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Simulating G F D L Predicted Climate Change Impacts on Rice Cropping in Iran

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ABSTRACT

Projected global climate change may have a major influence on crop yield. The likely effects of climate change caused by increasing atmospheric carbon dioxide levels on rice yield in Iran were evaluated using a mechanistic growth model for rice, GSAC-rice, running under a climate change scenario predicted for a doubled-CO2 (2xCO_2) atmosphere by the Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model (GCM). Simulations were run for two locations with contrasting climates, one in the north (Rasht) and one in the south (Ahwaz) of Iran. GFDL predicted that as a result of doubling CO_2, temperature increases by 4.5 and 4.6 ^{0}C during the rice growing season in Rasht and Ahwaz, respectively. Changes in solar radiation are minor, but rainfall during the rice growing season decreases by 38.8% (102 mm) for Rasht and 68.2% (5.8 mm) for Ahwaz. It was predicted that doubling [CO_2] alone increased rice yield by 30%, but that yield decreases by 3.7 and 11.6% for each degree centigrade rise in temperature in Rasht and Ahwaz, respectively. As a result of the combined effect of both doubling [CO_2] and the climate change accompanying it (predicted with GFDL), 8% greater rice could be produced in Rasht, but irrigation needs would be increased dramatically by 57%. In Ahwaz (the south of Iran), rice production could be halved and might not even remain a viable option unless plant breeders are able to produce more heat tolerant rice cultivars. It was concluded that rice production in the north and south of the country would change dramatically.

Keywords: Carbon dioxide, Climate change, Rice, Simulation.

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INTRODUCTION

As a result of human activity, carbon dioxide concentration in the atmosphere has increased from about 280 ppm before the industrial revolution to about 360 ppm today (Allen, 1998). Rising concentrations of this gas, as well as other greenhouse effect gases such as methane, is causing global changes through the absorption of long-wave radiation from the Earth's surface. Increases in carbon dioxide concentration in the atmosphere could cause climate change, i.e. global warming, and changes in precipitation and solar radiation. Substantial changes in hydrological regimes are also forecast (Houghton *et al.,* 1996).

General Circulation Models (GCMs) are frequently used to forecast future climates under elevated [CO_2]. Of the several GCMs, the Goddard Institute of Space Studies (GISS) (Hansen *et al*., 1983), The Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and wetherald, 1987) and United Kingdom Meteorology Office (UKMO) (Wilson and Mitchell, 1987) models have been used more frequently than others to assess the impacts of climate change on agriculture (Matthews *et al.,* 1997; Rosenzweig and Iglesias, 1998; Rosenzweig *et al.,* 1993; Yoshino *et al*., 1988).

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In recent years, a number of modeling studies of the likely effects of climate change on rice production have emerged. Yoshino *et al*. (1988) predicted that lowland rice yields could increase in Japan by about 9% following a doubling of [CO_2] and subsequent climatic changes as predicted by GISS GCM. Jansen (1990) used historic weather data from seven sites in eastern Asia and the MACROS crop simulation model (Penning de Vries *et al*., 1989) to evaluate the potential impacts of various climate change scenarios on regional rice production. Simulated yield rose when temperature increases were small, but declined when temperature increased more than 0.8°C per decade, with the greatest decline in crop yield occurring between the latitudes of 10° and 35°N. Similar results were obtained by Penning de Vries (1993). These effects were the result of increased photosynthesis at higher [CO_2] and a reduced length of the growing season at higher temperatures. Scenarios predicted by GCMs, however, were not considered and arbitrary changes in temperature and precipitation were used instead. Matthews *et al*. (1997) found that rice production in south-east Asia may decline by 3.8% under the climate predicted by GISS, GFDL and UKMO GCMs. Declines in yield were predicted under the GISS and UKMO scenarios for Thailand, Bangladesh, southern China and western India, while increases were predicted for Indonesia, Malaysia and Taiwan and parts of India and China. Lal *et al*. (1998), using CERES-rice simulation model, showed that rice yield in northwest India increases 15% for a doubled [CO_2], but a 2°C rise in air temperature nearly cancels out the positive effects of elevated [CO_2] on rice yield.

