Sugarcane and Climate Change: Effects of CO_2 on Potential Growth and Development

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Keywords: *Saccharum officinarum*, elevated CO_2, temperature, productivity, modeling

Abstract

A model of sugarcane (*Saccharum officinarum*) was made to predict the potential yield under climate change scenarios to analyze the sustainability of new expanded cultivation areas in Brazil and Australia due to increased of the ethanol production. The potential yield in terms of dry matter of sugarcane was adjusted to estimate the carbon dioxide absorption (CO_2), as C4 photosynthesis plant, in relation with air temperature and solar radiation to calculate monthly production of dry mass (DM), during the crop cycle. The sugarcane DM model takes in account a gross photosynthetic rate subtracting losses by maintenance respiration, senescence of leafs and tillers during the crop cycle. The projected increase in mean temperature up to 1.3 to 2.7 ºC would increase the suitability for sugarcane production. Our results indicate that the sugarcane increased its productivity under double CO_2. The simulated and observed productivity were 192 vs. 168 t/ha (sugarcane-plant) and 170 vs. 137 t/ha (ratoon). Sugarcane productivity under year 2070 scenarios will increase up to 13% both in São Paulo (Brazil) and Queensland (Australia).

INTRODUCTION

Since the beginning of the Industrial Revolution, the concentration of carbon dioxide (CO_2) in the atmosphere increased about 30% and the current forecasts values indicate that this concentration will reach approximately 720 ppmv until the middle of this century (Prentice, 2001).

The concentration of CO_2 on the atmosphere has increased as a direct result of human activities, at a rate of 0.4-0.5% per year or 1-1.8 μmol CO_2 per year (Intergovernmental Panel on Climate Change, IPCC, 2001; Streck, 2005). Also, there is an increase of global average temperature. In the last century the average global surface temperature increased by 0.6 ± 0.2 °C. Studies use general circulation numerical models of the atmosphere (GCM - general circulation models) indicate that it is very probable that there will be an increase of 1 to 6 °C in the average temperature of the air by 2070, at various sites of the world, including Brazil (Siqueira et al., 2001).

We need to know the effect of the global climate change on crop and bio-energy production. But climate effect is highly variable on crops. The increase in the concentration of atmospheric CO_2 is related with an increase in the rate of photosynthesis (Taiz and Zeiger, 1991), mainly on species that have a metabolism of photosynthesis type C3 (Souza, 2007; Siqueira et al., 2001).

But in practice, the increase of CO_2 concentration is accompanied by an increase of air temperature. High temperatures reduce the growth and productivity of some crops (Butterfield and Morison, 1992; Siqueira et al., 2001), due to shortening the crop cycle and to the increase in respiration of the plant tissue (Taiz and Zeiger, 1991). There are also doubts about the positive response of C4 photosynthesis species, such as sugarcane. Bowes (1993) showed that there were not significant differences when C4 plants were cultivated under high CO_2 concentration. Moreover, other studies showed that C4 plants can respond significantly to the increase of CO_2 on similar way than C3 species. In sugarcane was measured an increase of 26% and 15% in the assimilation of total soluble sugars, after 7 and 14 days after the emergence of the sheet respectively (Vu et al., 2006). Sugarcane grown in high CO_2 conditions showed a high photosynthesis rates (Souza, 2007).

Due to the economic importance of sugarcane for sugar and bioenergy production, it is important to know how this crop will respond to climate change. The goal of this work was to modeling CO_2 effect on sugarcane growth and development.

MATERIALS AND METHODS

Field Experiment

Field experiment was carrying out to compare sugarcane photosynthesis under two CO_2 concentrations in Piracicaba, São Paulo (Brazil). More methodological details were report in Souza (2007). During 12 months sugarcane crop was followed in Open-Top-Chambers with current (~ 370 ppmv) and double (~ 720 ppmv) CO_2 concentrations, without limitations of water and nutrients.

