Vol. 14, No. 2, pp. 137-142 (2014)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in

Research Article

Simulating the Effects of Elevated Temperature and CO_2 on Growth and Productivity of Winter Maize

GOURANGA KAR* AND ASHWANI KUMAR

Directorate of Water Management, Bhubaneswar - 751 023, Odisha

ABSTRACT

In this investigation, DSSAT 4.5 model was calibrated and evaluated to study the effect of elevated temperature and CO_2 on growth and productivity of the maize crop. A 1°C increase in temperature from the present (mean of 1985-2008) may reduce the duration of the crop, which was sown in 3rd week of November, by 8 days under both 370 (current) and 550 (projected) ppm CO_2 concentrations. A larger reduction (13 days) in crop duration was observed at 2°C increase in temperature, and the crop yield is likely to be reduced by 14% under 370 ppm CO_2 concentration. The increase in temperature had adverse effect on leaf area index, total dry matter and yield. However, the effect of rise in temperature was less under 550 ppm CO_2 concentration.

Key words: Temperature, CO_2, Crop duration, Yield, Maize, DSSAT

Introduction

Global mean temperature is projected to rise by 0.3-4.8 °C by late 21st century (IPCC AR5). The increase is likely to enhance crop water demand and reduce yield and biomass of the crops, particularly in the tropical region. The increase in CO_2 concentration in atmosphere from 280 (pre-industrial) to 370 ppm (present) is primarily caused by fossil fuel use and land use change. It is likely to affect the crop production through changes in physiological processes like photosynthesis, respiration and partitioning of photosynthates (Chartzoulakis and Psarras, 2005). However, the adverse effect of temperature may reduce because elevated CO_2 has a positive effect on photosynthesis, leading to increase in biomass and yield of the crops (Ludwig and Asseng, 2006; Krishnan *et al.*, 2007). Maize (*Zea mays* L.) could be a promising option for diversification in rice-based cropping systems in eastern India (Kar *et al.,* 2004), which is sown in both wet (rainy) and dry (winter) seasons. However, growing of maize in dry season in rice-fallow with supplemental irrigation is gaining popularity due to availability of favouarble agro-ecological and photo-thermal environments during the growth period (Kar and Verma*,* 2005). However, successful production of winter maize, which is usually sown between end-of-October to end-of-November months, may be a concern due to changes in global climate. An attempt has therefore been made to assess the impacts of climate change, particularly the temperature (1.0 and 2.0^{0}C increase from the present level) and CO_2 concentration (550 against 370 ppm at present) on growth and productivity of maize by using the Decision Support System for Agro-technology Transfer (DSSAT 4.5) model.

*Corresponding author, Email: kar_wtcer@yahoo.com

Materials and Methods

Study site

An on-farm experiment was carried out during winter seasons (2007-08 and 2008-09) at

Dhenkanal sadar block, Dhenkanal, Odisha (20°40′N, 85°38E, 69 m above mean sea level). The mean maximum temperature varies from 27 (January) to 37 (May) °C, and the minimum temperature ranges between 14 (December) to 21°C (May). The average annual rainfall is 1440 mm, 72% of which occurs during south-west monsoon period. In winter seasons, rainfall is meager and erratic and thus, cultivation may not be possible without supplemental irrigations.

Observations

The maize crop (cv. Novjyot) was sown on 25^{th} and 22^{nd} November in 2007 and 2008, respectively on 60 cm spaced ridges keeping plant-to-plant distance of 30 cm, with a seed rate of 25 kg ha^{-1} and N:P:K fertilizer dose of 120:80:80. Dates of major phenological stages *viz.,* emergence, knee-high stage, anthesis, 50% tassel initiation, 50% silking, and maturity were recorded from 3 replicated plots. Five plants from each plot were randomly selected and tagged for recording observations. Leaf area of the crop was measured weekly using graph paper. Total leaf area per ground area was expressed as leaf area index (m^2 m^{-2}). For dry biomass, plant samples were dried at 80 ^{O}C for 24 h and dry weights were recorded.

Calibration and validation of DSSAT 4.5

The model was calibrated with the current weather (Mean of 1985-2008; Source: NASA Grided data) and crop (2007-08) data to adjust the model parameters for local condition and to derive genetic coefficients for the cultivar. Simulation performance was evaluated by root mean square error (RMSE) (Wallach and Goffinet, 1989), percentage of error and d-statistics. Cultivar coefficients were standardized successively starting from P_1 (thermal time from seedling emergence to the end of the juvenile phase, expressed in ^{O}C-day, above base temperature of 7.5 ^{O}C), P_2 (extent in days to which development is delayed for each h increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate, 12.5 h), P_5 (thermal time from silking to physiological maturity) and PHINT [Phyllochron interval; the interval in thermal time (degree-days) between successive leaf tip appearances], G_2 (maximum possible number of kernels per plant), G_3 (grain number cob^{-1} and grain filling rate). An iterative approach (Hunt *et al.*, 1993) was used to select the most suitable set of coefficients until the observed and predicted values were close.

