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Potential for sugarcane production under current and future climates in South Africa: Sugar and ethanol yields, and crop water use

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Potential for sugarcane production under current and future climates in South Africa: Sugar and ethanol yields, and crop water use[§]

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Abstract

Spatial information on crop productivity and resource use are required to enable efficient sugarcane production with limited resources and under a changing climate. The objective of this study was to estimate biomass, sugar and ethanol yields for high-sucrose (HS) and high-fibre (HF) sugarcane cultivars for current and future climate in water limited South Africa. An upgraded version of the Canegro sugarcane model, calibrated for a HS and HF cultivar, was used to simulate biomass component yields for 1,986 agro-climatic zones. Ethanol yields were calculated from simulated biomass fractions and theoretical conversion efficiencies. Historical daily weather data for 1971-1990 were used to represent the baseline climate, while daily weather data generated from three global circulation models for 1971-1990 and 2046-2065 were used to project future changes in climate. Simulations show that the HF cultivar produced higher (15-35%) biomass and ethanol yields than the HS cultivar, but also used slightly more (~4%) water. Climate change is projected to increase dryland yields for both cultivar types (8-19%) Irrigated yields will not change much in current high potential areas (1-5%), given adequate water supply, while yields could increase substantially in current cool areas (~20%). Water and irrigation requirements are expected to increase (9-15%) under a future climate. New areas could be become suitable for irrigated and dryland production. The information produced in this study can be used to assist decision-making for: (1) optimizing production and processing processes; and (2) the development of sustainable greenfield projects in marginal areas of South Africa.

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Key words Biomass, climate change, crop model, ethanol, rainfall, sugar, water use

INTRODUCTION

There is increasing demand for renewable energy to replace the use of fossil fuel energy that causes global climate change and threatens agriculture, biodiversity and human survival. A growing human population also requires more food, while agricultural production systems have to adapt to a changing climate.

Sugarcane is a versatile crop that could contribute significantly to the world's increasing food and energy needs. Bio-ethanol can be produced from the fermentation of sugars in the cane juice ("first-generation" technology), as well as from sugars derived from lignocellulosic material in cane stalks and leaves ("second-generation" technology) (Waclawovsky *et al.* 2010; de Souza *et al.* 2013). Dedicated sugarcane cultivation for bio-ethanol production using high-yielding high-fibre genotypes (Alexander 1985) is an attractive option, as this could be conducted on lower potential agricultural land and avoid potential competition with food production.

Strategic planning of production and processing systems, and of programs to support these, is required for efficient and sustainable use of limited natural resources and making allowance for a changing climate (see e.g. Ngcobo and Jewitt 2017). This is particularly relevant for water-scarce South Africa where sugarcane is produced under marginal conditions. Effective planning for the future requires reliable spatial information on crop productivity potential and resource use.

Crop and climate models (GCMs) could provide this information. Linneluecke et al. (2017) comprehensively reviewed climate change studies for sugarcane. Singels et al. (2021) referred to more recent studies (such as Ruan et al. (2018) for China and Oliviera et al. (2018) for Brazil and Baez-Gonzalez et al. (2018) for Mexico). Model based studies for Southern Africa was conducted by Knox et al. (2010), Schulze and Kunz (2010), Singels et al. (2014) and Jones et al. (2015). These studies made use of the DSSAT-Canegro (Singels *et al.* 2008) or APSIM-sugar (Keating *et al.* 1999) models, or algorithms derived from these, and weather data derived from GCM ensembles of varying sizes.

These studies in some instances identified methodology shortcomings that required attention, such as inappropriate simulation of elevated atmospheric CO_2 concentration [CO_2] and/or temperature effects on plant growth, and lack of good quality climate and soil input data at high resolution over large areas. Jones and Singels (2018) addressed some of these shortcomings (specifically crop response to suboptimally high temperatures and elevated [CO_2]) and demonstrated improved capability of the DSSAT-Canegro model for climate change investigations.

None of these studies considered crop yield and water use predictions for high-fibre cultivars for bio-ethanol production. Nair *et al.* (2012) highlighted the need for parameterization and validation of crop models for bioenergy crops, so that they can be used for high resolution simulation of biomass production for planning purposes. Olivier *et al.* (2015) and Eksteen *et al.* (2014) provide quantitative information that enables the parameterization of sugarcane models for high-fibre sugarcane.

