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 in South Africa (a water-scarce country) are necessary to plan adaptation strategies. Although previous work has been done in this regard, methodologies and results vary considerably. The objectives were (1) to estimate likely impacts of climate change on sugarcane yields, water use and irrigation demand at three irrigated sugarcane production sites in South Africa (Malelane, Pongola and La Mercy) for current (1980-2010) and future (2070-2100) climate scenarios, using an approach based on the Agricultural Model Intercomparison and Improvement Project (AgMIP) protocols; and (2) to assess the suitability of this methodology for investigating climate change impacts on sugarcane production.

Future climate datasets were generated using the Delta downscaling method and three Global Circulation Models (GCMs) assuming atmospheric CO_2 concentration [CO_2] of 734 ppm (A2 emissions scenario). Yield and water use were simulated using the DSSAT-Canegro v4.5 model.

Irrigated cane yields are expected to increase at all three sites (between 11 and 14%), primarily due to increased interception of radiation as a result of accelerated canopy development. Evapotranspiration and irrigation requirements increased by 11% due to increased canopy cover and evaporative demand. Sucrose yields are expected to decline because of increased consumption of photo-assimilate for structural growth and maintenance respiration. Crop responses in canopy development and yield formation differed markedly between the crop cycles investigated.

Possible agronomic implications of these results include reduced weed control costs due to shortened periods of partial canopy, a need for improved efficiency of irrigation to counter increased demands, and adjustments to ripening and harvest practices to counter decreased cane quality and optimise productivity.

Although the Delta climate data downscaling method is considered robust, accurate and easily-understood, it does not change the future number of rain-days per month. The impacts of this and other climate data simplifications ought to be explored in future work. Shortcomings of the DSSAT-Canegro model include the simulated responses of phenological development, photosynthesis and respiration processes to high temperatures, and the disconnect between simulated biomass accumulation and expansive growth. Proposed methodology refinements should improve the reliability of predicted climate change impacts on sugarcane yield.

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

Highlights

- Climate change is likely to increase sugarcane yields in South Africa by 11%
- Climate change is likely to reduce cane quality and sucrose yields
- Sugarcane irrigation requirement is projected to increase by 11%
- Yield and irrigation changes are driven by accelerated canopy development
- Adaptations could include more efficient irrigation technology, reduced harvest age
- DSSAT-Canegro canopy development responses to climate change require improvement

1. INTRODUCTION

1.1 Background

South Africa is a water-scarce country. Sugarcane (complex hybrid of *Saccharum* spp.) is grown on a 12-month cycle under full irrigation in the northern KwaZulu-Natal and Mpumalanga regions of the South African sugar industry, where annual average rainfall is typically approximately 700 and 500 mm respectively, while atmospheric demand for water in these regions ranges from 1600 to 1800 mm/annum (Inman-Bamber, 1995). Supplementary irrigation is used in parts of the Zululand, North Coast and Midlands regions as well, where annual rainfall is generally just sufficient to sustain economically-viable rainfed sugarcane production (800-1200 mm/annum) on harvest cycles ranging from 12 to 24 months. Approximately 22 % by land area (77 000 ha) of the South African sugar industry is irrigated, but irrigated regions account for approximately 35 % of average total annual sugarcane production (7 million tons of cane). The economic sustainability of the irrigated sugarcane sector is of vital importance to the continued success of the South African sugar industry. Reliable predictions of climate change impacts on water use, irrigation requirements and yields of irrigated sugarcane are of critical importance for planning adaptation strategies.

Knox *et al.* (2010) used the DSSAT-Canegro v3.1 (Jones *et al.*, 2003) model to predict that expected climate change in the 2050s could increase sugarcane irrigation requirements by 21%, and sucrose yields by about 15%, in Swaziland. 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 to 8%, and cane yield increases of 4 to 20% for sites in SA, Australia and Brazil (2100s), while sucrose yield responses varied widely (between -33% and +13%). Schulze and Kunz (2010) reported likely increases in irrigation demand of 10-20% on average across the country for the end-of-century time period, although with considerable spatial variation: some hinterland catchments in the KwaZulu-Natal province in particular indicating either no change or reduced irrigation demand in the order of 0-10%, because of increased projected rainfall. Although these studies give a general indication of likely yield increases and probable increases in water use, there is much heterogeneity in the climate and crop models used as well as the assumptions made (such as whether or not effects of elevated atmospheric carbon dioxide content on the plant are considered). Impacts also vary as a result of soil and climate differences. In many cases single climate models are used, limiting insights into the uncertainty or likelihood of projected climate changes. These factors make it difficult to draw robust conclusions regarding the impacts of climate change on the irrigated sugarcane in South Africa, in terms of yield and irrigation water demand.

A deeper understanding of the impacts of climate change on irrigated sugarcane production in South Africa will facilitate the exploration of possible adaptation strategies for minimising the negative impacts, and maximising the positive aspects, of climate change. Easterling (2011) reports on technological innovation and 'human ingenuity' as key tools in a 'toolkit' for climate change adaptation of socio-agroecological systems. Technological innovation includes plant breeding and genetic diversification, and the conservation of energy, water and soil; the human ingenuity category includes changes to agronomic practices. Several authors have suggested adaptation strategies for irrigated sugarcane production that fall into these categories. Park *et al*. (2010) reported on adaptation of the Australian sugar industry to climate change. Suggested technological and management changes include implementation of improved irrigation water delivery technologies such as drip irrigation, land grading, use of residue layers and irrigation application scheduling; breeding of improved sugarcane varieties with traits for greater drought resistance, water use efficiency and tolerance of high temperatures; and the introduction of improved and more flexible agronomic management strategies including adjustments of crop start dates, choice of varieties, retention of crop residues and more careful management of nutrients and pest and diseases. Nkomo and van der Zaag (2004) for Swaziland and Chandiposha (2013) for Zimbabwe recommend adoption of micro- and drip irrigation, with the latter also recommending use of irrigation scheduling and expansion of irrigation and drainage infrastructure. Chandiposha (2013) speculated that genetic adaptation of varieties (by conventional breeding or genetic modification) to be tolerant of drought, water-logging and salinity, and to have 'self-trashing' traits (i.e. the tendency to detach dead leaves), would be appropriate for future sugarcane production in Zimbabwe. Schulze and Kunz (2010) suggest that age at harvest could be decreased by 3-5 months in the South African sugar industry in the intermediate and more distant future, and also highlight the probable need to breed more heat-tolerant varieties of sugarcane.

The Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig *et al.*, 2013) aims to characterise the impacts of climate change on food production and risk of hunger, globally, and for all crops. AgMIP has developed set of protocols (Rosenzweig *et al.*, 2013) for conducting regional climate change impact assessments that integrate sets (ensembles) of climate, crop and economic simulation models, at different time-scales and under different emissions scenarios. One of the future climate projection downscaling methods described in these protocols is the simple Delta approach, which imposes changes to rainfall amounts and temperature at a monthly resolution. The model ensemble approach allows for a better appreciation of the uncertainty associated with projections.

1.2 Objectives

The objectives of the study were to estimate likely impacts of climate change on sugarcane yields, water use and irrigation demand at three irrigated sugarcane production sites in South Africa, using the DSSAT-Canegro sugarcane model and the Delta climate projection downscaling methodology from the AgMIP protocols; and to assess the strengths and weaknesses of the methodology for simulating climate change impacts on sugarcane.

2. METHODOLOGY

Irrigated and rainfed sugarcane production was simulated at three sites in South Africa (Figure 1) for a 30-year historical baseline period and a future 30-year period using climate projections from three climate models. Model outputs were then analysed and summarised in order to address the objectives of the study.