Sugarcane Model

Field data was used to calibrate the sugarcane model of Barbieri (1993). This model is based on net photosynthesis model according with Heemst (1986). Monthly potential sugarcane productivity is calculated from:

$$MST = MSo \times Cr + \sum MS$$

Where,
MST = dry matter accumulated at the end of the month (kg/ha),
MSo = dry matter at the beginning of the month (kg/ha),
Cr = respiration coefficient,
MS = daily production of dry matter (kg/ha), that it depends on net photosynthesis.

The respiration coefficient depends linearly on temperature and plant age (growing degree days). The daily production of dry matter is calculate from daily production of carbohydrates that it depends on solar radiation, CO_2concentration, leaf area index, plant age, and temperature (Barbieri, 1993).

The experimental results were used to improve the estimates of potential daily growth. The sugarcane model was improved and adjusted to estimate the absorption of CO_2 for the C4 photosynthesis, in current and double concentration (720 ppmv).

The model was calibrated based on the assimilation rate of CO_2 from experiment and photosynthesis model for C_4 plant from literature. Driven variables of the model are the photosynthetically active radiation, temperature, and cropping variables such as leaf area index, harvest index and crop cycle duration.

Climate Change Scenarios

Climate change scenarios were derived from GCM-Runs from the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). Model calculations were by the IPCC Third Assessment Report version of MAGICC (Wigley, 2003; MAGICC/SCENGEN Version 4.1, September 2003). SRES marker scenarios A2 and B2 correspond to CO_2 concentrations of 834 ppmv and 601 ppmv at the end of the century.

The scenario of each family represents an estimation set of population growth, social and economic development, technology and environmental factors. We had chosen four scenarios: A1BAIM, A2MES, B1MES, and B2MES.

Table 1 shows the monthly projection temperatures for 2050 and 2070 (MAGICC/SCENGEN version 4.1) for Piracicaba (São Paulo, Brazil) and for Bundaberg (Queensland, Australia).

The monthly projections of temperature change for in each scenario were added to the current temperature data from weather stations in the area of Piracicaba and Bundaberg. The current observed data were from Araras in Piracicaba (latitude: 22° 18'S, longitude: 47º23'W, altitude: 617 masl) and from Bundaberg in Queensland (Bureau of Sugar Experiment Stations, Bundaberg, latitude: 24º 83’S, longitude: 152 º43'E).

RESULTS AND DISCUSSION

Net photosynthesis was higher under elevated CO_2 during all the crop cycle (Fig. 1). Field experiment showed an average sugarcane yield (dry matter) of 62.70 t/ha under current CO_2 concentration of 370 ppmv and 71.65 t/ha under double CO_2 concentration of 720 ppmv. Sugarcane yield increased 14% with double CO_2 concentration. The increment on dry matter was lower compared with field measures of net assimilation of CO_2. Net assimilation of CO_2 was increased a 24%, similar than Wand et al. (1999) and Ainsworth and Long (2005), they found that the photosynthetic rate of plants grown under high CO_2 increase up to 28%.

There is a little variability of sugarcane yield among scenarios, but there was a consistent increase in yield (Table 2). The temperature change is low compared with northern latitudes. Temperature changes ranged from 1.3 to 2.0 °C for 2050 among scenarios for the two regions Piracicaba (Brazil) and Bundaberg (Australia), the simulated yield increase among 12.1 to 13%. For the end of the century (2070) projected temperatures changes are from 1.8 to 2.7 °C and double CO_2 which reflect a gain in yield of 12.7 to 16.1%.

The simulated effect of CO_2 concentration was showed different accumulate yields over one sugarcane cycle (Fig. 2): a) Sugarcane crop yield in a current environment ($Y= 0.1176 X^{3.113}$, $r^2= 0.98$ significant at $P<0.01$); b) Sugarcane crop yield in a CO_2 enriched environment ($Y = 0.0995 X^{3.0847}$, $r^2=0.99$ significant at $P<0.01$); c) Sugarcane ratoon in the natural environment ($Y = 0.0995 X^{3.0847}$, $r^2=0.99$ significant at $P<0.01$); and d) Sugarcane ratoon under enriched CO_2 environment ($Y = 0.0655 X^{3.1765}$, $r^2=0.99$ significant at $P<0.01$). Our results indicate that sugarcane increased its productivity under double CO_2. The simulation results of total sugarcane yield were: 192 vs. 168 t/ha (sugarcane-plant) and 170 vs. 137 t/ha (ratoon), respectively for double and current CO_2 concentrations.

