selection of initial conditions for the simulations do not attempt to characterize changes in the soil due to local deforestation.

5. Climate Baseline Data and Sensitivity Analysis

A set of five years, 1967, 1973, 1974, 1981, 1983, in Turén and of three years, 1981, 1988, 1989 in Barinas were selected by Maytín (1991) to represent a variety of current climatic conditions at each one of these two sites. For example, in Turén 1973 showed temperatures above average, 1981 was rainy with low values of solar radiation and 1983 was also rainy but with a higher value of solar radiation. CERES-Maize simulations of CENIAP PB-8 at each site, using the weather data set of each one of these years, show the range of simulated yield and phenology at each site for current climatic variability (Maytín, 1991).

For the simulations reported here, the Yaritagua site was also included and only two years for each site were selected to represent average and dry conditions. These two years for each site will be referred to as baseline conditions, i.e. the daily data sets to be perturbed according to the prescribed values of each scenario. Other studies (e.g. Rosenzweig, 1989, 1990; Peart *et al.*, 1989; Ritchie *et al.*, 1989c) have

TABLE IV

Baseline years and growing season precipitation for each site

	Barinas	Turén	Yaritagua*
Dry year	1989	1974	1974
Rainfall in dry year (mm)	747	871	541
Average year	1988	1967	1987
Rainfall in average year (mm)	1151	1109	712

* Growing season is from May to September for Barinas and Turén, and from June to October for Yaritagua.

used as baseline a long-term average of the climate data. The selection of baseline conditions used in this paper allows for an exploration of the potential effects of climate change on extreme years. Only rainfall was used to define the extremes and only dry years were used as baseline years; an increase in precipitation for wet years might cause effects induced by excess water, but the CERES-Maize crop model does not account for the potential yield-reducing effects of excess water or flood damage.

Exploring a larger set of baseline climate conditions would require defining ranges for the combination of air temperature, precipitation, and solar radiation. For example, if only low, average, and high values for these variables are considered, then potentially $3^3 = 27$ baseline conditions can be defined. For Barinas, for instance, 1989 was a year of low precipitation, average radiation and temperature; while 1988 was a year of high temperature, average precipitation and solar radiation. The ranges are inferred from ten years of recent data; a longer history would be desirable. The accumulated precipitation during the growing season is given for each baseline year at every site (Table IV).

A sensitivity analysis of the CERES-Maize model response with respect to systematic changes in air temperature, precipitation, and solar radiation was conducted at all sites, for the average baseline years. These sensitivity runs were performed for initial soil water content corresponding to field capacity and to 40% extractable water in the soil. Precipitation was increased in steps of 5%, and a range of –40% to +40% was explored; air temperature was changed in steps of 1 °C from –4 °C to +4 °C; and radiation was changed in steps of 10% from –40% to +40%.

6. Results

6.1. SENSITIVITY ANALYSIS

The effects of changing precipitation on yield were small at Turén and Barinas, especially for increasing rainfall, suggesting that there is no water stress for the average baseline years at any of these two sites. The impact on yield of decreasing

