SHORT NON-REFEREED PAPER

A PRELIMINARY ASSESSMENT OF MID-CENTURY CLIMATE CHANGE IMPACTS ON SUGARCANE PRODUCTION IN SOUTH AFRICA

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Abstract

Previous studies mostly report positive impacts of climate change on sugarcane yields in South Africa (SA). Predictions vary considerably, however, and the limitations in methodologies and assumptions in these studies make it difficult to quantify impacts reliably at regional and industry scales.

The objective of this study was to provide a robust indication of climate change impacts on the SA sugar industry for the period 2040-2070 under a likely emissions scenario (571 ppm atmospheric CO_2), using methods based on the Agricultural Model Intercomparison and Improvement Project (AgMIP) protocol. Daily weather records for baseline (1980-2010) and future periods were prepared for 47 homogenous climate zones (HCZs) covering the SA sugarcane-growing regions. Future weather data were derived from five global climate models (GCMs). The DSSAT-Canegro model, modified with improved capability for simulating sugarcane growth under high temperatures and elevated CO_2, was used to simulate baseline and future cane and sucrose yields, using baseline crop management (but assuming no restrictions in irrigation supplies), at each HCZ.

GCM-averaged air temperature changes ranged from 0.66 to 1.02°C, while changes in annual rainfall ranged from -4 to +1%, depending on HCZ. Rainfall predictions were more uncertain than temperature predictions, with the standard deviation of predictions ranging from 1.11 to 5.24% for rainfall and from 1.08 to 3.80% for thermal time (a measure of effective temperature), depending on HCZ. GCM-averaged simulated cane yields per HCZ changed by between -3.0 and +15.5% (+7.1% on average) while sucrose yields changed by between -5.9 and +21.9% (+8.1% on average). Results indicate future increases in annual sugar production of between 127 000 and 202 000 t (average ≈159 500 t) from the 2009-2013 average of 2 024 000 t, provided that field management quality (including current pest and disease severity levels), area under cane and irrigation supplies are maintained.

Keywords: temperature, rainfall, modelling, simulation, Canegro, greenhouse gas

Introduction

Previous studies (Schulze and Kunz, 2010; Knox *et al.*, 2010; Jones *et al.*, 2013) mostly report positive impacts of climate change on sugarcane yields in South Africa (SA). Predictions vary considerably, however, and the limitations in methodologies and assumptions in these studies make it difficult to quantify impacts reliably at regional and industry scales.

The objective of this study was to provide a robust indication of climate change impacts on the SA sugar industry for the period 2040-2070, using methods based on the Agricultural Model Intercomparison and Improvement Project (AgMIP,) protocol (Rosenzweig *et al.*, 2012).

Methods

Baseline and future weather data

Daily weather records for baseline (1980-2010) and future (2040-2070) periods were prepared for 47 homogenous climate zones (HCZs, Bezuidenhout and Singels, 2007a) covering the SA sugarcane-growing regions. HCZ 40 was omitted as the baseline weather data were insufficient. Future monthly climate data were derived from five global climate models (GCMs) from the CMIP5 (World Climate Research Programme, 2011) ensemble – CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5 and MPI-ESM-MR (‘RCP 8.5’ emissions scenario, atmospheric CO_2 = 571 ppm). Five future daily weather datasets of 30 years each were generated for each HCZ by perturbing baseline daily temperature and rainfall data with monthly mean changes in temperature and mean monthly relative rainfall amount projected by each GCM, the so-called ‘Delta’ downscaling method (Wilby *et al.*, 2004), using AgMIP climate tools (Hudson and Ruane, 2013). This method preserves the observed daily temporal variability in air temperature and rainfall, while correcting monthly rainfall and average temperatures according to the GCM projections.

The uncertainty of GCM climate predictions was quantified by calculating the standard deviation of the predicted change in annual rainfall and thermal time (base 10°C) totals, expressed as a percentage of the baseline total. Thermal time is a measure of effective temperature integrated over time.

Crop modelling

The DSSAT-Canegro v4.5 model (Singels *et al.*, 2008), modified with improved capability for simulating sugarcane growth under high temperatures and elevated CO_2 (Singels *et al.*, 2013), was used to simulate baseline and future cane and sucrose yields, using baseline crop management configuration as described and used in the SASRI Sugarcane Crop Forecasting system (Bezuidenhout and Singels, 2007a, 2007b) as at December 2013. Sufficient irrigation water supplies were assumed for baseline and future periods. Thirty seasons (1980-2010) were simulated for each HCZ and weather dataset (i.e. baseline and five GCM datasets).

