SHORT NON-REFEREED PAPER

SIMULATED IMPACTS OF CLIMATE CHANGE ON WATER USE AND YIELD OF IRRIGATED SUGARCANE IN SOUTH AFRICA

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Abstract

Reliable predictions of climate change impacts on water use, irrigation requirements and yields of irrigated sugarcane are necessary to plan adaptation strategies. The objective of this study was to evaluate a methodology for this by using the DSSAT-Canegro sugarcane model to simulate growth and development of sugarcane crops under typical management conditions at Malelane, Pongola and La Mercy for current (‘baseline’, 1980-2010) and future (2070-2100) climate scenarios. Future climate datasets were generated from three Global Climate Models (GCMs) assuming atmospheric CO_2 concentration [CO_2] of 734 ppm. GCM choice was based on the range of uncertainty of projected future rainfall at La Mercy (-11, +3 and +14%). The study found that irrigated yields are expected to increase at all three sites (15% at La Mercy, 10% at Pongola and 7% at Malelane), due to (i) increased interception of radiation due to accelerated canopy development and (ii) the direct [CO_2] fertilisation effect on photosynthesis. Evapotranspiration increased by 6% due to increased canopy cover and evaporative demand, while irrigation requirements increased by ≈12%. Irrigation water use efficiency (*IWUE*, the increase in yield per unit irrigation applied) decreased by 6%, 11% and 12% at La Mercy, Pongola and Malelane, respectively. These results suggest that, at all sites, (i) economic returns on investment in irrigation could decline because of reduced *IWUE*; and (ii) increased irrigation capacity will be needed to achieve the increased yield potential of future irrigated sugarcane. For future climate impact studies it is recommended that high-temperature sensitivity of model processes be investigated further, and alternative GCM downscaling methods, which allow perturbations to the distribution (as well as amount) of rainfall, be explored.

Keywords: climate change, model, cane yield, irrigation requirement, water use

Introduction

Reliable predictions and an understanding of climate change impacts on water use, irrigation requirements and yields of irrigated sugarcane are necessary to plan adaptation strategies.

Knox *et al.* (2010) used the DSSAT-Canegro model to predict that expected climate change in the 2050s could increase sugarcane irrigation requirements in Swaziland by +9%, and sucrose yields by about 15%. Rainfed sugarcane yield increases of 15 to 40 t/ha to intermediate future (2050s) climate were also reported by Schulze and Kunz (2010) for South Africa. Marin *et al.* (2012) reported a 24% increase in rainfed sugarcane yields, and a 34% increase in water use efficiency in south-eastern Brazil (2100s). Singels *et al.* (2013) reported increases in future (2100s) crop water use of 1-8%, and cane yield increases of 4-20% for sites in SA, Australia and Brazil (2100s), while sucrose yield responses varied widely (between -33% and +13%).

The Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig *et al.*, 2012) aims to characterise the impacts of climate change on food production and risk of hunger, globally, and for all crops. AgMIP regional climate change impact assessments integrate sets (ensembles) of climate, crop and economic simulation models, at different time-scales and under different emissions scenarios. The model ensemble approach allows for a better appreciation of the uncertainty associated with projections.

The objectives of the this study were to use a subset of the AgMIP protocols to estimate likely impacts of climate change on sugarcane yields, water use and irrigation demand at three irrigated sugarcane production sites in South Africa and to assess the suitability of the methodology of linking climate and crop models for such investigations.

Methodology

The DSSAT-Canegro (v4.5) sugarcane model (Singels *et al.*, 2008) was used to simulate growth and development of sugarcane crops under typical management conditions at Malelane, Pongola and La Mercy for current (baseline, 1980-2010) and future (2070-2100) climate scenarios. The model simulates elevated atmospheric CO_2 concentration $[CO_2]$ impacts on photosynthesis and transpiration, as well as temperature effects on photosynthesis, respiration, biomass partitioning and crop phenological development. The model was previously calibrated for sites in South Africa, Zimbabwe, Brazil, Australia and Thailand (Singels *et al.*, 2010). Site details and cropping scenarios assumed for each site are summarised in Table 1. Overhead sprinkler irrigation was simulated, with 40 mm applied whenever the soil water content of the topsoil decreased below 60% of capacity. Cultivar parameters for NCo376 were used throughout.