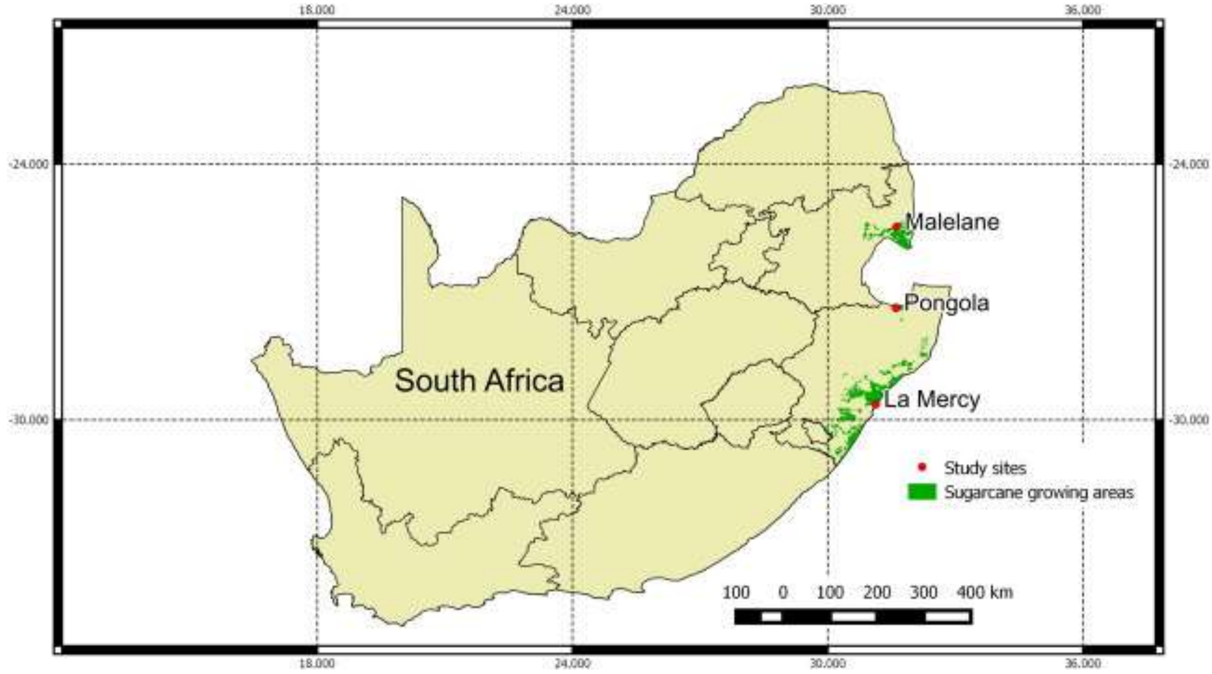

Figure 1. Map showing study sites and sugarcane-growing areas in South Africa.

2.1 Crop model description

Simulations were conducted using the DSSAT-Canegro v4.5 model (Singels *et al.*, 2008), modified to be sensitive to atmospheric CO_2 concentration (*[CO_2]*). The basic operation of the Canegro model is as follows: air temperature and soil moisture availability determine crop timing (germination and emergence, shoot and leaf appearance rates) and leaf and stalk growth rates; fractional interception of photosynthetically-active radiation is calculated from leaf area and drives gross photosynthesis (P_G, t/ha/d); daily net biomass accumulation is simulated as the difference between (1) gross photosynthesis, which is based on a temperature-dependent photosynthetically-active radiation conversion efficiency (i.e. radiation use efficiency (RUE)), and (2) the sum of growth respiration (*Rg* (t/ha/d) and temperature-dependent maintenance respiration (Singels *et al.*, 2005); biomass is partitioned into roots, leaves, stalk non-sucrose and stalk sucrose according to air temperature and soil water availability (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002). The DSSAT-Canegro v4.5 model was previously calibrated for sites in South Africa, Zimbabwe, Brazil, Australia and Thailand (Singels *et al.*, 2010). Validation of the model for 16 crops at two sites in South Africa revealed a root mean squared error (RMSE) of 6.62 t/ha for stalk dry mass and 3.59 t/ha for sucrose mass (Jones, 2013). An earlier stand-alone version of the Canegro model, the predecessor of the DSSAT-Canegro v4.5 model, underwent robust validation using data from 19 treatments from diverse experiments conducted in South Africa, producing RMSEs of 5.5 t/ha for stalk dry mass and 2.6 t/ha for sucrose yield (Singels *et al.*, 2002).

The DSSAT-Canegro v4.5 model was modified to be responsive to *[CO_2]* by reducing transpiration rates with increasing *[CO_2]* (as described by Singels *et al.*, 2013). No direct effect on photosynthesis of *[CO_2]* was simulated. Vu *et al.* (2006), de Souza *et al*. (2008) and Allen *et al.* (2011) found increased photosynthesis rates at elevated *[CO_2]* in pot experiments, but improved crop water status through stomatal response may have contributed significantly to these observed responses. Vu and Allen (2009) found significant increases in leaf area and dry biomass to elevated *[CO2]* for single plants in pots, but no response in leaf level photosynthesis rate. Stokes and Inman-Bamber (2014) also found no significant effect on photosynthesis when crop water status was optimal.

2.2 Site description, climate and model settings

2.2.1 Experimental sites

Three sites in South Africa (SA) were selected for this study (Figure 1). These were: La Mercy (29°34'30" S, 31°08'45" E (72 m a.s.l.)) on the KwaZulu-Natal (KZN) north coast, where supplementary irrigation is sometimes used, and represents a medium-potential cane production environment; Pongola (27°24'50" S, 31°35'35" E (308 m a.s.l.)) on the northern border of the KZN province, where sugarcane is mostly irrigated and represents a medium-high potential production environment; and Malelane (25°28'36"S, 31°32'08" E (301 m