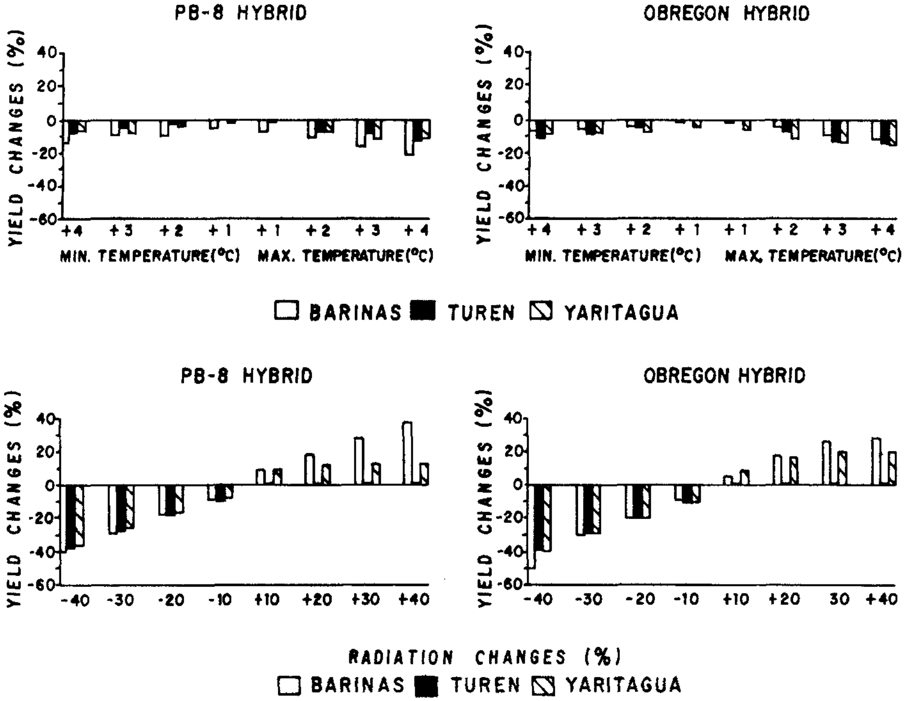

Fig. 3. Sensitivity of yield to changes in daily maximum and minimum temperatures and solar radiation. Results for PB-8 and OBREGON cultivars at the three selected sites.

precipitation in Yaritagua was much larger than in Barinas and Turén, reaching maximum yield reductions of –20% for PB-8 and –14% for OBREGON. No significant changes in phenology were demonstrated in these sensitivity simulations because the calculation of phenology in CERES-Maize is only a function of accumulated degree-days.

The effects of increasing air temperature, especially increases greater than 1 °C, on phenology and yield are important for both hybrids at all sites. The reduction in yield suggests that temperature is already too high for optimal growth of these hybrids at all sites. Maximum reductions in yield occur for an increase of 4 °C in the daily maximum temperature and ranged from –15% to –22%; but the reductions in yield are below –10% for a 1 °C temperature increase, both in the daily maximum and daily minimum (Figure 3). OBREGON appears to be less sensitive than PB-8 to temperature increases above 2 °C, especially in Barinas.

Changes in solar radiation caused a direct response in yield (Figure 3), i.e., positive for increasing radiation, and negative for decreasing radiation. Maize is a C_4 plant and therefore an increasing rate of photosynthesis for increasing solar radiation is expected, due to high light-saturation levels (*e.g.* Hattersley and Watson, 1992; Singh *et al.*, 1974; Lawlor, 1987; Edwards and Walker, 1983; Patterson, 1980; Hesketh, 1980; Jones, 1992). To reflect this characteristic, CERES-Maize uses a linear relationship of dry matter production rate with respect to daily solar radiation (Jones and Kiniry, 1986) and therefore the results reported in Figure 3 are not surprising. Both hybrids at Turén were slightly affected by increasing radiation, suggesting that solar radiation is not a limiting factor in this site. The potential number of kernels (genetic coefficient G2) is almost attained for baseline conditions and the increased productivity is allocated to other organs. At the other two sites, however, increasing radiation had a positive impact on yield. This increase in yield has a saturation in Yaritagua for both hybrids and in Barinas for OBREGON, suggesting that solar radiation is limiting in Yaritagua and Barinas, with a stronger limiting effect in Barinas. Maximum increase in yield reaches nearly 30% for both hybrids at Barinas, and 20% for the OBREGON hybrid at Yaritagua. Decreasing radiation had a negative impact on all sites for both hybrids, reaching a maximum of –50% at Barinas.

6.2. EFFECTS ON PHENOLOGY

The effects of the climate changes prescribed by the several scenarios on the duration of phenological phases for the two cultivars at the three sites were examined (Figure 4). A temperature increase produces a decrease in the duration of most phenological phases of both cultivars, except for the phase between germination and emergence (three days in all simulated cases). This result is expected because CERES-Maize formulates the durations of the phenological phases as functions of accumulated degree-days. In general, the PB-8 hybrid corn is more affected than OBREGON at all sites, due to the values specified for the genetic parameters in the simulations. For OBREGON major effects were simulated in the phase corresponding to the reproductive period and for the overall life cycle. The shortest life cycle of both hybrids occurred in Barinas, while the longest life cycle occurred in Yaritagua. This result is also expected due to the higher temperatures recorded in Barinas.