Despite technological advances, such as improved crop varieties and irrigation systems, weather and climate are still key factors in agricultural productivity and an assessment of the potential agricultural impacts of climate change is therefore needed. On the other hand, in order to ensure balanced growth and development in agriculture, a comprehensive assessment of the vulnerability of our agricultural productivity due to projected climate change is required. We have found no report on the response of rice yield to climate change in Iran, and the objective of this research was to determine the effect of doubling of the atmospheric carbon dioxide and the climate change that is predicted to accompany it on rice yield and water use in two contrasting environments in Iran.

MATERIALS AND METHODS

The methodology used in this study was similar to that purposed by Curry *et al.* (1990a). The GSAC-Rice model (Soltani *et al*., 1998) was used to simulate rice growth and development. This model is a combination of the EPIC crop growth model (Williams *et al*., 1989) and the models developed within Sinclair's framework (Sinclair, 1986; Amir and Sinclair, 1991; Soltani *et al*., 1999). The model is based on a daily time step and simulates crop growth and development as functions of temperature, solar radiation and water availability. Crop phenology is divided into two growth stages (before and after the beginning seed growth) which their durations are predicted based on daily temperature. Leaf area development is calculated as a function of the expansion and senescence of leaves. These functions are sensitive to temperature and water deficit. Daily biomass production is predicted from the leaf area index, light extinction coefficient and radiation use efficiency (RUE). In this model, the effects of non-optimal temperatures on plant growth of rice are considered by multiplying RUE by a scalar factor that has a value of 1 between 22° and 32°C of average daily temperature but declines to 0 at between 9^0 and 45 °C. The effect of higher temperature on hastening crop phenology and leaf senescence is also considered. Transpiration is calculated as a function of daily biomass production, the transpiration efficiency coefficient and the daily vapor pressure deficit. The accumulated biomass is partitioned into the grains after the begin-

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ning of seed growth, the rate of which depends on climatic conditions at and after the beginning of seed growth. Evaporation, soil water drainage, and runoff are also calculated in the soil water balance sub-model. The model uses readily available weather and soil information and was tested using independent data from a range of Iran's environmental conditions. In most cases, simulated grain yields were similar to that of observed yields. At this stage, the model does not account for the effects of pests, diseases and soil fertility.

Modifications were made to the model for elevated [CO_2]. The approach used to modify GSAC-Rice for differing [CO_2] is similar to that adopted by Sinclair and Rawlins (1993) who modified RUE and transpiration efficiency coefficient for soybean and maize based on observed values of plants grown under elevated [CO_2]. Under current, unstressed conditions, RUE is approximately 1.0 g MJ^{-1}. RUE was increased in the model under increased [CO_2]. In rice, increasing [CO_2] to about 700 ppm has been found experimentally to increase photosynthesis rates and biomass accumulation by about 30% (Baker *et al.*, 1992; and references cited in Bachelet *et al.*, 1993; Cure, 1985; Cure and Acock, 1986), and thus RUE was increased by 30%.

Crop transpirational water use efficiency (grams of biomass accumulated per gram of water transpired) is equal to a species-specific transpiration efficiency coefficient *(k)* divided by the atmospheric vapor pressure deficit, which is calculated from temperature (Tanner and Sinclair, 1983). At current [CO_2], the value of *k* was calculated at 5.8 Pa for rice by a procedure presented in Tanner and Sinclair (1983). The value of *k* increases in response to increased [CO_2] both as a consequence of an increase in the photosynthetic rate and of stomatal adjustments that decrease transpiration rates. Based on experimental work (Baker *et al.,* 1992; and references cited in Bachelet *et al.*, 1993; Cure, 1985; Cure and Acock, 1986), the value of *k* was increased by 37% for an increase in [CO_2] to 700 ppm.

The Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model (GCM) (Manabe and Wetherald, 1987) was used to provide the doubled CO_2 climate change scenario. Schlesinger and Mitchell (1985), Wilson and Mitchell (1987) and Grotch (1988) have studied the characteristics of this GCM. The climate scenario for doubled carbon dioxide was given as monthly adjustment ratios to rainfall, temperature and solar radiation. The monthly ratio was applied to data for each day of the month for all 15 years, (1981-1995) weather data at each location. This procedure produced, one additional set of data referred to from here on as the GFDL climate scenario. Therefore, in this study, two climate scenarios were used:

1) Historic climate data for 15 years for Rasht and Ahwaz, including maximum and minimum temperature, solar radiation and rainfall. Solar radiation data were calculated from sunshine hours as outlined by Doorenbos and Pruitt (1977) or were generated by a synthesis program (WGEN, Richardson and Wright, 1984; Soltani *et al.,* 2000) as implemented in WeatherMan (short for weather data manager- Pickering *et al.*, 1994), for years without sunshine hours data; and

2) Historic data modified by the ratios provided by the GFDL GCM model.

Rasht (37.25°N, 49.6°E, and 7 m below sea level) and Ahwaz (31.03° N, 48.07°E, and 23 m above sea level) were selected to compare the response of rice yields to climate change, because of their contrasting climates. Simulations were run using GSAC-Rice and four combinations of climate/CO_2 scenarios. These four scenarios were:

1. Base or historic climate with the current level of 350 ppm CO_2 (STD-350),
2. Base climate with a doubled CO_2 level (STD-700),
3. GFDL climate with current CO_2 concentration (GFDL-350), and
4. GFDL climate with doubled CO_2 (GFDL-700).

Neither of the STD-700 nor the GFDL-350 scenarios is realistic, since the climate and CO_2 concentration occur simultaneously. These two runs are instructive, however, in showing the direct effect ("fertilization effect") of elevated [CO_2] and its indirect effect via climate change.

Daily estimates of various crop state variables were calculated. The results presented here focus on the final status of the crop at maturity. For justifying yield changes, yield (GY) was defined as a product of biological yield (BY, total biomass produced by crop) and harvest index (HI):
GY= BY x HI

RESULTS AND DISCUSSION

GFDL Predicted Climate Change

Changes of temperature and rainfall during the rice growing season in Rasht and Ahwaz for a doubled [CO_2] climate, as predicted by GFDL, are presented in Figure 1 with average annual temperature increases of 4.2 and 4.1°C in Rasht and Ahwaz, respectively. The increases during the rice growing season in Rasht and Ahwaz are 4.5 and 4.6°C, respectively. It should be noted that optimal rice growth occurs at an average daily temperature of 22-32°C and that a temperature lower than 22°C or greater than 32°C can decrease the growth rate. Changes in solar radiation are minor (data not shown). In average, solar radiation decreased 1% in Rasht and Ahwaz. During the rice growing season solar radiation changed +4% (for Rasht) and -1% (for Ahwaz). Total annual rainfall increase by 12 and 9% for Rasht and Ahwaz equal to 174 and 21 mm, respectively. However, during the rice growing season, rainfall decrease by 38.0% (102 mm) and 68.2% (5.8 mm) for Rasht and Ahwaz, respectively. Any increase in temperature or decrease in rainfall during the rice growing season can substantially increase daily potential evaporation.