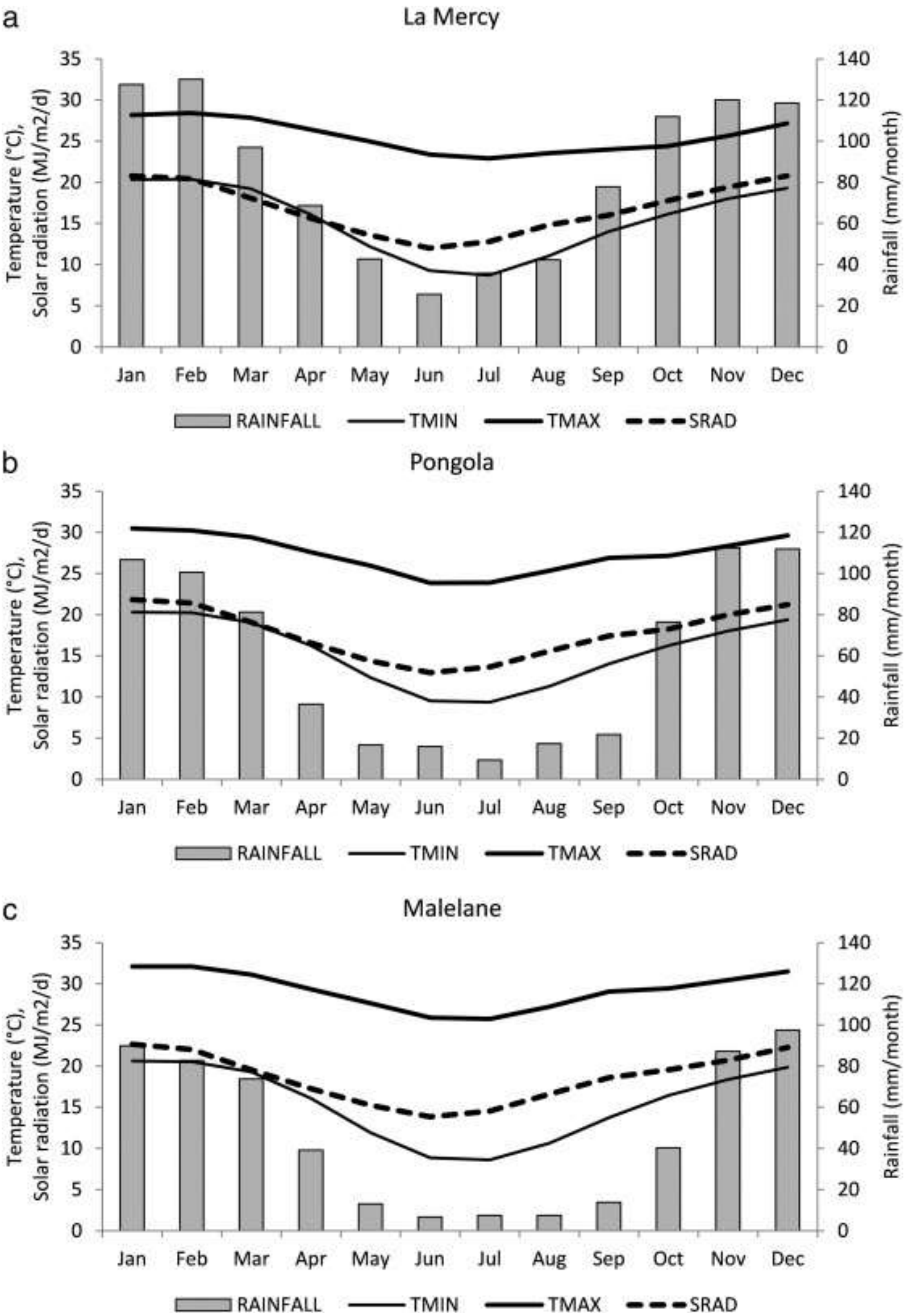

Figure 2. Monthly mean values for maximum daily air temperature (TMAX, °C), minimum daily air temperature (TMIN, °C), daily incident solar radiation (SRAD, MJ/m^2) and mean monthly total rainfall (RAINFALL, mm), 1980-2010, at La Mercy, Pongola and Malelane.

a.s.l.)), in the Mpumalanga province, where production is fully irrigated and is the highest-potential production region in the SA sugar industry. The key climatic descriptors for these sites are illustrated in Figure 2.

2.2.2 Model settings

Site details and cropping scenarios assumed for each site are summarised in Table 1. Overhead sprinkler irrigation was simulated, with 25 mm applied whenever the soil water content of the top 70 cm (i.e. maximum rooted depth) of the soil profile decreased below 60% of plant-available water-holding capacity. Cultivar parameters for NCo376 were used throughout. Although this cultivar is no longer grown widely under irrigation, it has been well researched, and its physiological traits are sufficiently similar to cultivars currently grown in irrigated areas for it to be a suitable cultivar for studies assessing climatic yield potentials. A single hypothetical soil profile (described in Table 2) was used in the simulations for all sites. A single soil facilitates meaningful comparison of climate change impacts between the different sites. The chosen soil is, in terms of water holding capacity, also representative of a large proportion of soils used for irrigated sugarcane production in South Africa. The soil water-holding capacity of the soil will have little effect on most of the results because water demand was adequately met in the simulations. Estimated irrigation demand, however, would depend on soil water-holding capacity. Both fully-irrigated and rainfed production were simulated at each of the sites. Ratoon crops were simulated in all cases.

Table 1. *Cropping details, baseline and future (average of three Global Circulation Model estimates) long-term annual rainfall, average maximum daily air temperature (TMAX), and average minimum daily air temperature (TMIN) for the three sites studied. Italicised values in parentheses show standard deviation of GCM-estimated average values.*

Site detail	La Mercy		Pongola		Malelane	
	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 *(0.47)*	15.5	19.0 *(0.68)*	15.4	19.1 *(0.81)*
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

Table 2. *Physical characteristics of the hypothetical soil used for crop model simulations.*

Characteristic	Value
Albedo	0.13
Runoff curve number	73
Maximum rooting depth (cm)	70
Bulk density (g/cm^3)	1.26
Saturated hydraulic conductivity (cm/h)	1.50
Lower limit of plant-available soil water (cm^3/cm^3)	0.15
Drained upper limit of plant-available soil water (cm^3/cm^3)	0.26
Saturated limit of plant-available soil water (cm^3/cm^3)	0.35
Plant-available soil water-holding capacity (mm)	77

2.3 Weather data

1.1.1 Historical weather data

Daily weather observations for minimum and maximum air temperature (*TMIN* and *TMAX* respectively, °C), incident solar radiation (*SRAD*, MJ m^{-2}), rainfall (*RAINFALL*, mm), wind run (*WIND*, km/d) and maximum and minimum relative humidity (*RHMIN* and *RHMAX* respectively, %), for 31 years (1980-2010), were assembled from weather station records for each site. Data gaps were patched using nearby stations or long-term mean values as necessary, and further corrections and gap-filling were performed using MERRA (Rienecker *et al.*, 2011) reanalysis data. The historical dataset at each site is termed the 'baseline' weather data set. Thirty-one years was chosen as the weather data period as (a) this accommodated the World Meteorological Organisation's recommendation of 30 years as the minimum period required to characterise climate at a site (World Meteorological Organisation, 2007), while also accommodating 30 complete 12-month crops that are started one year and harvested the following year; and (b) longer periods presented practical difficulties in terms of locating reliable weather data. These data are summarised in Figure 2.

1.1.2 Future climate data

Future climate scenarios were derived from three GCMs from the Coupled Model Intercomparison Project Phase 3 (CMIP3, 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 16 available in the AgMIP CMIP3 ensemble set (Hudson and Ruane, 2013)) to represent the uncertainty in projected rainfall changes at La Mercy, where sugarcane production is primarily rainfed. The average increase in annual rainfall for the subset of three chosen GCMs was 3% above baseline, compared with 4% for the entire set. The second highest (14% increase) and second lowest (11% decrease) projections, along with the nearest to neutral projection (3% increase), were selected. These corresponded with the MIROC3 2 MEDRES (K-1 model developers, 2004), MPI ECHAM5 (Jungclaus *et al.*, 2006) and UKMO HADCM3 (Gordon *et al.*, 2000) models. *[CO_2]* was assumed to be 734 ppm for the future scenarios and 360 ppm for the baseline scenario. Thirty crops were simulated for the baseline and future time periods (for each GCM) at each site and each harvest cycle (starting April and October).

1.1.3 Downscaling of future climate data

Future weather datasets were generated using the Delta method (Wilby *et al.*, 2004) whereby the observed (baseline) daily time series was adjusted to impose monthly temperature changes (difference between a GCM's future and baseline period) and percentage changes in rainfall, projected by each GCM. Although there may be more sophisticated methods for downscaling future weather data, the data produced by the Delta method are based on observations that contain local characteristics that are often lost in statistical climate data generation methods. It is also a relatively simple, easily understood method compared to more complicated approaches (for example the bias-corrected spatially disaggregated approach) for which the value added is not always clear. (Ruane *et al.*, 2015)