A summary of the reductions of the time from emergence to physiological maturity and of the duration of the kernel-filling phase is shown in Table V. Because temperature is the only factor determining duration of the cultivation phases in CERES-Maize, the same changes in the duration of the different stages was obtained for GH2 and GH3, in spite of the increase in precipitation and the decrease in radiation for GH3. The high sensitivity greenhouse scenario (GH4), with its warmer climate, resulted in the maximum shortening of the time from emergence to physiological maturity. Both deforestation scenarios, characterized by just slightly warmer conditions, resulted in a relatively minor decrease. Similar results are obtained for the dry baseline year because of the CERES-Maize thermal formulation of the duration of the phenological phases.

6.3. EFFECTS ON YIELD

In general, scenarios associated with the greenhouse-induced climate change caused a decrease in yield of both OBREGON and PB-8 hybrid maize in the

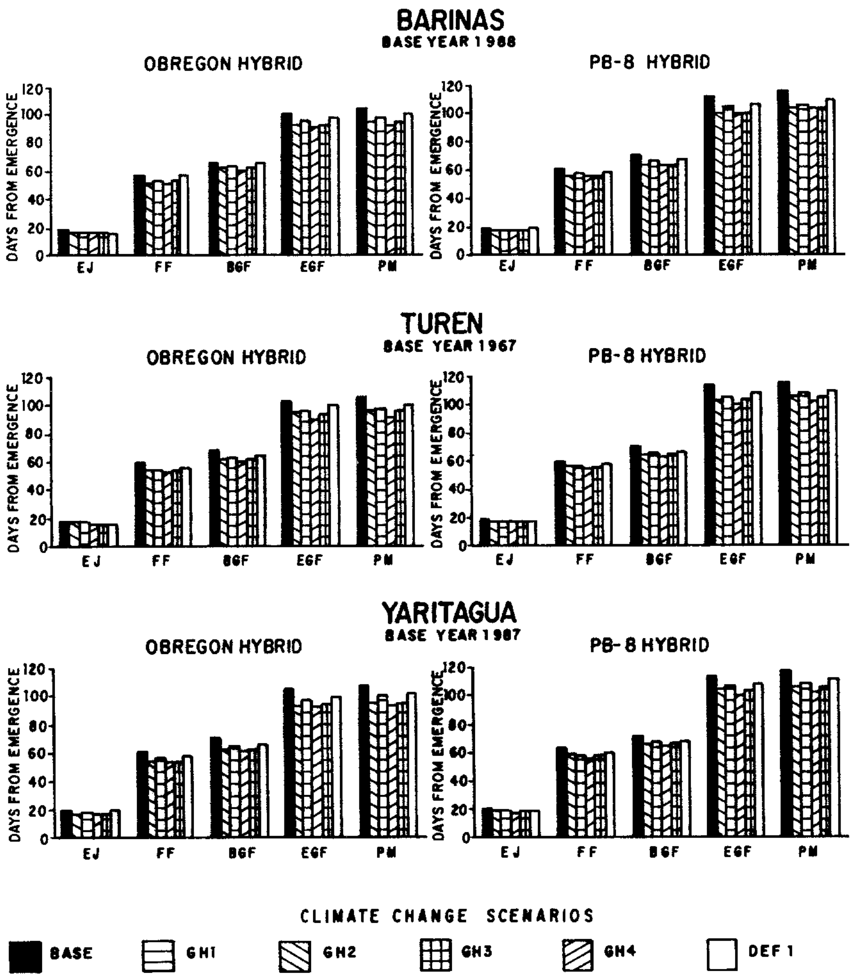

Fig. 4. Impact of climate change, caused by the enhanced greenhouse effect or deforestation on the phenology of PB-8 and OBREGON hybrid maize cultivars at Barinas, Turén, and Yaritagua. EJ = End of Juvenile; FF = Female floration; BGF = Beginning of grain filling; EGF = End of grain filling; PM = Physiological maturity; BASE = Baseline Year; GH1 = Low sensitivity greenhouse scenario; GH2 = Medium sensitivity greenhouse scenario; GH3 = Medium sensitivity greenhouse scenario with precipitation change; GH4 = High sensitivity greenhouse scenario; DEF1 = Deforestation scenario with soil moisture at field capacity.

three selected areas (Figure 5). However, the impact was larger in Barinas, than Turén or Yaritagua. In Turén and Barinas the OBREGON hybrid maize appeared to be less affected by greenhouse scenarios, while in Yaritagua the PB-8 hybrid was less affected than OBREGON. In the three localities, the yield was greater for perturbed runs corresponding to average baseline years, except for OBREGON in Turén.