Data analysis

Final simulated yields were averaged by HCZ, irrigation status and weather dataset (baseline and five GCMs (individually and aggregated)). Yield, rainfall and thermal time changes were expressed as percentage of the baseline value (*RC, %*):

$$RC = \left(\frac{Value_{future} - Value_{baseline}}{Value_{baseline}} * 100\right) \qquad \text{Equation 1}$$

where $Value_{future}$ is a future value (e.g. average cane yield over 30 years for one HCZ simulated using one GCM-derived weather dataset, or average annual rainfall or thermal time projected by one GCM for one HCZ) and $Value_{baseline}$ is the corresponding value simulated for the baseline period.

Variability in rainfall and thermal time projections between GCMs was calculated as the standard deviation (σ) of *RC* values calculated for each GCM.

Results and Discussion

Future climate

GCM-averaged air temperature changes ranged from 0.66 to 1.02°C (**Table *1***), while relative changes in annual rainfall were small (-4% to +1%). The standard deviation (σ) of future rainfall ranged from 1.11 to 5.24%, with southerly/coastal HCZs (24-48) showing substantially lower variability ($\sigma \approx 1.80$) than northerly/inland HCZs (1-10, $\sigma \approx 4.79$). The σ values for thermal time totals ranged from 1.08 to 3.80%, suggesting relatively greater agreement between GCMs predictions of future temperature than for rainfall.

Indicative future yields relative to baseline yields

Table 1 shows average rainfall, thermal time and yield changes (*RC*) expected for each HCZ of simulated future cane and sucrose yields (using five GCMs), relative to baseline. Simulated cane yields increased in all but one HCZ (14, Mzondeni Strip). The decrease in HCZ 14 is explained by increased water stress (arising from 2.2% higher evapotranspiration, 2.8% lower rainfall, and slightly faster canopy development drying-out the soil earlier in the season), but is partially offset by 1.1% higher radiation use efficiency (from higher temperatures) and earlier partitioning to stalk fibre. Simulated sucrose yields decreased in three HCZs (Mzondeni Strip¸ Mtubatuba (13) and Amatikulu (25)). Cane yield increases are attributed to (a) accelerated plant development rates and photosynthesis rates due to increased temperatures, particularly in irrigated regions; and (b) increased water use efficiency, particularly in dryland areas, as a result of reduced stomatal conductance (and transpiration) due to elevated atmospheric CO_2 content. Sucrose yields increased with cane yields, and with increased sucrose content in currently cooler regions (South Coast and Midlands regions). Sucrose content did not change in the northern irrigated regions, and decreased in dryland HCZs on the North Coast and in Zululand.

Simulated yield variation between GCMs was higher in dryland HCZs compared with irrigated HCZs due to variability in rainfall predictions. Increases in rainfed cane and sucrose yields are more certain in the South Coast, Midlands and lower North Coast regions, with greater uncertainty in rainfed yield changes indicated in the upper North Coast and Zululand regions. Cane and sucrose yields increased in all irrigated regions, with relatively greater increases in currently cooler areas – the Midlands and South Coast areas, for example – as the future temperature increases in these areas were greater relative to baseline average temperatures, compared with currently warmer areas, e.g. Mpumalanga.

Across the industry, results suggest that cane yields could increase by between +5.16 and +8.19%, corresponding to climate projections by the MPI-ESM-MR and GFDL-ESM2M models respectively, and by 6.92 % on average. This translates to an average increase in cane production of 1 218 500 t/annum, ranging between +908 000 and +1 442 000 t/annum, based on average industry cane production 2008/09-2012/13 of 17 601 000 t/annum, and assuming no changes to area under cane, irrigation supplies or severity of pest and disease impacts. Industry average sucrose yields also increased, by between +6.28 and +9.97% (average: 7.87%) compared with baseline, indicating an increase in sucrose production of 127 000 to 202 000 t/annum (average 159 500 t/annum), again assuming no other changes to the production system.

Caveats and future work
Impacts on yields of potential shifts in rainfall patterns (more intense rainfall with longer dry spells) and possibly reduced irrigation water supplies were not considered in this study. Changing environments also expose the SA sugar industry to elevated risks of existing and new pests and diseases.

The uncertainty of the climate change impact estimates on yield could be reduced by including additional climate model projections, additional climate data downscaling methods, and additional sugarcane crop growth simulation models. Sugarcane crop responses to hot and dry climates are not yet fully understood, and research progress in this area will increase the reliability of climate change impact projections.