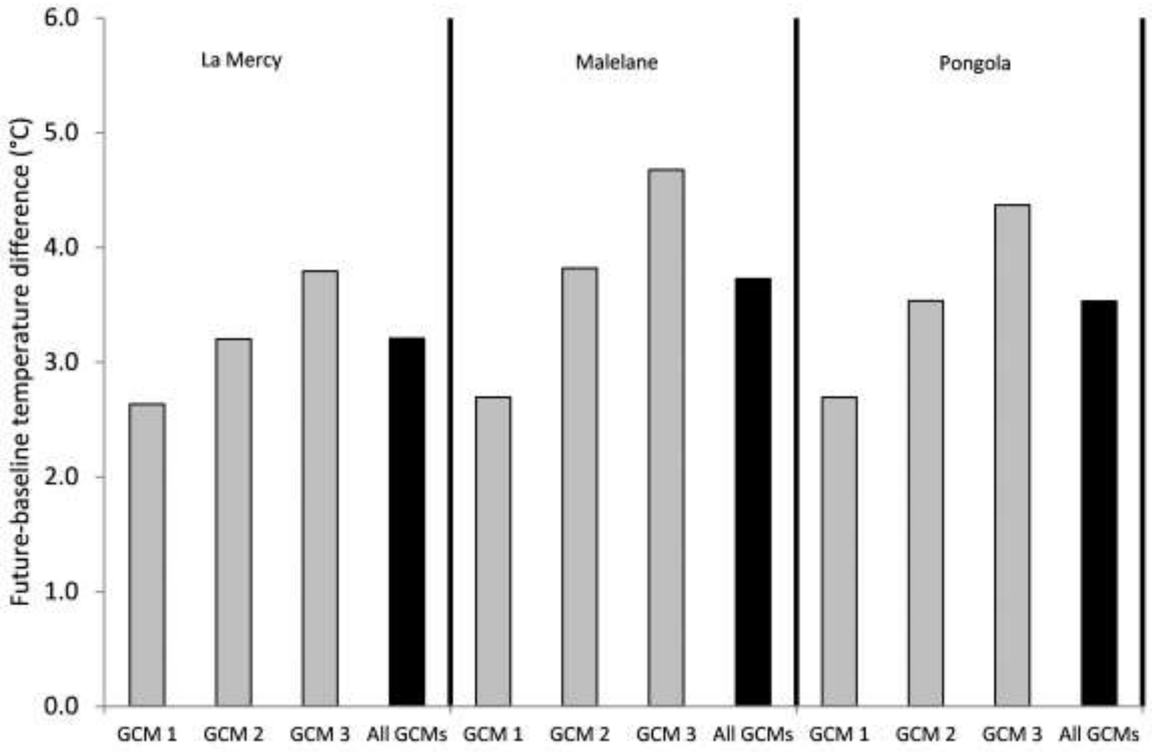

Figure 3. Future:baseline relative rainfall projected by each of the global circulation models (GCMs), for each site. GCMs 1, 2 and 3 refer to the MIROC3 2 MEDRES, MPI ECHAM5, UKMO HADCM3. The average of all GCMs is also shown for each site.

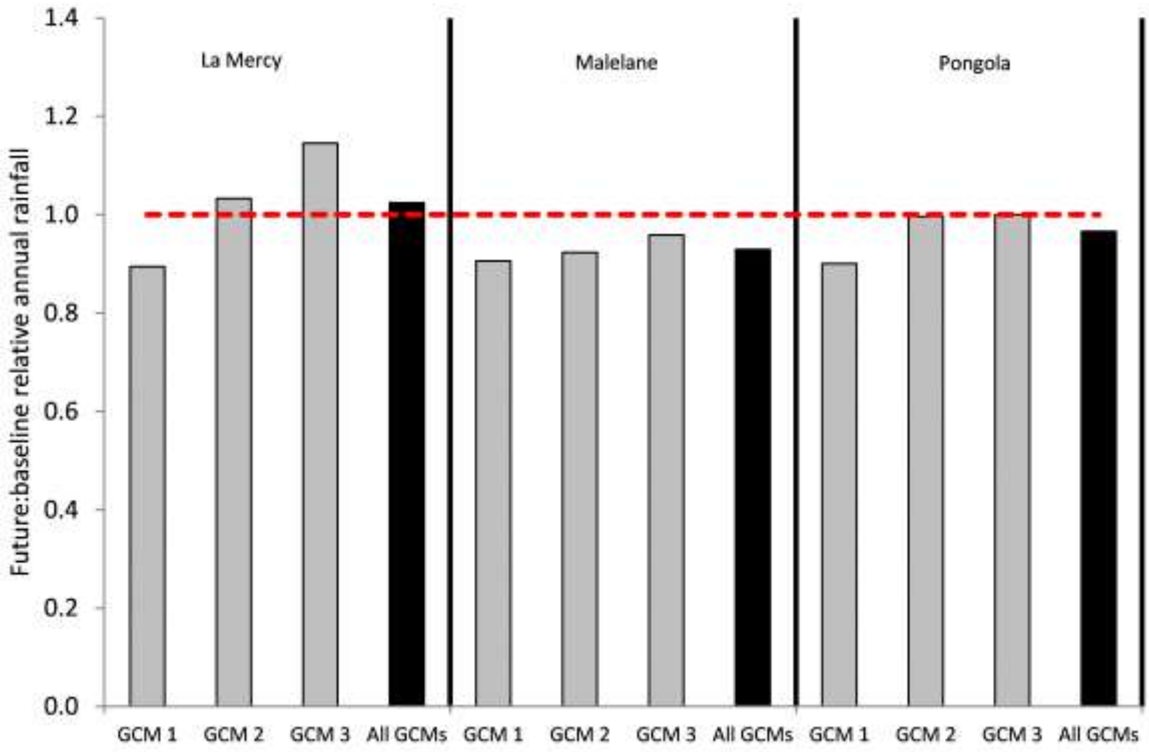

Figure 4. Future-baseline difference in air temperatures projected by each of the global circulation models (GCMs), for each site. GCMs 1, 2 and 3 refer to the MIROC3 2 MEDRES, MPI ECHAM5, UKMO HADCM3. The average of all GCMs is also shown for each site.

2.3.1 Data processing and analysis

Model outputs were aggregated and analysed using custom software implemented in the PHP v5 language and SQL, using a MySQL v5.1 database.

Water use efficiency (*WUE*, t/ha/100mm (equivalent to kg/m^3)) was calculated as the cane yield (t/ha) accrued per unit of water used by the crop (*ET*, 100 mm/d). The water-use efficiency of irrigation water (*IWUE*, t/ha/100 mm (equivalent to kg/m^3)) was defined as the increase in cane yield per unit irrigation applied (V_{irr}, 100 mm):

$$IWUE = \frac{Y_{Irrigated} - Y_{Rainfed}}{V_{irr}} \qquad (1)$$

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.

Long-term means (*LTM*) of several variables per site were calculated by analysing simulation outputs either on a daily basis or at harvest, over 30 seasons for each time period. Long-term future variability per site was calculated as the standard deviation (σ) of long-term average simulated values per GCM (i.e. the standard deviation of three values per site).

Inter-seasonal yield variability was calculated as σ of yield values at harvest over 30 seasons for each site, time period and GCM (i.e. the standard deviation of 30 values per site, time period and GCM).

The coefficient of variation, expressed as a percentage (CV%), was calculated as:

$$CV\% = \frac{\sigma}{LTM} * 100 \qquad (2)$$

3. RESULTS

3.1 Weather data

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% = 10.00) 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).

3.2 Long-term mean impacts of climate change per site

Table 3 summarises baseline and future simulated long term mean values. Figure 5 illustrates the impacts of future climate change, by expressing future simulated values relative to baseline simulated values. Both Table 3 and Figure 5 show variation (uncertainty) in future arising from differences in GCM projections.