TABLE V

Ranges of reductions of days for the time from emergence to physiological maturity (PM) and time for kernel filling with respect to average baseline years obtained by considering all three sites and both cultivars

Scenario	*Range (days)*	
	From emergence to PM	Kernel filling
Low GH1	–6 to –9	–2 to –4
Medium GH2	–10 to –13	–3 to –5
Medium GH3	–10 to –13	–3 to –5
High GH4	–11 to –16	–4 to –7
DEF1	–3 to –6	–2 to –3
DEF2	–3 to –6	–2 to –3

TABLE VI

Ranges of change (%) in yield with respect to baseline years obtained by considering all three sites and both cultivars

Scenario	*Range (%)*	
	Average baseline year	Dry baseline year
Low GH1	–1 to –13	–8 to –24
Medium GH2	–9 to –18	–13 to –30
Medium GH3	–19 to –23	–23 to –36
High GH4	–32 to –41	–35 to –48
DEF1	+4 to –8	–1 to –18
DEF2	+2 to –8	–8 to –22

The results are summarized in Table VI for an average (i.e. average rainfall) baseline year and for a dry (i.e. lower than average rainfall) baseline year. Maximum reductions of yield are in the order of 20% or less for the average baseline year, except for the high sensitivity scenario. Larger yield reductions were obtained for the drier baseline years, exceeding 20% for all greenhouse scenarios. Deforestation scenarios increased yield levels slightly for the average baseline year. This effect occurred in the simulations for Barinas, but not for Turén or Yaritagua.