Some of these studies, and particularly in South Africa (the focus of this study) only provided information for a few locations due to the lack of reliable weather and soil input data. This limited their usefulness for assessing new areas for production. Kang *et al.* (2014) emphasized the importance of accurate natural resource and crop management input data and the need for high-performance computing power to produce high resolution spatial estimates of biofuel crop productivity for very large areas. In South Africa, Schulze *et al.* (2011) compiled a database of daily weather data for each of 5838 quinary catchments in South Africa, Lesotho and Swaziland (Schulze and Horan 2011), based on long-term weather observations. Downscaled GCM future weather data are also available for these catchments (described in Lumsden *et al.* 2019), as well as properties of the dominant soil in each catchment. This database provides an ideal opportunity for studies on spatial climate-change impacts.

The goal of this study was to generate detailed spatial information for strategic planning purposes, on potential yields and water use of sugarcane production for sugar and ethanol in South Africa for the immediate future (next 30 years), using improved models and climate data. Specifically, the objective was to generate estimates of biomass, stalk, sugar and ethanol yields, water use and irrigation requirements for two sugarcane types (conventional sucrose cultivar, and high-fibre cultivar) for a baseline and future period. This was done using an upgraded DSSAT-Canegro model and high-resolution weather and soil data for areas considered suitable for future sugarcane production.

METHODOLOGY

The model

We used an upgraded version of the DSSAT-Canegro model (Jones and Singels 2018). It included a revised calculation of thermal time to account for the limiting effect of very high temperatures, and improved algorithms for simulating tillering, photosynthesis, respiration, transpiration and water stress responses. Briefly, air temperatures above the process-specific optimal value cause reductions in the rates of crop development, photosynthesis and expansive growth. Process rates reach zero when temperatures exceed the specified ceiling temperatures. The model further simulates reduced stomatal conductance in response to elevated [CO_2], thereby reducing transpiration rate and increasing water use efficiency, as reported in various studies. The model also simulates zero CO_2 fertilization effect on photosynthesis, based on the findings by Stokes et al (2016). Jones and Singels (2018) demonstrated good accuracy for simulating stalk dry mass (SDM) and sucrose yields (SY) of conventional sugarcane (cultivar NCo376) for present climate conditions for well-watered and water-limited situations in South Africa (R^2=0.84, root mean square error RMSE=5.58 t/ha, n =134 for SDM; R^2=0.81, RMSE=3.14t/ha, n=135 for SY). They also demonstrated credible simulation of crop growth for expected future climates with elevated temperatures and [CO_2].

Model input

Eighteen seasons of dryland (non-irrigated) and fully irrigated crops, harvested in April and October in 1971-1990 (baseline) and 2046-2065 (future), were simulated for each of 1986 agro-climatic zones [referred to as quinary catchments (QCs) by Schulze and Horan (2011)]. The QCs were selected based on their apparent suitability for sugarcane production under baseline and future conditions for temperature regimes, annual rainfall and expected yields (fully described by Lumsden 2016).

For dryland crops, the growing season duration for both periods was determined from the annual thermal time and varied from 12 to 23 months (Lumsden 2016). For irrigated cane, the crop season was set at 12 months. A row spacing of 1.2 m was assumed for all runs.

Simulations were conducted for a hypothetical high-sucrose (HS) and high-fibre (HF) cultivars. Trait parameters for these were derived using two datasets from seven experiments conducted in four locations in South Africa (Singels et al 2016). The first data set was used for determining cultivar trait parameters for the model for three clones (conventional cultivars N19 and N31, and a high fibre clone 04G0073) grown under different water regimes in Mount Edgecombe (experiment described by Eksteen et al. 2014 and Ngxaliwe, 2014) and Komatipoort (experiment described by Olivier et al. 2016). Simulation accuracy was acceptable (R^2=0.88, RMSE=6.71t/ha, n=31 for SDM prediction and R^2=0.92, RMSE=2.53 t/ha, n=28 for SY prediction). The second data set was used for model evaluation for three clones in two locations (cultivar NCo376 and high fibre type clone 11F0551 in irrigated breeding trial in Pongola, cultivar NCo376 and high fibre clone 11K1393 in rainfed breeding trial in Kearsney; Pers. comm., M. Zhou, SASRI, Mount Edgecombe). Parameter values for NCo376 was used as previously determined by Jones and Singels (2018). The set of parameter values derived from the first data set for 04G0073 was used for the 11F0551 and 11K1393 , except for radiation use efficiency, which had to be increased from 6.2 to 6.9 g/MJ to more accurately predict tobserved stalk yields. In addition, the thermal time requirement for primary shoot emergence for 11F0551 and 11K1393 was set 1000 ºCd (the NCo376 value as determined by Jones and Singels (2018)), because there was no experimental data available and because there was no strong evidence of genotypic differences in the first dataset. Reasonable accuracy of SDM predictions was achieved (R^2=0.73, RMSE=7.79 t/ha, n=8). Cultivar N19 and high fibre clones 11F0551 and 11K1393 (identical parameter set) was chosen to represent the hypothetical HS and HF cultivars respectively, for this study. Compared to the HS cultivar, the HF cultivar had a higher (19%) radiation conversion efficiency (RUE) and lower fractions of biomass increment partitioning to stalk fibre and sucrose, a higher rate of tillering and canopy development, and was less sensitive to drought stress. See supplementary Table S1 for the various parameter sets as reported by Singels et al. (2016). It was concluded that the model and its parametrization for HS and HF cultivars are credible for predicting responses for these types to climate change.