Table 3. *Simulated 30-year mean time to 80% canopy cover (fractional interception of photosynthetically-active radiation), time to the start of stalk growth, average daily canopy cover, cumulative seasonal evapotranspiration (ET), cumulative seasonal irrigation demand, cane and sucrose yield at harvest, and irrigation water use efficiency (IWUE) for the three sites studied, for baseline (1980-2010) and future (2070-2100) periods. Values in parentheses show standard deviation of GCM-estimated average values.*

Variable	La Mercy (rainfed)		La Mercy (irrig.)		Pongola		Malelane	
	Baseline	**Future**	**Baseline**	**Future**	**Baseline**	**Future**	**Baseline**	**Future**
Time to 80% canopy cover (d)	178.5	123.3 *(16.81)*	116.1	73.5 *(3.24)*	107.5	76.9 *(4.39)*	97.8	72.1 *(4.07)*
Time to start of stalk growth (d)	133.8	98.7 *(5.04)*	131.1	96.4 *(4.34)*	120.2	92.8 *(5.53)*	111.6	80.0 *(5.36)*
Average canopy cover (%)	67.2	74.2 *(1.93)*	75.0	82.7 *(0.65)*	76.8	83.9 *(0.87)*	78.9	84.8 *(0.77)*
Intercepted radiation ($MJ/m^2/d$)	4202	4583.2 *(117.37)*	4666	5088 *(38.03)*	5032	5438 *(53.98)*	5392	5751 *(50.27)*
ET (mm)	1141	1258.8 *(21.48)*	1180	1309 *(18.74)*	1407	1555 *(27.38)*	1527	1687 *(34.30)*
Irrigation demand (mm)	-	-	531	589 *(6.89)*	802	894 *(13.86)*	971	1082 *(31.59)*
Cane yield (t/ha)	71.9	82.9 *(5.75)*	110	125 *(1.94)*	122	137 *(2.54)*	131	145 *(2.64)*
Sucrose yield (t/ha)	8.2	8.7 *(0.56)*	13.7	13.6 *(0.18)*	15.1	13.7 *(0.40)*	15.7	13.3 *(0.63)*
WUE (t/ha/100 mm)	6.3	6.6 *(0.35)*	9.3	9.6 *(0.01)*	8.7	8.8 *(0.01)*	8.6	8.6 *(0.02)*
IWUE (t/ha/ 100 mm)	-	-	7.2	7.2 *(0.71)*	8.5	8.2 *(0.39)*	9.0	8.8 *(0.39)*

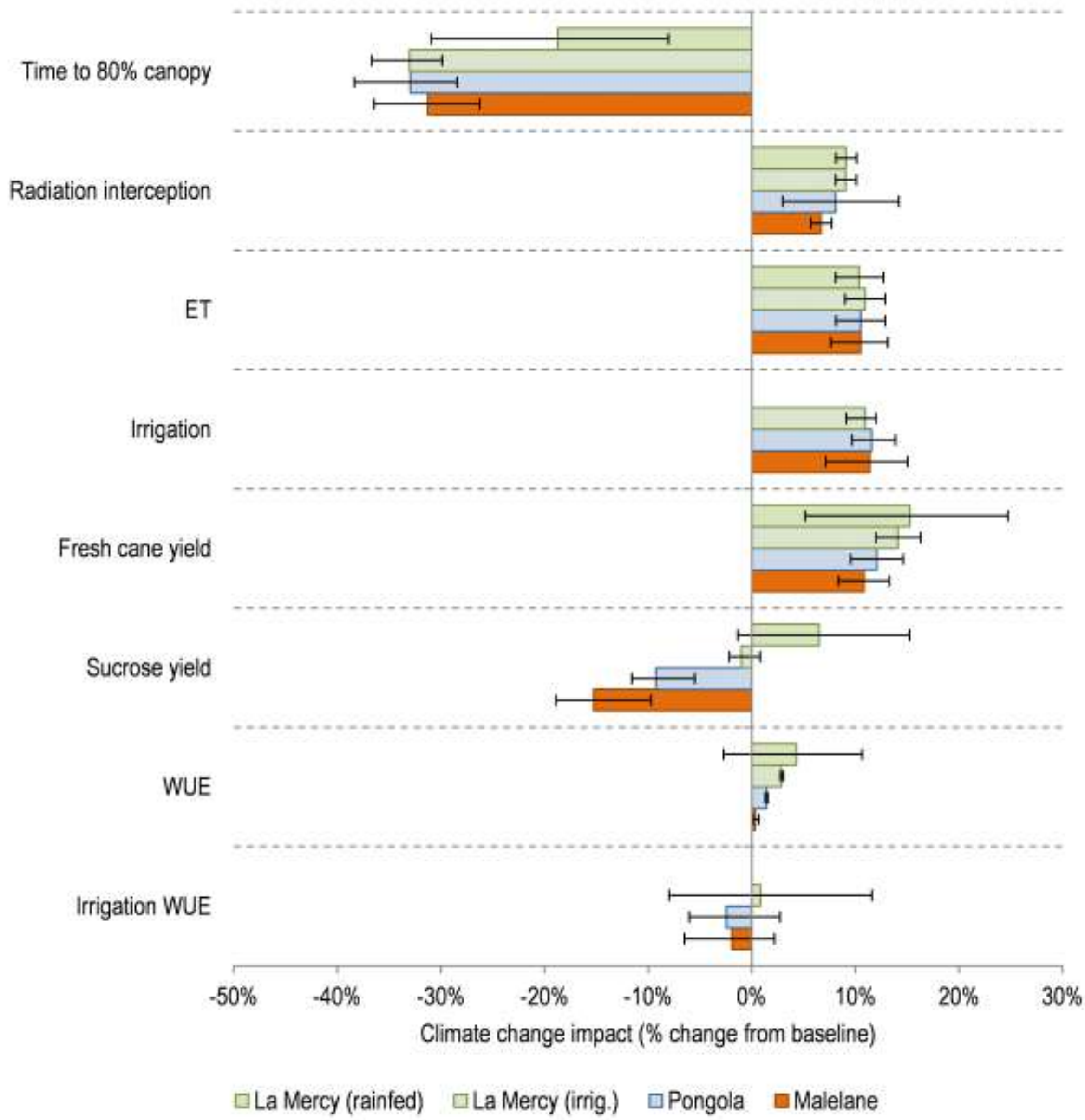

Figure 5. Average climate change impact (difference in long term mean values of each variable between future scenarios and the baseline scenario) predicted for the three sites. The error bars show the range (minimum to maximum) of impacts predicted by the three climate models.

Simulated cane yields increased under all future scenarios, at all sites; this is consistent with the findings of Knox *et al*. (2010), Marin *et al*. (2012), Schulze and Kunz (2010) and Singels *et al*. (2013). The relative increases were greatest at La Mercy (irrigated: 14 %; rainfed: 15 %), and smallest at Malelane (11 %). Simulated yields were higher than the 47 t/ha, 90 t/ha and 95 t/ha recent average yields reported respectively for the Maidstone (La Mercy rainfed), Pongola and Malelane mill supply areas (Singels *et al*., 2015; data for irrigated cane at La Mercy were not available), but show similar values relative to each other compared with the simulated yields shown in Table 3. The yield increases are ascribed to (1) greater interception of radiation (Figure 5) at all sites in future, arising from faster canopy development driven by higher air temperatures (especially at sites and times of the year when average temperatures increase in future above the base temperatures for expansive growth); and (2), increased gross photosynthesis rates (offset to some extent by increased maintenance respiration rates, however), also as a consequence of higher air temperatures. Results suggest that yield increases due to climate change are likely to be greater at currently lower-potential sites, and *vice versa*. This is explained by two factors. Firstly, at lower-potential sites, a unit increase in temperature results in a relatively larger increase in thermal time (*TT*, °C d) accumulation, by virtue of average baseline temperatures being closer to the threshold base temperatures; secondly, at higher temperatures and biomass yields, the burden of maintenance respiration as a proportion of gross photosynthesis increases; higher-potential sites are generally warmer and have greater biomass yields, so a unit increase in temperature results in a smaller relative increase in net photosynthesis – and hence yield – at currently higher-potential sites. Variation in simulated cane yields was relatively low at all irrigated sites, suggesting high levels of agreement between the GCMs' predictions of temperature.