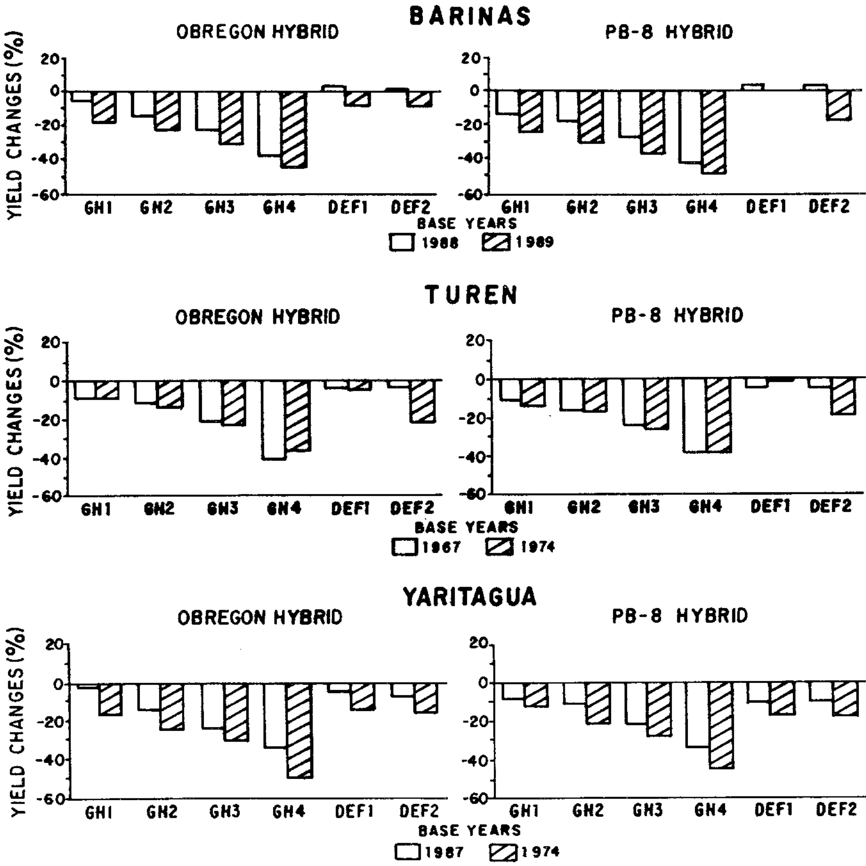

Fig. 5. Impact of climate change, caused by the enhanced greenhouse effect or deforestation on the yield of PB-8 and OBREGON hybrid maize cultivars at Barinas, Turén, and Yaritagua. Solid white bars are for average climate years and striped bars are for dry climate years. GH1 = Low sensitivity greenhouse scenario; GH2 = Medium sensitivity greenhouse scenario; GH3 = Medium sensitivity greenhouse scenario with precipitation change; GH4 = High sensitivity greenhouse scenario; DEF1 = Deforestation scenario with soil moisture at field capacity; DEF2 = Deforestation scenario with soil moisture at 40% of potential water extractable by the cultivar.

7. Discussion

7.1. THERMAL EFFECTS

An increase in the daily maximum and minimum air temperatures above those of the present Venezuelan climate has a negative effect on yield of maize because of the decrease in the duration of the life cycle, especially the time for kernel filling. Similar results were found for the United States by Curry *et al.* (1990) and Peart *et al.* (1989). Moreover, respiration rates in the current climate restrain the productivity because the minimum temperature in the three sites is higher than the optimum for maize. Therefore, an increase in the daily maximum and minimum temperatures may cause a major thermal stress, with a concomitant increase in respiration rates consuming an important part of gross production, impeding the cultivars from achieving the potential number of kernels and a more effective kernel filling.

7.2. SOLAR RADIATION EFFECTS

In the vegetative phase, a low solar radiation level caused a smaller foliar area at the beginning of the reproductive phase. This is an important limitation at a time when the plant needs high levels of net photosynthesis for kernel development (number and weight of kernels).

In the CERES-Maize model, the number of kernels per ear basically depends on the average accumulated photosynthesis in the phase from pollination to the beginning of kernel filling. The current solar radiation levels in Barinas and Yaritagua are, in most years, less than optimal for the achievement of the potential kernel number. In Turén, the radiation conditions of the present climate are better than the other two sites for achieving the potential kernel number. Greenhouse scenarios with decreased solar radiation (GH3 and GH4) resulted in an adverse effect: a 20% decrease in solar radiation on additional rainy days and a 10% decrease on other days, resulted in a 10 to 30% reduction in the total number of kernels. A 40% decrease in solar radiation on additional rainy days caused an approximately 20 to 40% reduction in the total number of kernels per ear.

7.3. THERMAL-RADIATIVE EFFECTS

According to the previous discussions, a combination of daily temperature increases with solar radiation decreases should produce a lower number and weight of kernels. A decrease in solar radiation had a larger impact on the reduction of kernel number than on the weight for both hybrids. This effect is stronger in Yaritagua than in the other localities.

Under both deforestation scenarios, a slight yield increase could be produced in Barinas for the average baseline year, because of the increase in kernel number from increased solar radiation, which compensates for the shortening of the grain-filling time induced by higher temperatures. For the dry baseline year, the increase in the solar radiation was insufficient to compensate for the negative impact of both the thermal and water stress.

7.4. PRECIPITATION EFFECTS

According to the simulations with the CERES-Maize model, increasing rainfall associated with greenhouse scenarios GH3 and GH4 does not affect yield levels, especially in Turén and Barinas, where the model suggests sufficient water from rainfall under baseline conditions. Moreover, the simulations for the greenhouse scenarios assume that planting was conducted with soil at field capacity. The version of the model used does not have the capacity to detect excess water problems in maize cultivation, which is known to be sensitive to flooding conditions. On the other hand, a more humid climate favors the increase of fungi and weed damage; in this sense, a drier climate (deforestation scenario) could be beneficial, specially in Barinas, and even more if we add the possible beneficial impact of the increase in the current solar radiation levels associated with the deforestation scenarios when sufficient soil water is available.