Yield Results

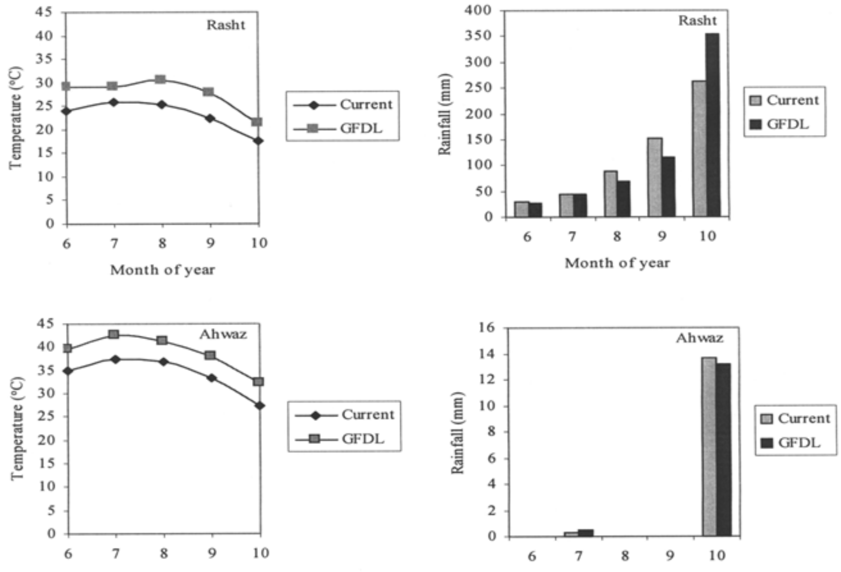

Figure 1. Mean monthly temperature (a,b) and total rainfall (c,d) for Rasht and Ahwaz during the rice growing season (Current=1986-1995). Geophysical Fluid Dynamics Laboratory (GFDL) climate.

Figure 2. Effect of climate/CO_2 scenarios on rice yield (as a percent of current conditions) in Rasht and Ahwaz. Simulated yields are 3.52 and 3.46 t ha^{-1} under current climate/CO_2 for Rasht and Ahwaz, respectively. STD and GFDL are the current and Geophysical Fluid Dynamics Laboratory climates, respectively.

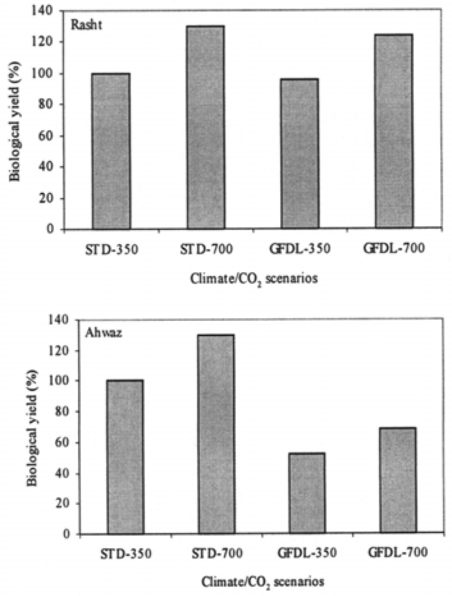

Figure 3. Effect of climate/CO_2 scenarios on rice biological yield (as a percent of current conditions) in Rasht and Ahwaz. Simulated biological yields are 13.486 and 11.808 t/ha under current climate/CO_2 for Rasht and Ahwaz respectively. STD and GFDL are the current and Geophysical Fluid Dynamics Laboratory climates, respectively.

The effect of climate/CO_2 scenarios on rice yield is shown in Figure 2. For the doubled CO_2 alone scenario (STD-700), yield is increased by 30% for both Rasht and Ahwaz. This increase is the result of a 30% increase in biological yield (Fig. 3). Harvest index is not affected by doubling [CO_2] as presented in Figure 4. Kimball (1983) summarizing data from several experimental studies, found a 30% increase in growth with a doubling of the CO_2 level, also midway between the values of the two model predictions of 36% predicted by ORYZA1 and 24% predicted by SIMRIW reported in Matthews *et al.* (1997). Increase in growth is the result of the 'CO_2 fertilizing effect' on photosynthesis (Allen, 1998).

For the climate effect alone scenario (GFDL-350), the yield decreased for both Rasht and Ahwaz by 16.6 and 53.5%, respectively (Fig. 2). Yield decrease in Rasht is due to a 4.7% decrease in biological yield (Fig. 3) and a 11.5% decrease in the harvest index (Fig. 4). A decline in biological yield (47.7%, Fig. 3) and harvest index (10.3%, Fig. 4) are the reasons for a yield decrease in Ahwaz. Therefore, yields are decreased by 3.7% and 11.6% per ^{o}C (Fig 1) in Rasht and Ahwaz, respectively. Matthews *et al.* (1997), working with ORYZA1 and SIMRIW rice models, predicted this figure to be -7.4% $^{o}C^{-1}$ and -5.3% $^{o}C^{-1}$, respectively, in southeast Asia. Baker *et al.* (1992) measured a -7 to -8%$^{o}C^{-1}$ yield decrease for rice in controlled environment experiments.