Water use efficiency (*WUE*, t/ha/mm) was calculated as the cane yield (t/ha) accrued per unit of water used by the crop (*ET*, mm/d)The water-use efficiency of irrigation water (*IWUE*, t/ha/100 mm) was defined as the increase in cane yield per unit irrigation applied (V_{irr}, 100 mm):

$$IWUE = \frac{Y_{Irrigated} - Y_{Rainfed}}{V_{irr}}$$

where $Y_{irrigated}$ (t/ha) is simulated yield under irrigation, and $Y_{rainfed}$ (t/ha) is simulated non-irrigated yield. Both rainfed and irrigated scenarios were simulated at each site in order to calculate these values.

The baseline scenario consisted of a 31-year time series of historical daily weather records (1980-2010), with $[CO_2]$ set at 360 ppm. Future climate scenarios were derived from three GCMs from the Coupled Model Intercomparison Project Phase 3 (Meehl *et al.*, 2007) for the end-of-century (2070-2100) A2 greenhouse gas emission scenario (Nakićenović *et al.*, 2000) and $[CO_2]$ set at 734 ppm. The three GCMs were chosen (out of a set of 19) to represent the uncertainty in projected rainfall changes at La Mercy (-11, +3 and +14%) (see Table 1). Scenarios were generated using the Delta method (Wilby *et al.*, 2004; Ramirez-Villegas and Jarvis, 2010), whereby the observed daily time series was adjusted to impose monthly temperature changes (difference between a GCM's future and baseline period) and percentage changes in rainfall.

Table 1. Cropping details, baseline and future (average of three Global Circulation Model estimates) long-term annual rainfall, maximum daily air temperature (TMAX), minimum daily air temperature (TMIN), and simulated average daily canopy cover (fractional interception of photosynthetically-active radiation), cumulative seasonal evapotranspiration (ET), cumulative seasonal irrigation demand, cane and sucrose yield for the three sites studied. Italicised values in parentheses show standard deviation of GCM-estimated average values.

Site	La Mercy		Pongola		Malelane	
Climate scenario	**Baseline**	**Future**	**Baseline**	**Future**	**Baseline**	**Future**
Coordinates and altitude	29°34'30" S; 31°08'45" E (72 m)		27°24'50" S; 31°35'35" E (308 m)		25°28'36" S; 31°32'08" E (301 m)	
Weather station	Tongaat-Klipfontein		Pongola		Malelane-Mhlati	
Rainfall (mm)	998	1023 *(102.5)*	707	683 *(32.6)*	559	520 *(12.4)*
TMAX (°C)	25.6	28.8 *(0.47)*	27.4	30.9 *(0.68)*	29.3	33.0 *(0.81)*
TMIN (°C)	15.4	18.6	15.5	19.0	15.4	19.1
Crop start dates	1 Apr, 1 Oct	1 Apr, 1 Oct	1 Apr, 1 Oct	1 Apr, 1 Oct	1 Apr, 1 Oct	1 Apr, 1 Oct
Age at harvest (months)	12	12	12	12	12	12
Row-spacing (m)	1.2	1.2	1.4	1.4	1.4	1.4
Days to 80% canopy (d)	119.2	78.4 (3.44)	106.0	71.3 (4.33)	96.8	66.9 (3.79)
Canopy cover (%)	74.4	82.5 *(0.68)*	77.1	84.0 *(0.83)*	79.1	84.9 *(0.71)*
ET (mm)	1082	1146 *(19.6)*	1267	1348 *(27.4)*	1371	1462 *(34.0)*
Irrigation demand (mm)	417	474 *(24.2)*	737	830 *(12.2)*	934	1057 *(32.6)*
Cane yield (t/ha)	110.6	126.7 *(1.39)*	120.1	132.4 *(1.50)*	125.8	134.7 *(1.54)*
Sucrose yield (t/ha)	13.9	14.2 *(0.17)*	14.9	14.3 *(0.36)*	15.4	13.6 *(0.36)*
IWUE (t/ha/100 mm)	7.7	7.2 *(0.91)*	9.1	8.1 *(0.59)*	9.0	7.9 *(0.51)*

Results

Under the projected future climate scenarios, rainfall increased on average by 2% at La Mercy, but decreased by 7% at Malelane and by 3% at Pongola. However, there was considerable variation in rainfall between GCM projections, particularly at La Mercy (CV%=10.0) and to a lesser extent at Pongola (CV%=4.77) and Malelane (CV%=2.38). Future average temperatures increased by between 3.2°C (La Mercy) and 3.7°C (Malelane), with little variation between GCM projections (Table 1).