For Yaritagua, an area with less rainfall than the other areas, the deforestation scenarios, especially DEF2, and the greenhouse scenarios with temperature changes only (GH1 and GH2) could cause significant impacts on maize production in some years, caused by insufficient water for normal plant development. In this way, climate change in the form of greater levels of rainfall (GH3 and GH4) would have different effects in Turén and Barinas than in Yaritagua, given that the former two sites can have excess precipitation for a crop such as maize, while in Yaritagua an increase in precipitation could be favorable by increasing water availability in an area where the current climate presents a lack of water in some years.

7.5. STUDY LIMITATIONS

In this study only the indirect effects of climatic change caused by an increase in CO_2 are estimated; the direct effect of increased CO_2 concentration on the eco-physiological processes of cultivars was not studied. Various processes, such as an increase of photosynthesis rates and an increase in stomatal resistance, could be produced under an atmosphere with doubled concentration of CO_2 (Rosenberg, 1981; Cure and Acock, 1988). However, simulation results combining direct and indirect effects (e.g. Peart *et al.*, 1989; Rosenzweig, 1989, 1990) and experimental data (see the review by Rose, 1989) indicate that this direct effect is not as significant in plants with the C_4 photosynthetic mechanisms such as maize.

The CERES Maize model does not include such processes as nutrient cycles (except nitrogen), erosion, chemical changes in the soils, pests (insects, fungi, etc.), and weeds. The version of the model used here does not include nitrogen dynamics. For this reason, it is possible that the simulated yield values are larger than those which can occur in reality.

7.6. CONCLUSIONS AND PERSPECTIVES

The simulation results obtained here suggest that maize production in Venezuela could potentially be reduced by climate changes induced by an enhanced greenhouse effect ($2 \times CO_2$) and Amazon deforestation. Yield decrease is associated with shortening of the grain-filling phase and increasing plant respiration rates. The effect of temperature and solar radiation changes as well as precipitation decreases can be examined with the crop model used, but the total effect of precipitation increases (except for dry baseline years) cannot be reliably inferred because of limitations of the crop model to treat excess rainfall. Therefore, the results obtained here may represent adequate estimates for the low sensitivity greenhouse scenario (GH1), the medium sensitivity with no precipitation change greenhouse scenario (GH2) and the deforestation scenarios (DEF1 and DEF2). The results may underestimate the potential effects for the medium sensitivity with precipitation change greenhouse scenario (GH3) and high sensitivity greenhouse scenario (GH4), because the effects due to excess water, e.g. soil erosion, nutrient leaching, are not accounted for in these simulations. These additional effects would be especially important for wet baseline years which were not simulated in this paper due to the model limitations. However, even if underestimated, predicted changes in yield for the medium or high climate sensitivity greenhouse scenarios given in this paper are significant and suggest that a more comprehensive assessment is necessary.

A different model, such as the *Erosion Productivity Impact Calculator* (EPIC, Williams *et al.*, 1990), a semi-empirical model simulation model also developed by the U.S. Agricultural Research Service, is able to simulate the effects on erosion and nutrients of increased precipitation. This model has been recently used for the assessment of climate change effects in the Missouri-Iowa-Nebraska-Kansas region (MINK, Easterling *et al.*, 1991) of the U.S.A. Application of this model would provide an assessment of the climate change effects due to increased precipitation prescribed by the medium and high sensitivity greenhouse scenarios for Venezuela and would allow an exploration of the effects when superimposing the changes on wet baseline years.

The results reported here are cultivar- and site-specific, inasmuch as they depend on the particular cultivar and the soil-climate combinations at each site. The three sites and the two cultivars examined here are important representatives of maize cultivation in Venezuela, but do not account for all maize producing areas in the country. Extrapolation to larger spatial scales, such as regional and national, requires examining a multitude of soil-climate combinations, because of the spatial heterogeneity in soils and climate. Computer simulation runs to cover a larger number of sites in the Llanos region are currently underway in the PAN-EARTH project. Identification of areas within the Llanos with similar climate and soil are being used to produce areal units where the crop model predictions can be considered similar. These simulations also assume that nitrogen is limiting, and thereby expand the results of the present paper. The outcome of these efforts will be reported in a subsequent paper.

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