For the combined effects of both increased [CO_2] and climate change (GFDL-700), yield is increased for Rasht by 8.4% (Fig. 2) due to a 23.9% increase in biological yield (Fig. 3), although the harvest index (Fig. 4) is decreased by 11.5%. In Ahwaz, however, yield is greatly decreased by 39.5% (Fig. 2) due to 32.0 and 10.3% decreases in biologi-

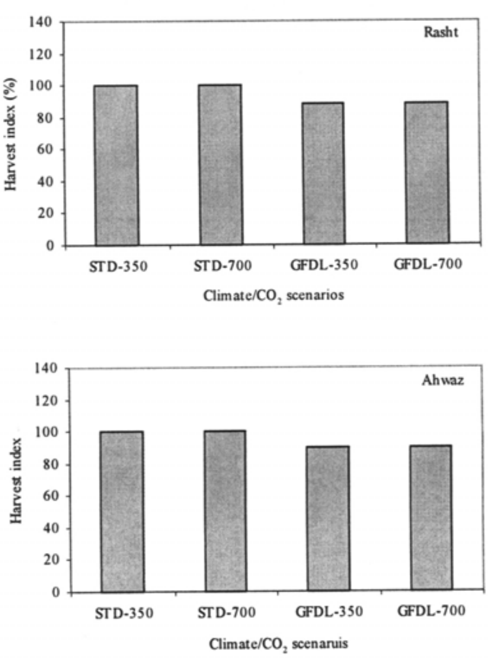

Figure 4. Effect of climate/ CO_2 scenarios on harvest index (as a percent of current conditions) in Rasht and Ahwaz. Simulated harvest index are 26 and 29% under current climate/CO_2 for Rasht and Ahwaz, respectively. STD and GFDL are the current and Geophysical Fluid Dynamics Laboratory climaes, respectively.

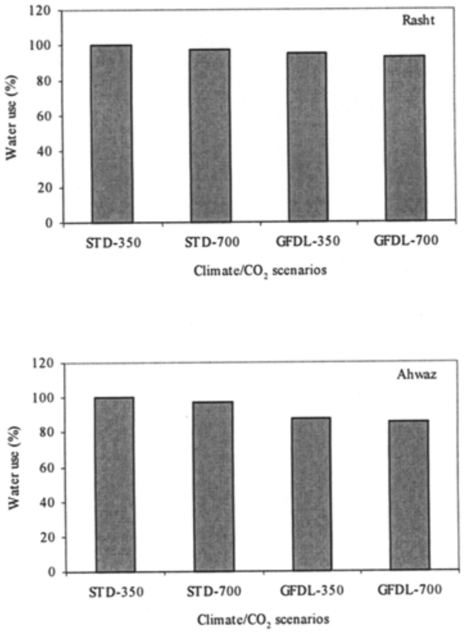

Figure 5. Effect of climate/Co_2 scenarios on crop water use (as a percent of current conditions) in Rasht and Ahwaz. Simulated crop water use are 408 and 1327 mm under current climate/CO_2 for Rasht and Ahwaz, respectively. STD and GFDL are the current and Geophysical Fluid Dynamics Laoratory climates, respectively.

cal yield (Fig. 3) and harvest index (Fig 4), respectively. This is in agreement with the findings of Rosenzweig and Iglesias (1998) and Rosenzweig *et al.* (1993). Working with collaborators from 22 countries, they used a number of crop models to simulate likely changes in the production of various crops, including rice, under different GCM scenarios. They predicted that crop yields are likely to decline in low-latitude regions, but could increase in mid- and high-latitudes.