CONCLUSIONS

The model has been consistently adjusted to estimate the effects of increased CO_2 and temperature on simulation of growth of sugarcane. The evaluation of potential productivity of sugarcane for different scenarios showed a yield increase of 12 to 16%.

Current agronomic practices and cultivar could be adapted to increased productivity in different climate scenarios. The main impact in these different climate scenarios is related with warmer temperatures. Although, this sugarcane model does not take into account water availability, in these regions precipitation changes are low. New varieties for warmer environment must be tested.

ACKNOWLEDGEMENTS

Thanks to EMBRAPA (Brazil) and Fundación Carolina (Spain) for financial assistance, and AgSystems research group for supporting Fabio da Silva postdoctoral stage.

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Tables

Table 1. Average monthly change temperatures in the years of 2050 and 2070 in four simulated scenarios IPCC (A1BAIM, A2MES, B1MES, and B2MES) in the Piracicaba (São Paulo, Brazil) and Bundaberg (Queensland, Australia).

Year	Month	Piracicaba (Brazil)				Bundaberg (Australia)			
		A1	A2	B1	B2	A1	A2	B1	B2
2050	1	+1,5	+1,3	+1,3	+1,4	+1,7	+1,3	+1,1	+1,0
	2	+1,6	+1,2	+1,3	+1,3	+1,9	+1,1	+1,3	+1,1
	3	+1,4	+1,2	+1,4	+1,3	+1,4	+1,2	+1,2	+1,1
	4	+2,0	+1,5	+1,5	+1,6	+1,5	+1,4	+1,3	+1,4
	5	+1,8	+1,6	+1,9	+1,7	+1,4	+1,2	+1,4	+1,3
	6	+2,1	+1,7	+1,9	+1,8	+1,4	+1,3	+1,4	+1,3
	7	+1,9	+1,6	+1,8	+1,7	+1,5	+1,5	+1,4	+1,3
	8	+1,9	+1,6	+1,8	+1,7	+1,4	+1,2	+1,6	+1,2
	9	+2,0	+1,7	+1,9	+1,8	+1,4	+1,4	+1,2	+1,1
	10	+ 1,3	+1,7	+1,9	+1,2	+1,3	+1,2	+1,3	+1,2
	11	+1,3	+1,1	+1,3	+1,2	+1,4	+1,1	+1,3	+1,2
	12	+1,3	+1,2	+1,3	+1,2	+1,4	+0,9	+1,1	+1,0
2070	1	+ 2,0	+1,9	+1,3	+1,7	+ 1,6	+1,5	+1,3	+1,4
	2	+1,9	+1,9	+1,4	+1,7	+1,8	+1,7	+1,2	+1,5
	3	+2,1	+2,0	+1,4	+1,8	+1,8	+1,6	+1,2	+1,6
	4	+2,6	+2,4	+1,5	+1,9	+1,9	+1,8	+1,3	+1,6
	5	+2,3	+2,5	+1,8	+2,2	+2,1	+2,0	+1,6	+1,7
	6	+2,9	+2,7	+1,6	+2,4	+2,0	+2,1	+1,4	+1,7
	7	+2,7	+2,5	+1,5	+2,2	+2,1	+2,2	+1,4	+1,8
	8	+2,7	+2,5	+1,8	+2,3	+2,0	+1,9	+1,3	+1,7
	9	+2,9	+2,7	+2,0	+2,4	+1,9	+1,8	+1,6	+2,0
	10	+1,9	+2,8	+2,4	+2,4	+1,9	+1,8	+1,6	+2,4
	11	+1,9	+1,8	+1,4	+1,6	+1,9	+1,8	+1,6	+1,7
	12	+2,0	+1,8	+1,5	+1,6	+1,9	+1,7	+1,3	+1,5

Table 2. Simulated sugarcane yield (t dry matter/ha) for four scenarios of IPCC (A1BAIM, A2MES, B1MES and B2MES) in the projections for the years 2050 and 2070, in Piracicaba (Brazil) and two CO_2 concentrations.