Model output processing

Theoretical ethanol yields [first (1G) and second (2G) generation], derived from simulated stalk sugars and stalk plus leaf fibre, respectively, were calculated from simulated biomass fractions and theoretical conversion efficiencies [see Olivier *et al.* (2015) for a full description]. This calculation assumed full recovery from all aboveground plant material from the field, and conversion efficiencies of cellulosic material to sugar conversion, and sugar to ethanol conversion of 85% each. The ethanol yield estimations should be considered a theoretical maximum – operational yields are likely to be lower.

Weather data generation, crop model configuration and data processing methods were fully described by Lumsden (2016). In brief, crop simulations were performed for three sets of weather data namely, observed data for the baseline period (1971-1990, BLobs), and simulated data for the baseline (1971-1990) and future (2046-2065) periods (BLsim, FUTsim) derived from statistical downscaling of three global circulation models (GCMs) that contributed to the IPCC 4th Assessment report (IPCC 2007), namely CSIROmk3.5, GFDLcm2.1 and MPI-ECHAM5. (Singels *et al*. 2017). Climate projections from these GCMs assumed the A2 emission scenario (IPCC, 2000), with an assumed [CO_2] of about 550 pm for the future period, which corresponds roughly to “Representative Concentration Pathway” 8.5 (IPCC 2013). GCM data were downscaled empirically using a methodology developed by the Climate Systems Analysis Group of the University of Cape Town (CSAG). Soil information were sourced from the Quinary Catchments Database developed by Schulze et al. (2011).

Future crop water use and yield parameters (e.g. sucrose yield, SY_{FUT}) for a given set of GCM weather derived data for each of the 18 seasons were calculated as the product of the mean ratio between values derived from simulated weather data for the future (SY_{FUTsim}) and baseline (SY_{BLsim}) periods, and the values derived from observed weather data for the baseline period (SY_{BLobs}). Each of these 18 values were then averaged for the three weather data sets derived from the three GCMs:

$$SY_{FUT} = 1/3\ \Sigma\ [\ (1/18\ \Sigma\ SY_{FUTsim}) / (1/18\ \Sigma\ SY_{BLsim})]\ .\ SY_{BLobs} \qquad \text{(Eq. 1)}$$

where the number 3 refers to the number of GCM derived weather data sets, and 18 refers to the number of crops simulated for each time period. Eq. 1 attempts to mitigate model deviations due to simulated weather data, whilst maintaining the climate change effect.

RESULTS

Climate change

Projected climate change in a representative catchment of each of the current production regions is summarized in Table 1. Temperatures are expected to increase by about 2°C, and there was little spatial variation in this change or differences between GCM projections. Projected annual rainfall increases for the representative catchments varied from 6% to 15%. It should be noted that two of the GCMs (CSIROmk3.5 and GFDLcm2.1) projected increases in rainfall for almost all catchments (1-21%), while MPI-ECHAM5 projected decreases for 38% of catchments situated in northern Kwazulu-Natal and Limpopo (data not shown). These differences suggest a considerable degree of uncertainty in rainfall projections. Solar radiation is not expected to change markedly.

Table 1 Summary of climate conditions for a representative catchment (QC#) in each agro-climatic region for the baseline (1971-1990, BLobs) and future (2046-2065, FUT) period. Long-term mean values of annual rainfall (Rain in mm), daily mean temperature (Tave in °C), daily incoming shortwave radiation (SRAD in $MJ/m^2/d$). Future period values were derived by multiplying observed values for the baseline period with the ratio between simulated values for the baseline and future periods.