Conclusion

The results of this study support the view that medium-term (moderate) climate change could be largely positive for the SA sugar industry, purely in terms of crop yield response to climate. Simulated yield increases in rainfed regions are attributed to increased water use efficiency induced by elevated atmospheric CO_2 content, while in both irrigated and rainfed regions increased temperatures allowed faster plant development and increased radiation use efficiency. Projected cane yield increases of between 5.16 and 8.19%, and sucrose yield increases of 6.28-9.97%, suggest that future cane and sucrose production have the potential to increase, on average, by 1 218 500 and 159 500 t/annum respectively, assuming no changes to area under cane and severity of pests and disease impacts, and no shortages of irrigation water. These favourable indicative yield responses, combined with appropriate adaptation strategies (better-adapted varieties, agronomic management approaches and use of appropriate technologies), have the potential to offset possible negative consequences of climate change impacts on other aspects of the sugarcane production system.

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Table 1. Summary of climate changes (annual rainfall and thermal time base 10°C) and the impacts of climate change on sugarcane and sucrose yields for each homogenous climate zone and production region in the South African sugar industry.

HCZ number and name (irrigation status)	Pro-duction region*	Thermal time (effective temperature)		Annual rainfall		Cane yield (t/ha)		Cane yield change (%)			Sucrose yield (t/ha)		Sucrose yield change (%)		
		Avg. future change%	Std dev. future change%	Avg. future change%	Std dev. future change%	Base-line	Avg. future	Min	Max	Avg.	Base-line	Avg. future	Min	Max	Avg.
1: Komati (I)	NI	6.27	1.89	1.62	4.98	*90.6*	*97.5*	5.68	8.64	7.60	*10.8*	*11.6*	5.97	8.81	7.27
2: Nelspruit (I)	NI	6.58	1.98	1.28	4.57	*97.2*	*105.3*	6.11	9.62	8.26	*12.0*	*13.0*	6.55	9.80	8.31
3: Hectorspruit (I)	NI	6.41	1.94	1.47	4.76	*92.0*	*99.4*	5.96	9.27	8.03	*11.1*	*12.0*	6.45	9.49	7.97
4: Malelane / Kaapmuiden (I)	NI	6.41	1.94	1.47	4.76	*92.0*	*99.4*	5.96	9.28	8.03	*11.1*	*12.0*	6.46	9.48	7.98
5: Louws Creek (I)	NI	6.43	1.94	1.20	4.58	*91.7*	*99.1*	6.02	9.32	8.06	*11.1*	*12.0*	6.47	9.57	8.02
6: Kaalrug / Inala (I)	NI	6.43	1.94	1.17	4.72	*92.3*	*99.4*	5.88	8.80	7.70	*11.2*	*12.0*	6.35	8.91	7.54
7: Barberton (I)	NI	6.57	1.98	1.28	4.76	*96.3*	*104.2*	6.12	9.48	8.20	*11.9*	*12.8*	6.64	9.73	8.25
8: Komati projects (I)	NI	6.27	1.89	1.35	4.93	*90.6*	*97.4*	5.67	8.66	7.56	*10.8*	*11.6*	6.09	8.66	7.19
9: Makatini Flats (I)	ZL	6.37	1.91	-0.84	5.24	*96.2*	*103.3*	5.82	8.10	7.30	*11.6*	*12.4*	6.15	8.39	7.01
10: Pongola (I)	NI	7.13	2.04	-0.52	4.58	*84.6*	*92.6*	7.47	10.96	9.45	*10.1*	*11.2*	8.71	11.92	10.46
11: Mkuzi (I)	ZL	7.07	2.02	-0.51	4.62	*86.6*	*94.7*	7.18	11.02	9.33	*10.4*	*11.5*	8.55	11.67	10.26
12: Hluhluwe (I)	ZL	6.39	2.28	-2.94	3.58	*86.0*	*92.9*	6.52	9.33	7.92	*10.2*	*10.9*	6.92	8.91	7.76
13: Mtubatuba (I)	ZL	5.76	2.21	-2.80	3.57	*88.6*	*95.2*	5.96	8.93	7.38	*10.4*	*11.2*	6.77	8.53	7.58
13: Mtubatuba (D)	ZL	5.76	2.21	-2.80	3.57	*47.8*	*47.8*	-4.86	6.48	-0.01	*4.2*	*4.2*	-9.23	8.41	-0.96
14: Mzondeni strip (D)	ZL	5.76	2.21	-2.79	3.57	*65.1*	*63.1*	-7.64	4.67	-3.00	*6.7*	*6.3*	-14.80	4.67	-5.86
15: Umfolozi flood plains (D)	ZL	5.86	2.25	-2.90	3.66	*67.9*	*69.4*	-2.48	6.22	2.28	*7.7*	*7.9*	-3.22	8.26	2.64
15: Umfolozi flood plains (I)	ZL	5.86	2.25	-2.90	3.66	*88.9*	*95.4*	5.70	9.16	7.35	*10.6*	*11.5*	7.15	8.86	8.08
16: Melmoth mistbelt (D)	ZL	7.55	2.60	-2.16	2.41	*88.5*	*91.0*	-0.11	4.30	2.84	*11.0*	*11.2*	-1.28	4.64	1.97
17: Melmoth hinterland (D)	ZL	7.55	2.60	-2.16	2.41	*85.1*	*87.7*	-0.32	4.71	3.05	*10.4*	*10.6*	-1.18	5.15	2.34
18: Heatonville (D)	ZL	6.14	2.11	-2.34	2.47	*62.6*	*64.5*	1.12	5.11	2.99	*6.5*	*6.7*	-1.26	6.30	2.64
18: Heatonville (I)	ZL	6.14	2.11	-2.34	2.47	*95.9*	*103.1*	6.69	9.02	7.54	*11.7*	*12.5*	6.71	8.32	7.37