Water Use Results

Since higher temperature and CO_2 enrichment both effected the transpiration of water from plant leaves to the air, it is of interest to see how the climate change scenarios compared in terms of water use (crop evapotranspiration), irrigation requirements and water use efficiency. Water use results from the model runs are based on the evapotranspiration of the crop calculated by the model and summed over the period from transplanting until physiological maturity. The percent changes are (Fig. 5)*:*

1. Doubled CO_2 effect alone scenario (STD-700) gives a 2.5% decrease in water use efficiency for Rasht and a 3.1% decrease for Ahwaz, probably because of the slightly lower transpiration rates.
2. Climate effect alone GFDL scenario gives a 4.7% decrease for Rasht and a 12.6% decrease for Ahwaz probably due to shortening the growing season and a lower biological yield.
3. The combined effect of doubled CO_2 and climate GFDL scenario produced a 7.4% decrease for Rasht and a 14.5% decrease for Ahwaz.

These results are in agreement with the

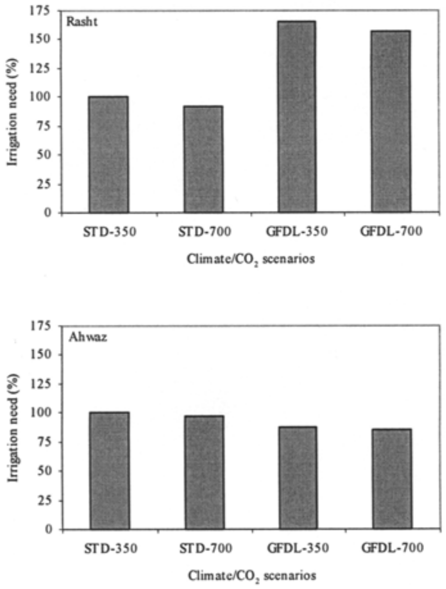

Figure 6. Effect of climate/CO_2 scenarios on irrigation needs (as a percent of current conditions) in Rasht and Ahwaz. Simulated irrigation need are 127 and 1319 mm under current climate/CO_2 for Rasht and Ahwaz, respectively. STD and GFDL are current and Geophysical Fluid Dynamics Laboratory climates, respectively.

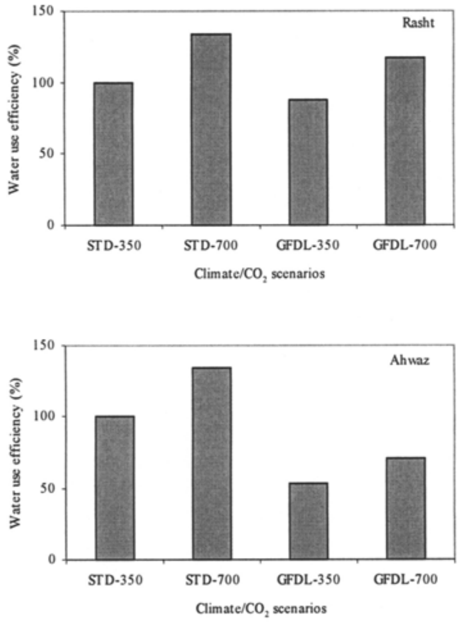

Figure 7. Effect of climate/CO_2 scenarios on water use efficiency (as a percent of current conditions) in Rasht and Ahwaz. Simulated water use efficiency is 8.62 and 2.61 kg ha^{-1} mm^{-1} under current climate/CO_2 for Rasht and Ahwaz, respecively. STD and GFDL are the current and Geophysical Fluid Dynamics Laboratory climates, respectively.

findings of Curry *et al.* (1990a, b).