Results presented in Table 1 suggest that irrigated cane yields are expected to increase at all three sites (15% at La Mercy, 10% at Pongola and 7% at Malelane), due to (i) increased interception of radiation from accelerated canopy development (as a result of higher future temperatures) and (ii) the direct CO_2 fertilisation effect on photosynthesis (see Figure 1). Evapotranspiration increased by approximately 6% due to increased canopy cover and evaporative demand, despite the inhibiting effect on transpiration of elevated [CO_2]. As the crop canopies developed faster in future scenarios, relatively less soil moisture was lost to non-productive soil surface evaporation. This, combined with elevated [CO_2] effects on transpiration and photosynthesis, improved overall *WUE*. The combination of the larger canopy and increased *ET* meant that irrigation requirements increased by about 12% at all sites. *IWUE* decreased by 6%, 11% and 12% respectively at La Mercy, Pongola and Malelane.

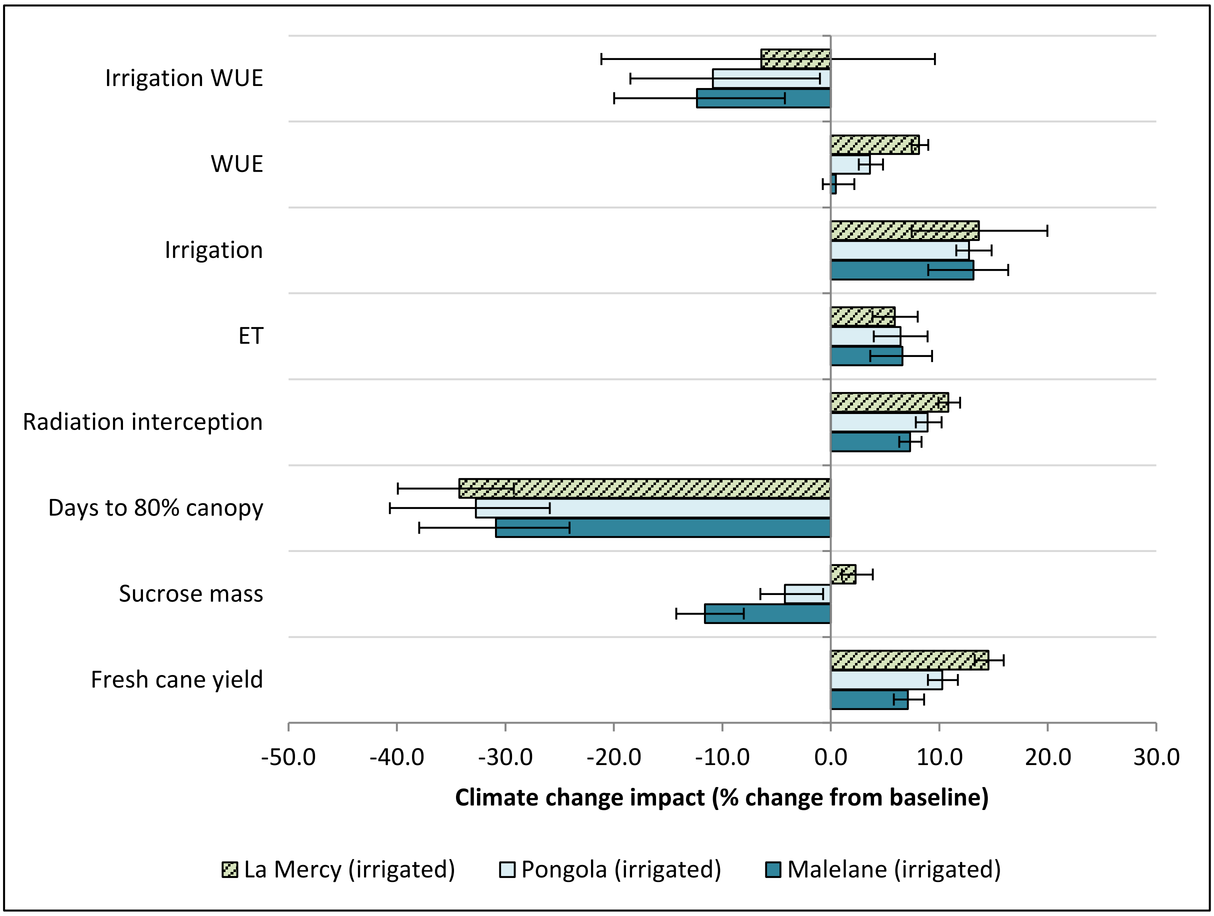

Figure 1. The average climate change impact (difference in long term mean values of various model output variables between future scenarios and the baseline scenario) predicted for the three sites. The error bars show the range of impacts predicted using the different climate scenarios projected by the three climate models.

Season-to-season variation in simulated cane yields decreased in future scenarios compared with the baseline. The coefficient of variation of simulated cane yields decreased from 5.26% to 3.53% at Malelane, from 7.45% to 4.84% at Pongola, and from 9.76% (baseline) to 7.62% at La Mercy.

The magnitude of future cane yield increases decreased with increased current climatic potential as determined by latitude (see Table 1). This is caused primarily by the greater response in canopy develop rate to future temperature increases when current temperatures are at or below the assumed base temperature of 16°C, below which plant development ceases. The future climate scenario significantly reduced the number of days below 16°C at La Mercy, while Pongola and Malelane have very few days in the baseline climate that have daily mean temperatures below 16°C. The physiological impact of the reduction in the number of future days below 16°C was greater for crops started in April than October in the La Mercy simulations. This resulted in faster canopy development in the April crops compared with October crops in future.