Sucrose yields increased under rainfed production at La Mercy, but decreased under irrigated production at all three sites. This is in contrast with the findings of Knox *et al*. (2010) for Swaziland (which is geographically situated between Malelane and Pongola), who reported that sucrose yields might increase by 15%. Their (single GCM) projections were for a nearer time period (2050s), with smaller temperature increases; also, a different version of the DSSAT-Canegro model (v3.1) was used, in which radiation use efficiency and maintenance respiration are not linked to temperature, and sucrose accumulation follows a more empirical approach than in v4.5. Generally, the currently warmer the site, the greater the decrease in sucrose yields (Figure 5). Sucrose content (a measure of cane quality) decreased at all sites. Impacts on sucrose yield and content are driven by (1) increased simulated maintenance respiration rates leading to a reduction in assimilate supply, and (2) increased simulated demand of assimilate for structural growth (see Fig 20.6 in Singels, 2014), both caused by increased temperatures, and (3) relatively little response in assimilate supply (photosynthesis rate) to temperature. The last two effects have been well documented in field and controlled environment studies (Hatch and Glasziou, 1962; Ebrahim *et al.*, 1998; Lingle, 1999; Inman-Bamber *et al.*, 2010; Grof *et al.*, 2010; Singels *et al.*, 2010). These responses were particularly evident for high biomass crops approaching an early season harvest (April) when temperatures are relatively high. The effect was much less pronounced in October crops when temperatures during the period leading up to harvest are lower than that of April crops.

Irrigation demands increased consistently across all sites (because of increased *ET*, a consequence of increased radiation interception, higher biomass, increased temperatures, and decreased annual rainfall at Malelane and Pongola). The increases were not as large as the 20-22% increase for the mid-century scenario reported by Knox *et al*. (2010) for Swaziland. This discrepancy is attributed to the different GCM and time period used – a similar increase in *ET* was reported (11%), but with a larger decrease (5%) in future annual rainfall. The increases are, however, similar to the findings of Schulze and Kunz (2010), who indicate irrigation demand increases at La Mercy, Pongola and Malelane of 10-20%, 0-10%, and 10-20% respectively. The value of irrigation water in terms of yield (as captured by *IWUE*, Figure 5) decreased in future at Pongola and Malelane. The *IWUE* results depend on the future increase in yield compared with the future increase in irrigation demand, but are also partly influenced by the increased *WUE* – increased radiation interception (less non-productive soil surface evaporation) and reduced stomatal conductance (from elevated $[CO_2]$)

led to more effective use of rain water. Despite relatively higher variability in rainfall projections compared with those for temperature, GCM variation in irrigation demand between the irrigated sites was low. Irrigation supplies and the capacity of water delivery infrastructure will need to increase in future at Pongola and Malelane.

3.3 Inter-seasonal variation in yields

Season-to-season variation in simulated cane yields decreased in future scenarios compared with the baseline (Figure 6). Variation in simulated yields is driven primarily by variability

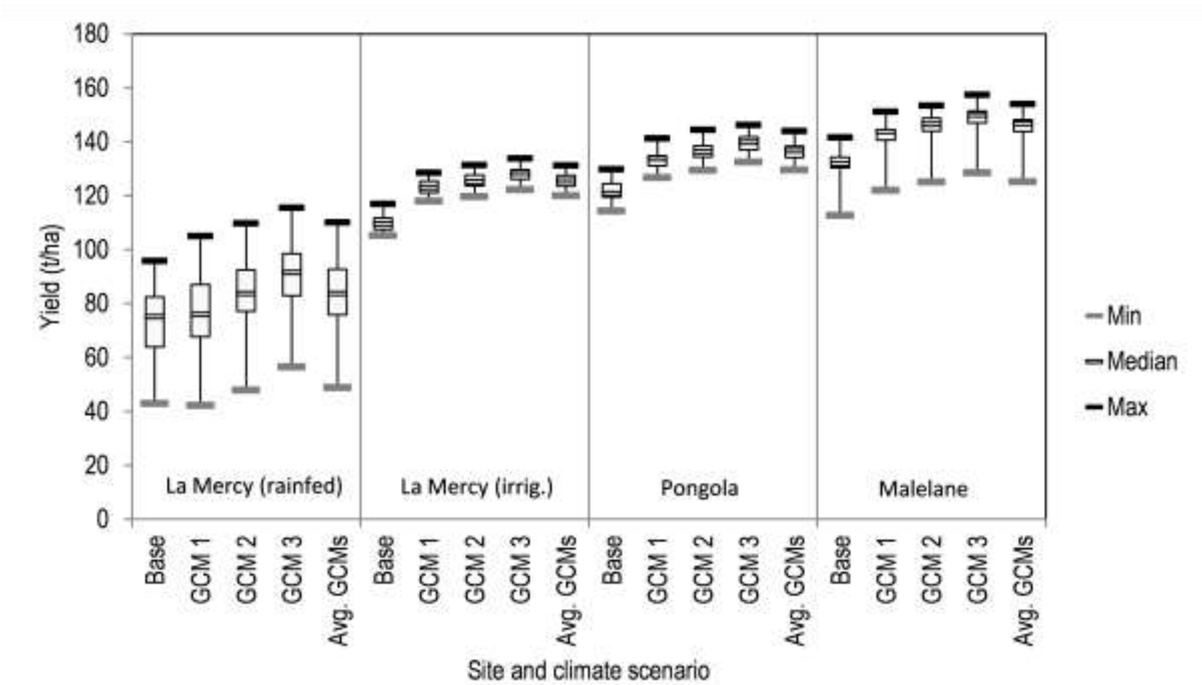

Figure 6. Box and whisker plot showing simulated sugarcane yields for rainfed and irrigated production at La Mercy, and irrigated production at Malelane and Pongola, for the historical baseline scenario ('Base'), each of three GCM-projected scenarios ('1' = MIROC3 2 MEDRES, '2' = MPI ECHAM5, '3' = UKMO HADCM3) and the average of the three GCM scenarios ('Avg. GCMs'). The boxes show values between the first and third quartiles. The average of April and October cropping cycle yields is shown.

in seasonal temperature and solar radiation under fully-irrigated production, and to a relatively much greater extent also by rainfall amount and distribution under rainfed production. This is evidenced by the greater variability in simulated yields at La Mercy under rainfed production, compared with the irrigated sites. The coefficient of variation of simulated cane yields decreased from 19.5 % to 16.8 % under rainfed production at La Mercy, 2.7 % to 2.3 % under irrigated production at La Mercy, 3.2 % to 2.7 % at Pongola, and 4.3 % to 3.8 % at Malelane.

Results presented in Figure 5 and Table 3 suggest that irrigated cane yields are expected to increase at all three sites (by 14.1% at La Mercy, 12.1% at Pongola and 10.8% at Malelane), due to increased interception of radiation from accelerated canopy development (as a result of higher future temperatures), as well as increased radiation use efficiency simulated for higher temperatures. Evapotranspiration increased by 10.6% 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 the elevated [CO_2] effect on transpiration, improved overall *WUE*. The increase in *ET* meant that irrigation requirements increased by about 11% at all sites. *IWUE* increased by 0.9% at La Mercy and decreased 2.5% and 2.0% respectively at Pongola and Malelane.

Simulated inter-seasonal variation in irrigated cane yields (as indicated by CV%) decreased at all sites, with the largest decrease (14%) at La Mercy. This confirms that (low) temperature is currently a limiting factor at La Mercy, and to a lesser extent at the other sites. These results imply that future sugarcane production might become more consistent from season to season, which should be beneficial.