After calibration, the cultivar had values of 323 (°C day), 0.658 (day) and 765 (°C day) for P_1, P_2 and P_5, respectively. The kernel filling rate (G_5) of 6.50 mg day^{-1} was estimated and PHINT (Phylochron interval) value was estimated as 38.4 °C-day for the cultivar. The model result was validated with experimental data of 2008-09.

Crop growth and yield under future climate

The climate change impacts on crop growth and yield were assessed with current (Mean of 24 years, 1985-2008) and future (1 & 2°C increase over the current maximum and the minimum) climates. The weather series for simulations of future climate was modified and run under both present (370 ppm) and future CO_2 level (550 ppm). The impact of increased CO_2 concentration on phenology, grain yield and total dry matter of maize under current climatic condition was also studied.

All together, we evaluated the following conditions: (1) Daily maximum and minimum temperatures; current (mean of 1985-2008) +1°C with CO_2 concentration of 370 ppm; (2) Daily maximum and minimum temperatures; current (mean of 1985-2008) +1°C with CO_2 concentration of 550 ppm; (3) Daily maximum and minimum temperatures; current (mean of 1985-2008) +2°C with CO_2 concentration of 370 ppm; and (4) Daily maximum and minimum temperatures; current (mean of 1985-2008) +2°C with CO_2 concentration of 550 ppm.

Results and Discussion

Soils

The soils within the experimental area were relatively homogeneous and texture was sandy loam to clay loam with clay content varying

Table 1. Soil profile inputs for the DSSAT 4.5 model

Soil parameters	Soil profile depth (m)					
	0-0.15	0.15-0.30	0.30-0.45	0.45-0.60	0.60-0.90	0.90-1.20
Lower limit (m^3m^{-3}) of soil moisture	0.098	0.097	0.093	0.098	0.117	0.129
Upper limit, drained (m^3m^{-3}) of soil moisture	0.265	0.260	0.259	0.276	0.315	0.325
Upper limit, saturated (m^3m^{-3}) of soil moisture	0.422	0.435	0.418	0.425	0.438	0.468
Root growth factor (0-1)	1.0	1.0	0.512	0.509	0.378	0.245
Saturated hydraulic conductivity, macropore (cm h^{-1})	23.8	13.7	8.0	7.1	4.7	2.7
Bulk density (Mg m^{-3})	1.44	1.46	1.47	1.48	1.50	1.54
Organic carbon (g kg^{-1})	8.6	6.9	5.9	5.8	3.9	4.0
Clay (<0.002 mm) (%)	23.1	25.9	21.9	22.6	23.9	34.5
Silt (0.05-0.002) (%)	11.9	12.9	14.4	13.9	14.4	13.5
pH (soil-water)	5.8	5.7	5.9	5.8	6.0	6.7

between 21.9 and 34.5% (Table 1). The bulk density was 1.44 Mg m^{-3} at 0-0.15 m layer and increased with soil depth. The pH was low to moderately acidic and no salt was detected. The organic carbon content was higher (8.6 g kg^{-1}) at upper layer (0-0.15 m) and progressively decreasing down the profile. The water contents at field capacity and at wilting point were varying between 0.26 and 0.33 m^3m^{-3}, and 0.09 to 0.13 m^3 m^{-3}, respectively.

Calibration performance of DSSAT 4.5 model for predicting phenology, crop growth and yield

The model performance in simulating phenology, grain yield and biomass during calibration process was satisfactory (Table 2). There was only 1 day difference between observed and simulated values of days to anthesis/flowering and maturity with RMSE of 0.42 and 0.58, respectively. The model simulated number of days from planting to physiological maturity with RMSE of 0.58 and d-index of 0.88. The peak LAI was simulated with RMSE 0.36 and -6.3% error. Observed and simulated grain yield were also in good agreement (RMSE 198.7 kg ha^{-1}; -0.72% error and 0.94 d-index value).