IPPC Scenario	CO_2	Simulated yield t/ha	
	ppmv	2050	2070
A1	370	70,98	72,83
	720	72,71	74,80
A2	370	70,34	70,75
	720	72,08	74,20
B1	370	70,67	70,78
	720	72,81	76,30
B2	370	70,51	70,92
	720	72,51	75,80

Figures

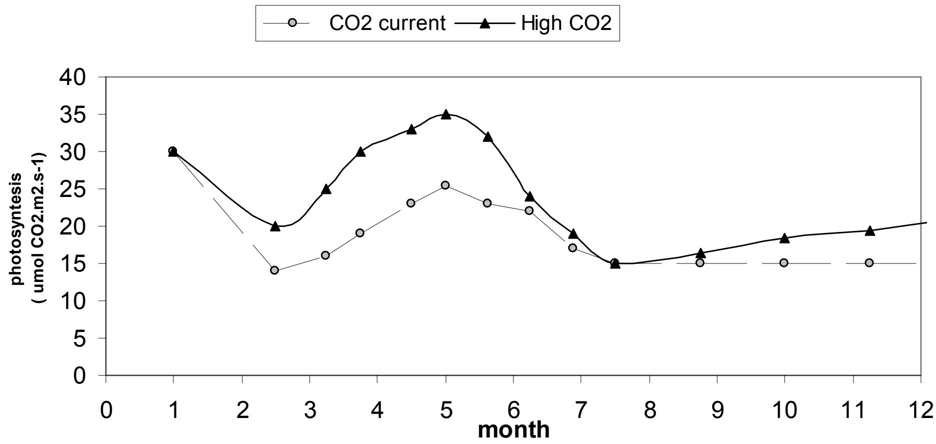

Fig. 1. Net photosynthesis (µmol CO_2 m^{-2} s^{-1}) of sugarcane grown in current CO_2 (370 ppmv) and high CO_2 (720 ppmv) field chambers (adaptation of Souza, 2007).

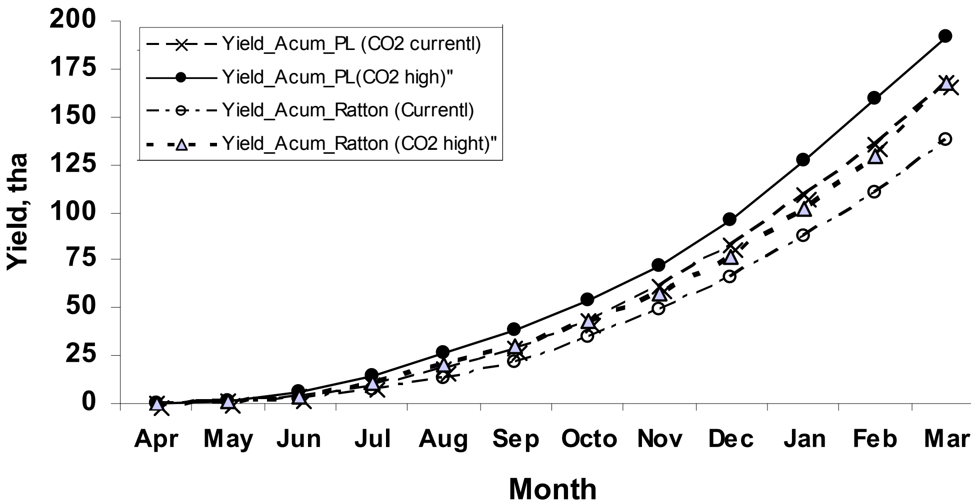

Fig. 2. Sugarcane accumulated plant yield (PL) and ratoon (Ratton) (t/ha) over the crop cycle, under current and elevated CO_2 concentrations.