3.4 Crop cycle variation

Figure 7 shows a comparison of baseline and future average fractional interception of photosynthetically-active radiation (canopy cover) by days after crop start at La Mercy, and reveals much-accelerated canopy development in future, particularly for April crops that develop their canopy in the cooler autumn months. Figure 8 shows the interaction of crop cycle and climate change on yield at each site.

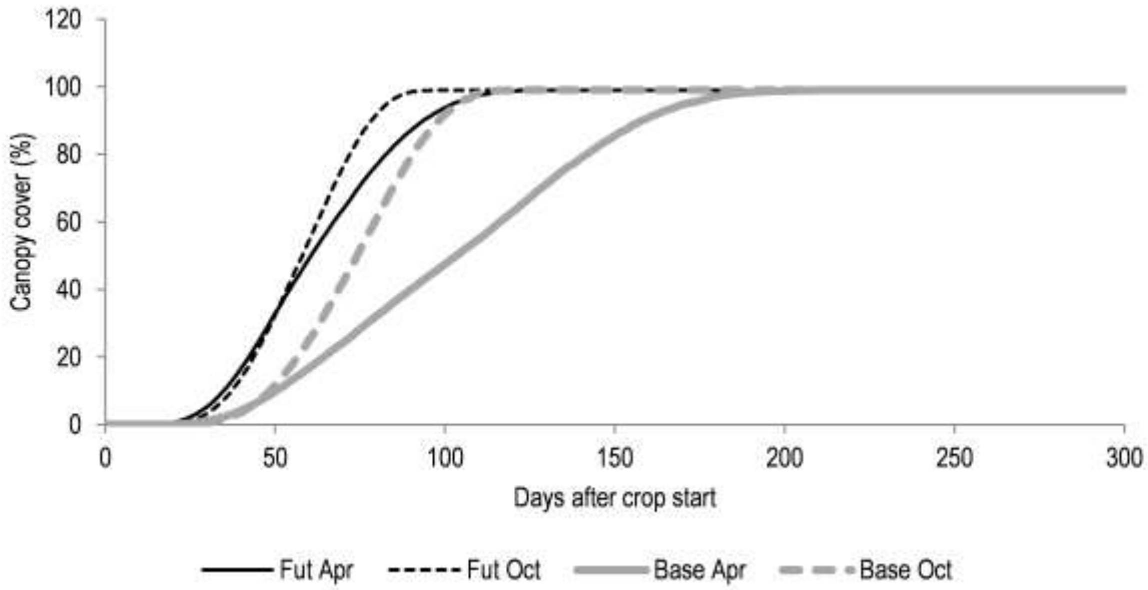

Figure 7. Simulated canopy cover (fractional interception of photosynthetically-active radiation) for irrigated production at La Mercy. April (‘Apr’) and October (‘Oct’) cycles, for the historical baseline scenario (‘Base’), and the average of three GCM scenarios (‘Fut’), are shown.

Substantial increases in annual thermal time accumulation rate, and therefore canopy development rate, resulted at sites and times of the year when future climate change was projected to increase average temperatures from below to above the base temperatures for expansive growth, and where baseline temperatures were relatively low. At the currently coolest site, La Mercy, future irrigated canopy development for April crops was substantially accelerated compared with the baseline period (Figure 7).

Radiation interception increased for all future crops, with relatively larger increases in April crops (+10.6 %) than October crops (+6.2 %). This translated into greater future yield

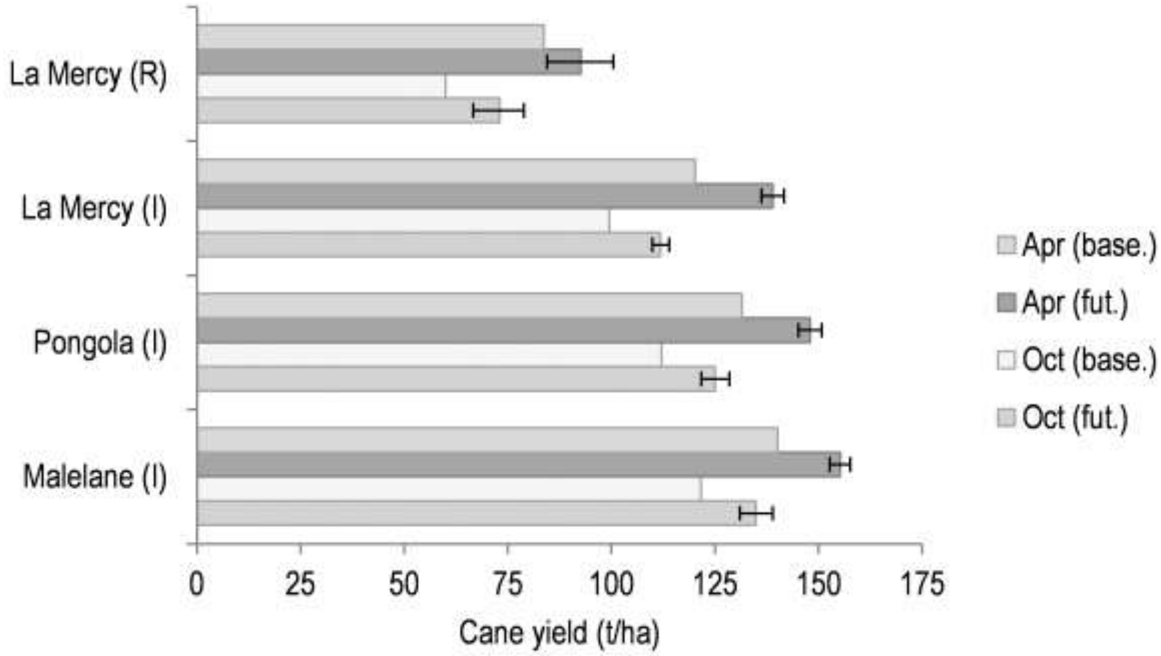

Figure 8. Impact of projected climate change on simulated average seasonal cane yield per crop, at each site. Averages of 30 crops each, for April ('Apr') and October ('Oct') growth cycles, baseline ('base.') and future ('fut.') time periods. The error bars indicate the maximum and minimum values (averaged over 30 seasons) with variation from GCMs. 'R' indicates rainfed crops while 'I' indicates irrigated crops.

increases relative to baseline for April crops compared with October crops (Figure 8), for irrigated production at all three sites. The rainfed treatment at La Mercy showed relatively higher yields for October crops, however, due to higher levels of water stress in the future April crop.

4. DISCUSSION

4.1 Possible adaptation measures

This work has revealed insights that could lead to climate change adaptations and farming system changes which have the potential to increase yields under climate changed future conditions, and/or mitigate against cost increases associated with climate change.

The faster canopy development noted in these results implies a shorter period in which weeds can effectively grow. Weeds are also likely to develop faster in future, but spraying operation costs tend to be linked to the number of spraying operations rather than the level of weed infestation, so weed control costs might decrease in future.

Increased demand for irrigation water in future could be countered by changing to more efficient irrigation technologies (such as sub-surface drip) and precision scheduling of irrigation, consistent with the recommendations made by Knox *et al.* (2010), Park *et al.* (2010), Schulze and Kunz (2010) and Chandiposha (2013). Retention of crop residues has been identified by Park *et al.* (2010) as a possible climate change adaptation to improve water management in sugarcane. Crop residue blankets have the potential to reduce non-productive soil surface evaporation losses: van den Berg and Jones (2006) reported increased soil moisture availability of 100 mm per season for rainfed crops, while Olivier and Singels (2014) recorded reductions in crop water use in irrigated sugarcane of up to 150 mm. This might, however, be a less effective farming system change in future with the shorter partial canopy period and/or if sub-surface drip irrigation is used. Retention of crop residues could also become a more desirable management practice in future in areas where the current temperature climate is too cold to gain any yield advantage from doing so.