HCZ number and name (irrigation status)	Pro-duction region*	Thermal time (effective temperature)		Annual rainfall		Cane yield (t/ha)		Cane yield change (%)			Sucrose yield (t/ha)		Sucrose yield change (%)		
		Avg. future change%	Std dev. future change%	Avg. future change%	Std dev. future change%	Base-line	Avg. future	Min	Max	Avg.	Base-line	Avg. future	Min	Max	Avg.
19: Empangeni (I)	ZL	5.99	2.30	-2.85	3.73	*84.6*	*91.5*	6.55	10.11	8.12	*9.9*	*10.7*	7.57	9.53	8.51
19: Empangeni (D)	ZL	5.99	2.30	-2.85	3.73	*65.4*	*66.7*	-3.51	5.44	1.93	*7.0*	*7.1*	-5.88	6.41	1.21
20: Nkwaleni (I)	ZL	6.14	2.11	-2.33	2.47	*91.8*	*99.1*	7.10	9.69	8.01	*11.0*	*11.8*	7.27	8.89	7.98
21: Entumeni mistbelt (D)	ZL	7.50	2.59	-2.09	2.38	*81.3*	*83.8*	0.96	6.40	3.04	*9.8*	*10.0*	-1.46	7.34	2.75
22: Eshowe hinterland (D)	ZL	7.50	2.59	-2.09	2.38	*68.0*	*71.2*	3.47	7.78	4.74	*7.7*	*8.1*	2.51	10.06	5.68
23: Emoyeni (D)	ZL	6.17	2.12	-2.37	2.44	*55.7*	*58.7*	1.74	9.52	5.39	*5.5*	*5.8*	0.43	11.73	5.45
24: Muden (I)	ML	8.42	2.78	-0.36	1.11	*71.1*	*80.2*	10.26	17.35	12.79	*8.2*	*9.6*	14.26	22.35	16.97
25: Amatikulu (I)	ZL	6.00	2.06	-2.28	2.35	*86.9*	*93.8*	7.06	9.54	7.94	*10.1*	*10.9*	7.27	9.00	8.09
25: Amatikulu (D)	ZL	6.00	2.06	-2.28	2.35	*55.3*	*55.7*	-4.43	6.53	0.65	*5.3*	*5.2*	-10.03	6.85	-1.51
26: Kranskop mistbelt (D)	NC	10.27	3.53	-1.30	2.05	*61.6*	*65.8*	4.05	12.02	6.82	*7.0*	*7.6*	5.58	16.91	9.04
27: Doornkop (D)	NC	6.52	2.46	-1.87	1.99	*58.6*	*60.7*	0.23	7.93	3.58	*6.1*	*6.4*	-0.15	11.01	3.96
28: New Hanover (D)	ML	10.06	3.33	-0.60	1.66	*69.4*	*74.5*	3.06	11.34	7.39	*8.2*	*9.0*	4.00	14.57	9.21
29: Darnall/San Souci/ ShakasKraal (I)	NC	6.29	2.37	-2.03	1.93	*84.7*	*92.6*	7.49	11.94	9.33	*10.1*	*11.1*	9.02	12.00	10.50
29: Darnall/San Souci/ ShakasKraal (D)	NC	6.29	2.37	-2.03	1.93	*55.9*	*58.8*	3.72	8.70	5.30	*5.6*	*5.9*	2.75	10.79	6.11
30: Wartburg / Fawnleas (D)	ML	10.06	3.80	-1.15	1.79	*63.2*	*68.3*	2.92	13.70	8.06	*7.2*	*8.0*	3.51	18.28	10.07
31: Upper Tongaat (D)	NC	6.24	2.48	-1.95	2.12	*54.4*	*56.8*	0.88	8.66	4.42	*5.4*	*5.7*	-0.28	12.19	5.27
32: Windy Hill mistbelt (D)	ML	9.80	3.67	-1.09	1.65	*68.7*	*73.5*	1.36	11.01	7.07	*8.1*	*8.9*	1.86	14.41	9.23
33: Lower north coast (I)	NC	6.67	2.64	-1.99	2.10	*80.9*	*90.4*	9.21	16.21	11.74	*9.7*	*11.2*	11.61	19.02	14.50
33: Lower north coast (D)	NC	6.67	2.64	-1.99	2.10	*51.6*	*55.7*	5.08	10.50	7.94	*5.1*	*5.6*	6.43	14.72	11.00
34: Hilton / Umgeni Valley (I)	ML	8.47	2.76	-0.54	1.33	*64.0*	*73.9*	12.65	21.46	15.48	*7.0*	*8.5*	18.40	29.79	21.94
34: Hilton / Umgeni Valley (D)	ML	8.47	2.76	-0.54	1.33	*72.2*	*77.1*	4.45	8.55	6.82	*8.5*	*9.2*	4.63	11.57	8.15