Sucrose yields increased at La Mercy but decreased at the warmer, more northerly sites (Figure 1). This ascribed to the larger crop biomass and higher temperatures for Pongola and Malelane resulting in relatively larger maintenance respiration (R_m) burdens with less photo-assimilate available for sucrose accumulation. The increased R_m effect was strongest at Malelane (the warmest site) and had the least impact at La Mercy (the coolest site).

Although not directly comparable, the findings of increased cane yields and irrigation requirements in future are consistent with the findings of Knox *et al.* (2010), Schulze and Kunz (2010) and Jones *et al.* (2012), while the impacts on sucrose yields are less certain.

The study by Singels *et al.* (2013) highlighted possible shortcomings in the methodology that apply here as well. A weakness of the climate data used was the assumption of no change in rainfall distribution, solar radiation and relative humidity – variables that are crucial in determining the water status of rainfed sugarcane and irrigation requirements. Crop model aspects that need refinement include simulation of (i) elevated [CO_2] effects on crop photosynthesis and transpiration, and (ii) high temperature effects on crop development, photosynthesis and respiration.

Conclusions

This simulation study suggests that canopy development of future crops is likely to be much more rapid than current crops, due to elevated temperatures, especially for autumn crops. The quicker canopy development led to increased interception of radiation and increased transpiration. As a result, cane yields are expected to increase, provided that increased irrigation requirements can be met. Sucrose yields are expected to decrease because of the additional consumption of photo-assimilate by increased rates of maintenance respiration, particularly in currently warmer regions. Increased irrigation demand will require increased capacity to store and convey water to fields.

The study also suggests that climate change impacts are likely to be more favourable for lower-potential areas such as La Mercy, compared to higher-potential areas such as Malelane.

Future work

Future work includes: (i) crop model refinement to improve simulation of [CO_2] and high temperature impacts; (ii) extending the methodology described in this short paper to use projections from a larger number of GCMs, at additional sugarcane producing sites in southern Africa; (iii) investigating crop management approaches and variety traits to maximise yields under future climatic conditions; and (iv) comparing responses of different sugarcane crop models to future environments at sites in South Africa, Australia, Zimbabwe, Reunion and the USA.

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