The increases in thermal time accumulation rates noted across all sites in the future scenarios suggest that there may be some opportunity to reduce age at harvest (consistent with the findings of Schulze and Kunz, 2010), although this is countered against reduced radiation interception. Decreasing net photosynthesis (due to increasing respiration) as the crop ages suggests that there might be an optimal thermal time age at harvest at which annualised yields are maximised. Higher yields in future might increase the incidence and severity of lodging, and reducing harvest age might also combat this, by ensuring that cane crops are cut before severe lodging sets in (typically around 130 t/ha cane yield, van Heerden (2014)), which might reduce associated yield losses and additional harvesting costs. Given the likelihood of increased lodging in future, there may be a prerogative for sugarcane breeders to focus on lodging resistance as a desirable trait.

Results suggest that cane quality (sucrose content) will be negatively affected by climate change, especially at the beginning and end of the conventional harvesting periods when hot weather is likely to prevail. Chemical ripening will be an important practice to counter this impact, and methodologies may have to be adjusted for optimal efficiency for future climates. Changes to the duration and timing of the harvesting season could also be explored to minimise negative impacts of climate change (as suggested by Park, 2008).

4.2 Methodology issues

The AgMIP integrated assessment framework provides a methodology that proved to be robust and useful. The climate-crop model 'interface' is accessible and requires minimal input other than baseline weather data. Some very valuable insights have been gleaned from this study: (1) indicative impacts of climate change on yield in irrigated sugarcane; (2) indicative impacts of climate change on likely future irrigation demand; and (3) the identification of possible model weaknesses. The AgMIP protocol allows for including additional GCMs (and GCMs from the more recent CMIP5, Taylor *et. al.*, 2013), time periods, emissions scenarios and more sophisticated downscaling techniques.

The study by Singels *et al.* (2013) highlighted possible shortcomings in the methodology that apply here as well. Future assessments may find greater adherence to historical conditions by utilising the agricultural-impacts oriented version of the MERRA dataset for gap-filling (AgMERRA; Ruane *et al.*, 2014). The Delta climate change projection downscaling technique is relatively unsophisticated. Results here indicate that shifts in mean temperature are the driving force behind sugarcane yield changes. GCM projections of temperature change are far more consistent than precipitation change projections, suggesting it is sufficient to analyse a small ensemble such as that assembled here. A weakness of the climate data used was the assumption of no changes in the number of rain-days per month, solar radiation and relative humidity in future scenarios – variables that are important in determining crop water status and irrigation requirements. Future assessments are therefore advised to explore the use of AgMIP's mean-and-variability scenario approaches, which adjust the number of rain-days and the distribution of extreme temperatures in addition to mean changes (Ruane *et al.*, 2015).

Low levels of variation in the predictions of cane yield and irrigation demand were noted in this study. This is probably due to relatively high levels of agreement between the GCMs with respect to temperature projections, which in turn had a more dominant effect on yield and irrigation demand than rainfall. It is tentatively suggested that in regions where GCMs show agreement on temperature and annual rainfall projections are within -10 to +10% of the baseline, small GCM ensembles may be sufficient for climate change impact assessment studies in irrigated sugarcane.

4.3 Model limitations

The study also demonstrated some limitations of the DSSAT-Canegro model. These include the calculation of effective temperature, simulated response of photosynthesis and respiration to temperature, and the disconnect between biomass accumulation and expansive growth.

Effective temperature drives phenological and growth processes in the model and is a linear function of daily mean temperature above the specified base temperature. There is no cap on effective temperature. As a result, the crop develops and grows faster with increasing temperature, even when temperatures are so high that the plant is unlikely to function effectively. For most current climates this algorithm produced reasonable results because temperatures seldom exceeded optimal (about 30 to 35 °C, van Dillewijn, 1952; Liu *et al.*, 1998; Ebrahim *et al.*, 1998; Keating *et al.*, 1999; Bonnet, 2014) of the relevant plant processes. For the projected future climates studied here, average daily temperatures remained below well below 30 °C (Table 1), although the average number of days per annum with daily average temperatures above 30 °C increased to 9, 33 and 71 for La Mercy, Pongola and Malelane respectively. We conclude that crop responses, particularly canopy development rate, to increased temperatures simulated in this study may be slightly over estimated and that the model needs refinement to mimic temperature responses more accurately for scenarios where temperatures often exceed optima. The APSIM-Sugar (Keating *et al.*, 1999) model makes use of minimum (base), optimal and maximum cardinal temperatures for the calculation of effective temperature (thermal time). It is suggested that a similar approach is implemented in the DSSAT-Canegro model.

Simulated radiation use efficiency increases at a decreasing rate with daily mean temperature, while simulated maintenance respiration rate increases exponentially with increasing daily mean temperature, again without a cap on the response (see Singels *et al.*, 2005). The daily amount of assimilate required by maintenance respiration is also proportional to the amount of dry biomass. This means that when the crop becomes very large, most assimilate may be consumed by respiration, leaving little or no assimilate for growth and sucrose storage. This point is reached sooner when temperatures are higher. It is suggested that the respiration algorithm be revised to reflect a decrease in maintenance respiration rate above an optimal temperature, and to account for the different maintenance requirements of different plant materials (dead and live leaf, stalk and root fibre, and stalk sugars) (Amthor, 2000). This should result in lower respiration rates in big crops or at very high temperatures, and could lift the current simulated cane yield cap and increase simulated sucrose yields.

In DSSAT-Canegro the simulation of canopy expansion is driven primarily by effective temperature (and water status), and is disconnected from the biomass accumulation algorithm. In reality, canopy expansion requires the allocation of assimilate produced by photosynthesis. The very rapid canopy expansion simulated under future high temperature will only be realised if it can be supported by a concomitant increase in carbon assimilate rate. This is unlikely because the primary driver of simulated carbon assimilation is solar radiation, which is not expected to increase to the same extent as temperature. It is suggested that the canopy expansion algorithm be linked to the biomass accumulation algorithm (see Jones *et al.*, 2011) to ensure biological integrity.

5. CONCLUSIONS

This simulation study suggests that canopy development of future crops is likely to be far 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. Increased evapotranspiration (and decreased rainfall in some cases), caused increases in irrigation demand of about 11% at all sites. Cane yields are expected to increase by between 11 and 14%, provided that increased irrigation requirements can be met. Sucrose yields decreased because of the additional consumption of photo-assimilate by increased rates of maintenance respiration and greater partitioning of biomass to structural growth rather than sucrose.

Inter-seasonal variations in climate change responses were also minimal, for the same reason. These outcomes suggest that small GCM ensembles may be sufficient for climate change impact assessments in irrigated sugarcane. Crop response in canopy development and yield formation to climate change differed markedly between the two crop cycles investigated, highlighting the need to include this aspect in climate change impact studies for sugarcane.

Results point to several agronomic implications that require actions to minimize negative impacts and exploit positive impacts. These include reduced weeding costs due to shortened periods of partial canopy, a need for improved efficiency of irrigation to counter increased demands, and adjustments to ripening and harvest practices to counter decreased cane quality and optimize productivity.

Although the Delta climate data downscaling method is considered robust, accurate and easily-understood, future weather data generated using the Delta downscaling method has the possible weakness that it does not change the future number of rain-days per month. Additionally, in this study, future solar radiation and relative humidity were assumed not to change from the baseline. The impacts of these simplifications ought to be explored in future work. Shortcomings of the DSSAT-Canegro model include the calculation of effective temperature, simulated response of photosynthesis and respiration to temperature, and the disconnect between simulated biomass accumulation and expansive growth. Proposed refinements to the methodology should improve the reliability of predicted climate change impacts on sugarcane yield.

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