HCZ number and name (irrigation status)	Pro-duction region*	Thermal time (effective temperature)		Annual rainfall		Cane yield (t/ha)		Cane yield change (%)			Sucrose yield (t/ha)		Sucrose yield change (%)		
		Avg. future change%	Std dev. future change%	Avg. future change%	Std dev. future change%	Base-line	Avg. future	Min	Max	Avg.	Base-line	Avg. future	Min	Max	Avg.
35: Umlaas Road (D)	ML	9.06	2.95	-0.66	1.54	*65.4*	*71.3*	7.33	11.45	9.07	*7.5*	*8.4*	9.30	14.52	11.46
36: Bainsfield (D)	ML	9.13	2.97	-0.57	1.47	*74.4*	*81.2*	7.73	10.79	9.09	*8.9*	*9.9*	9.95	13.48	11.57
37: Tala Valley / Shongweni (D)	NC/ML	9.08	2.95	-0.71	1.60	*62.9*	*69.2*	8.41	12.97	10.09	*7.0*	*8.0*	12.05	17.85	14.00
37: Tala valley / Shongweni (I)	NC/ML	9.08	2.95	-0.71	1.60	*85.7*	*98.4*	12.18	19.80	14.78	*10.6*	*12.6*	15.70	24.62	18.72
38: Eston (D)	ML	9.09	2.95	-0.73	1.55	*64.9*	*70.8*	6.73	10.58	9.16	*7.5*	*8.3*	8.69	13.80	11.55
39: Mid Illovo (D)	ML	8.96	2.91	-0.75	1.64	*82.8*	*87.8*	5.53	6.56	6.00	*10.3*	*11.0*	6.06	8.33	7.27
41: Illovo (D)	SC	7.05	2.60	-1.22	2.16	*51.5*	*56.6*	7.27	11.32	9.80	*5.1*	*5.7*	10.09	15.51	12.83
42: High flats (D)	SC	8.88	2.98	-0.31	1.98	*75.9*	*80.4*	5.28	6.52	5.82	*9.1*	*9.8*	5.82	8.76	7.43
43: Dumisa (D)	SC	7.17	2.40	-0.37	2.00	*67.1*	*70.4*	1.69	8.38	4.95	*7.5*	*7.8*	-2.60	9.28	4.08
44: Sezela (D)	SC	7.15	2.40	-0.40	1.99	*51.2*	*56.9*	10.16	11.86	11.24	*5.1*	*5.9*	13.91	17.44	15.40
45: Umzimkulu coastal/North Bank (D)	SC	5.59	1.08	1.40	1.73	*52.5*	*58.8*	9.05	13.99	12.05	*5.3*	*6.2*	12.93	19.29	16.66
46: Paddock (D)	SC	6.50	1.26	1.34	1.76	*63.2*	*68.0*	4.90	13.47	7.56	*7.1*	*7.8*	5.27	17.16	9.70
47: Hlaku / Nqabeni (D)	SC	6.58	1.28	1.38	1.88	*71.6*	*77.0*	3.92	13.65	7.60	*8.5*	*9.3*	4.41	16.98	9.07
48: Oribi (D)	SC	6.50	1.26	1.35	1.78	*59.7*	*63.7*	2.62	12.87	6.69	*6.6*	*7.1*	2.30	16.28	8.65

*ML: Midlands; NC: North Coast; NI: Northern Irrigated; SC: South Coast; ZL: Zululand

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