The irrigation need (with an irrigation efficiency of 100% and ignoring deep drainage losses) was calculated as crop water use minus rainfall. Results are shown in Figure 6. For the doubled [CO_2] effect alone case, the irrigation need was reduced by 7.9% and 3.1% for Rasht and Ahwaz, respectively. For the climate effect alone case, the irrigation need increased by 65% for Rasht and decreased by 12.3% for Ahwaz. The combined effects of [CO_2] and climate show a 56.7% increase for Rasht and a 14.3% decrease for Ahwaz. The irrigation demand results for the climate effects alone compared with the combined effects are not greatly different, even though yields are about 24% (Rasht) and 14% (Ahwaz) less for the climate effects alone. Curry *et al.* (1990b) also reported the same responses for soybean for 19 locations in southeastern USA.

The results of water use efficiency (WUE) are shown in Figure 7 for the four climate/CO_2 scenarios. Study of the GSAC-Rice yield results in Figure 2 along with the WUEs shown in Figure 7, shows a close relationship between WUE and yield. Allen *et al.* (1985) and Jones *et al.* (1985) pointed out that changes in WUE were strongly related to changes in photosynthesis rates and only weakly related to changes in transpiration rates under various CO_2 treatments at constant temperature. Similar responses have been reported by Curry *et al.* (1990a).

Implications of Results

The study shows that under 2xCO_2 GFDL predicted climate change at Rasht, more (8%) rice could be produced, but irrigation needs would be dramatically increased by 57%. This would increase competition for water resources between greater agricultural use (mainly rice in that region) and nonagricultural demands. As a result, many farmers in the north of Iran may replace rice with other crops that require less water. It seems that increases (8%) in rice production by the remaining rice farmers might not maintain overall total production. On the other hand, rice production at Ahwaz (southern of Iran) could be halved and might not even remain a viable option unless plant breeders will be able to produce more heat tolerant rice cultivars. Overall, it can be concluded that rice production in the north and south of the country will dramatically change under any future elevated [CO_2] and climate change accompanying it as predicted by the GFDL model.

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شبیه سازی اثرات تغییر اقلیم پیش بینی شده با GFDL بر زراعت برنج در ایران

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چکیده

تغییر اقلیم آینده ممکن است اثرات زیادی بر عملکرد گیاهان زراعی داشته باشد. اثرات احتمالی تغییر اقلیم ناشی از افزایش غلظت CO_2 برعملکرد برنج درایران با استفاده ازیک مدل مکانیستی (GSAC-Rice) ارزیابی شد. برای پیش بینی تغییر اقلیم آینده از مدل GFDL استفاده شد. شبیه سازی برای دو مکان با اقلیمهای متفاوت یکی در شمال (رشت) و دیگری در جنوب (اهواز) صورت گرفت. GFDL پیش بینی کرد که در نتیجه دو برابر شدن غلظت CO_2 ، دما درطی فصل رشد برنج در رشت و اهواز به ترتیب ٤/٥ و ٤/٦ درجه سانتیگراد افزایش می‌یابد. تغییرات تشعشع اندک است. اما بارندگی در طی فصل رشد برنج در رشت ۳۸/۰ درصد (۱۰۲ میلی‌متر) و دراهواز ٦۸/۲ درصد (٥/۸ میلی‌متر) کاهش می‌یابد. پیش بینی شد که دو برابر شدن غلظت CO_2 به تنهایی عملکرد را ۳۰ درصد افزایش می‌دهد ولی به ازای هر درجه افزایش دما در رشت و اهواز به ترتیب ۳/۷ و ۱۱/٦ درصد کاهش می‌یابد. در نتیجه تاثیر توام افزایش CO_2 و تغییر اقلیم ناشی از آن (پیش‌بینی شده با GFDL) در رشت امکان تولید بیشتر (۸ درصد) برنج وجود دارد. ولی نیاز آبیاری به مقدار زیاد یعنی ٥۷ درصد افزایش می یابد. در اهواز تولید برنج به نصف کاهش می‌یابد و کشت برنج منسوخ خواهد شد مگر آن که واریته‌های مقاومتر برنج به دمای بالا اصلاح شوند. نتیجه گیری شد که تولید برنج در کشور دراثر تغییر اقلیم آن چنان که با مدل GFDL پیش‌بینی می‌شود، به طور گسترده‌ای تغییر پیدا می‌کند.

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