Impact of present and enhanced CO_2 levels

The impact of current (370 ppm) and elevated CO_2 concentration (550 ppm) under present temperature scenario on crop duration, growth and productivity of maize was studied on first sown crop and results are presented in Table 3. The duration of the crop was same when CO_2 concentration increased from 370 to 550 ppm. Marginal increase in peak LAI (0.2) was recorded with increasing CO_2. An increase of 704 kg ha^{-1} increase in total dry matter under elevated CO_2 concentration (without change in temperature) was recorded. Similarly, 294 kg ha^{-1} higher grain yield was recorded when CO_2 concentration increased to 550 ppm CO_2. Similar results were reported by Bunce (2000), who showed that higher ambient CO_2 will allow reducing the transpiration rate through decreased stomatal conductance especially at higher temperature. This would lead to improved water use efficiency and thereby to a lower probability of water stress occurrence. Trnka *et al.* (2004) also reported that increased CO_2 contributed to the intensified photosynthesis and improved water use efficiency.

Impact of change in temperature

Impact of current (370 ppm) and elevated (550 ppm) CO_2 on phenology, growth and yield was simulated with 1 and 2^{O}C increase in temperature from the current level. Study revealed that temperature exerted a major effect on the rate at which plants develop and growth can be slowed down when the temperature is either too low or too high, as also explained by Ong and

Table 2. Summary of observed and simulated results during model calibration under current climatic condition (with maize 2007-08 data)

Crop parameters	Unit	Observed	Simulated	RMSE	Error (%)	d-index
Anthesis	days	55	54	0.42	- 1.81	0.96
Maturity	days	113	112	0.58	- 0.88	0.87
Maximum LAI	-	6.4	6.0	0.36	- 6.25	0.80
Grain yield	kg ha^{-1}	5847	5805	198.7	- 0.72	0.94
Total biomass	kg ha^{-1}	13440	13250	245.6	- 1.41	0.92

Table 3. Impact of elevated CO_2 on crop duration, growth and productivity of maize (simulated with maize 2008-09 under current weather condition)

Attributes	CO_2 concentration (ppm)		Difference
	370	550	(absolute)
Crop duration (days)	114	114	0
Maximum leaf area index	6.1	6.3	0.2
Total above ground dry biomass (kg ha^{-1})	13600	14304	704
No. of grains m^{-2}	2357	2445	88
Mean grain weight (g)	0.247	0.249	0.002
Grain yield (kg ha^{-1})	5800	6094	294

Table 4. Impact of temperature and CO_2 scenarios on phenology, growth, yield and yield component of maize (simulated with crop data of 2008-09 under current weather)

Temperature	Current (av. of 1985-2008)	1.0 °C	Difference (absolute)	2.0 °C	Difference (absolute)
CO_2 concentration: 370 ppm					
Crop duration (days)	114	106	8	101	13
Maximum leaf area index	6.1	5.6	0.5	5.45	0.65
Total above ground dry biomass (kg ha^{-1})	13600	12306	1294	11515	2085
No. of grains m^{-2}	2357	2340	17	2314	43
Grain yield (kg ha^{-1})	5800	5318	482	4996	804
CO_2 concentration: 550 ppm					
Crop duration (days)	114	106	8	101	13
Maximum leaf area index	6.3	5.8	0.5	5.65	0.65
Total above ground dry biomass (kg ha^{-1})	14304	12805	1499	12374	1930
No. of grains m^{-2}	2445	2345	100	2325	120
Grain yield (kg ha^{-1})	6094	5504	590	5298	796

Monteith, 1985. We have observed that increase in temperature shortened the duration from planting to physiological maturity, affected growth and decreased yield (Table 4). Crop duration was almost same under the 370 and 550 ppm CO_2 concentrations at a particular temperature. But at the same level of CO_2 concentration, increased temperature had negative impact on biomass and leaf area.

Effect of temperature was, however, less under 550 ppm CO_2 concentrations compared to 370 ppm. The reduction in LAI was 0.5 and 0.65 at 1.0 and 2.0°C increase in temperature, respectively, under 370 ppm CO_2 concentration.