Region	QC#	Rain BLobs	Rain FUT	Tave BLobs	Tave FUT	SRAD BLobs	SRAD FUT
Dryland							
Zululand	5085	1169	1284.6	21.5	23.4	16.1	16.0
North Coast	4719	1036	1111.1	20.3	22.2	15.4	15.2
Midlands	4775	728	819.3	18.1	20.1	16.4	16.3
South Coast	4799	997	1069.8	20.1	22.0	12.9	12.7
Irrigated							
Mpumalanga*	5744	842	912.5	22.2	24.5	16.2	16.2
Pongola*	5217	765	887.4	20.6	22.7	18.1	18.0
Zululand	5082	1146	1265.0	20.1	22.1	15.1	15.1
North Coast	4715	1048	1120.2	19.1	21.0	16.9	16.7
Midlands	4686	942	1014.8	18.2	20.2	17.2	17.1
South Coast	4793	964	1006.0	18.7	20.5	15.6	15.5

*Sub-regions of the "Northern Irrigated" region (see Figure 1).

Dryland crop production

Spatial variation in baseline and future sucrose and ethanol yields under dryland production are shown in Figure 1. Simulated HS sucrose yields for the baseline period varied from about 1-10 t/ha/annum, while increases from the baseline to future period varied from about -10% to 200% with highest increases in relatively high-altitude inland areas. Yield decreases were observed in only 3% of the catchments. Simulated HF ethanol yields for the baseline varied from about 3.5 -12.5 kL/ha/annum, while increases varied from about -10% to 150%, with yield decreases in only 5% of catchments. Highest yields for the baseline were achieved in coastal Eastern Cape and KwaZulu-Natal provinces, while highest future yield increases were obtained in the relatively high-altitude inland areas.