The LAI increased by 0.2 under 550 ppm concentration under similar temperature increase. Dry matter accumulation was also negatively affected with increase in mean temperature. The reduction in dry matter was 1294 and 2085 kg ha^{-1} at 1 and 2°C increase in temperature, respectively with 370 ppm CO_2, while the equivalent reduction in dry matter at 550 ppm CO_2 concentration was 1499 and 1930 kg ha^{-1}. Yield and yield components were also adversely affected through increase in temperature at both concentrations of CO_2, although 550 ppm CO_2 had marginal positive effect. The reduction in grain yield was simulated as 482 and 804 kg ha^{-1} under 370 ppm CO_2 concentration with 1 and 2°C increase in temperature, respectively. However, with 550 ppm CO_2 concentration, the grain yield reduced but to a lesser degree (590 and 796 kg ha^{-1} under 1 and 2^0C rise, respectively). Reduction in grain yield under elevated temperature could be attributed to the impact on number of grains m^{-2} and mean grain weight, although the crop response to change in temperature depend on the temperature optima for photosynthesis, growth, and yield of the crop (Conroy *et al.*, 1994). Similar observations were reported in rice (Lal *et al.,* 1998) and in wheat and maize (Rosenzweig, 1990). Trnka *et al.* (2004) also reported that increased CO_2 contributed to the intensified photosynthesis and improved water use efficiency. The CO_2 fertilization effect on stomatal resistance and photosynthesis might offset the yield reduction significantly (Wang *et. al.,* 2013). The DSSAT simulation projected a decrease in yield of maize under current level of CO_2 (330 ppm), caused by a shorter growing season due to higher temperatures and a precipitation deficit (Alexandrov and Hoogenboom, 2000).

Conclusions

Increased temperature reduced the duration of the crop from planting to physiological maturity, retarded growth and decreased yields. The CO_2 fertilization demonstrated a compensation effect on the reduction of maize yield. Further experiments are required to validate the effect. Future research on adaptation measures like increasing the irrigation efficiency, switching of maize cultivar, changing sowing dates etc. may be undertaken.

References

Alexandrov, V.A. and Hoogenboom, G. 2000. The impact of climate variability and change on crop yield in Bulgaria. *Agric. For. Meteorol.* **104**: 315–327.

Bunce, J.A. 2000. Responses of stomatal conductance to light, humidity and temperature in winter wheat and barley grown at three concentrations of carbon dioxide in the field. *Glob. Change Biol.* **6**: 371-382.

Conroy, J.P., Seneweera, S., Basra, A.S., Rogers, G. and Nissen-Wooler, B. 1994. Influence of rising atmospheric CO_2 concentration and temperature on growth, yield and grain quality of cereal crops. *Aust. J. Plant Physiol*. **21**: 741-758.

Chartzoulakis, K. and Psarras, G. 2005. Global change effects on crop photosynthesis and production in Mediterranean: the case of Crete, Greece. *Agric. Ecosys. Environ.* **106**: 147-157.

Hunt, L.A., Parajasingham, S., Jones, J.W., Hoogenboom, G., Imamura, D.T. and Ogoshi, R.M. 1993. Gencalc-Software to facilitate the use of crop models for analyzing field experiments. *Agron. J.* **85**: 1090-1094.

IPCC AR5. The fifth assessment report of IPCC, http://www.ipcc.ch/report/ar5/wg3.

Kar, G., Singh, R. and Verma, H.N. 2004. Alternative cropping strategies for assured and efficient crop production in upland rainfed rice areas of eastern India based on rainfall analysis. *Agric. Water Manage.* **67**: 47-62.

Kar, G. and Verma, H.N. 2005. Phenology based irrigation scheduling and determination of crop coefficient of winter maize in rice fallow of eastern India. *Agric. Water Manage.* **75**: 169-183.

Krishnan, P., Swain, D.K., Bhaskar, B.L., Nayak, S.K. and Dash, R.N. 2007. Impacts of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. *Agric. Ecosys. Environ.* **122**: 233-242.

Lal, M., Singh, K.K., Rathore, L.S., Srinivasan, G. and Saseendran, S.A. 1998. Vulnerability of rice and wheat yields in north-west India to future changes in climate. *Agric. For. Meteorol.* **89**: 101-114.

Ludwig, F. and Asseng, S. 2006. Climate change impacts on wheat production in a Mediterranean environment in Western Australia. *Agric. Sys.* **90**: 159-179.

Ong, C.K. and Monteith, J.L. 1985. Response of pearl millet to light and temperature. *Field Crops Res.* **11**: 141-160.

Rosenzweig, C. 1990. Crop response to climate change in the Southern Great Plains: a simulation study. *Prof. Geogr.* **42**: 20-37.

Trnka, M., Dubrovsky, M. and Zalud, Z. 2004. Climate change impacts and adaptation strategies in spring barley production in the Czech Republic. *Clim. Change* **64**: 27-255.

Wallach, D. and Goffinet, B. 1989. Mean squared error of prediction as a criterion for evaluating and comparing system models. *Ecol. Model.* **44**: 200-306.

Wang, L., Feng, Z. and Schjoerring, J. 2013. Effects of elevated atmospheric CO_2 on physiology and yield of wheat (*Triticum aestivum* L.): a meta-analytic test of current hypotheses. *Agric. Ecosys. Environ*. **178:** 57–63.

Received: 18 February 2014; Accepted: 17 December 2014