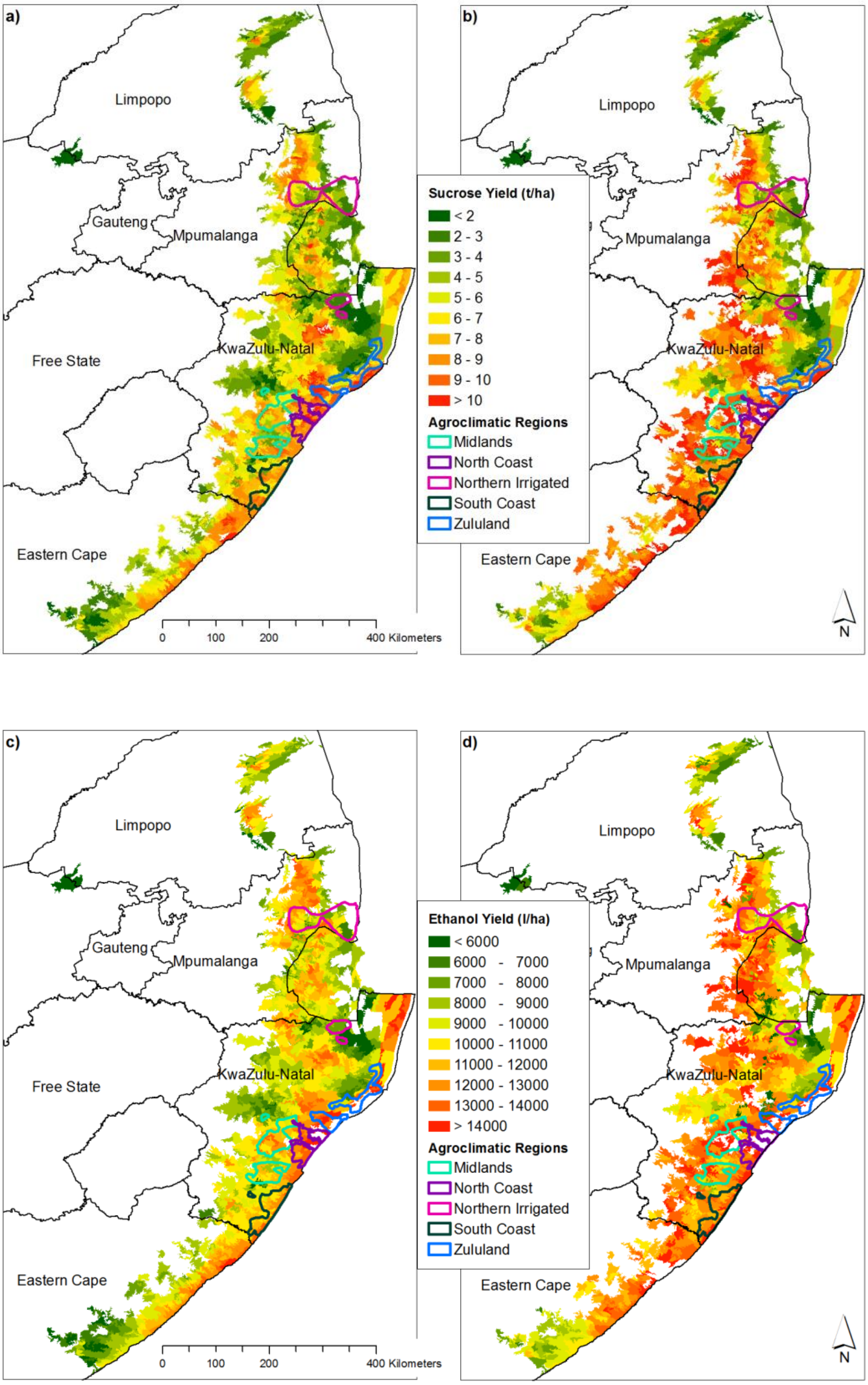

Fig. 1 Spatial variation in long term median annualised simulated dryland sucrose yields for the HS cultivar (a, b) and ethanol (1G+2G) yield for the HF cultivar (c, d) for the baseline (1971-1990; a, c) and future (2046-2065; b, d) climate. Also shown are boundaries of current production regions.

Results for representative QCs in each of the current production regions are given in Table 2. For the **baseline period** simulated HS sucrose, 1G and 2G ethanol yields varied from about 6.3-8.4 t/ha/annum, and 4.4-5.7 and 5.0-6.0 kL/ha/annum, respectively. Relatively warm and humid North Coast had the highest yields, while cool and dry Midlands had the lowest yields. The HS water use ranged from 620 mm/annum in the cool Midlands to 780 mm/annum in hot Zululand.

Although HF biomass and stalk yields were higher (by 18-45% and 8-29% receptively), especially in warm areas, HF sucrose and 1G ethanol yields were much lower (by 3-30%) than those for the HS cultivar (Table 2). HF 2G ethanol yields were much higher (43-62%) than HS yields, because of higher biomass yield and higher stalk fibre and leaf fractions. HF water use was marginally higher (~4%) than HS water use.

Climate change is projected to bring about substantial increases in crop yields, with the HS cultivar grown in currently cool areas showing largest increases (21%) in sucrose and 1G ethanol yields (Table 2). 2G ethanol yields show smaller increases of 8-12 and 6-7% for the HS and HF cultivars, respectively. Water use for both cultivars are expected to increase by 8-11% due to accelerated canopy development, increased capture of radiation and increased atmospheric evaporative demand.

Irrigated production

Baseline HS sucrose yields varied from about 6.5-16.5 t/ha/annum, while future increases varied from about zero to 50% in cool high- lying areas (not shown). Highest yields for the baseline were obtained in the north-eastern part of the country (Limpopo and Mpumalanga provinces).

In current production regions HS sucrose, 1G and 2G ethanol yields for the baseline period varied from 10.9-18.3 t/ha/annum, and 7.0-11.4 and 7.4-13.6 kL/ha/annum, respectively (Table 2). Highest yields were obtained in Mpumalanga, and lowest in the Midlands, which is not considered a recognized irrigated area. HS water use ranged from 990 to 1240 mm/annum, while irrigation requirements varied from 370 to 790 mm/annum.

Although HF biomass yields were higher (~10%), sucrose and 1G ethanol yields were much lower. 2G ethanol yields for HF cultivar were substantially higher (34-50%) than for the HS cultivar. HF water use and irrigation demand were slightly higher than that for the HS cultivar (3-7%) (Table 2).

Biomass and stalk yields are expected to increase in **future** in all regions. Projected stalk yield increases range from 14% in the cool Midlands (not a recognized irrigation area) to 1% in high potential Mpumalanga. **Future increases** in sucrose and ethanol yields are projected in lower potential areas, with increases of as high as 23% in the Midlands. Sucrose and 1G ethanol yields are projected to be slightly depressed in Mpumalanga. Similar trends are observed for 2G ethanol yields for HF cultivar. Water use and irrigation requirements are expected to increase by 9-15%.

DISCUSSION

The study has produced a spatial database of projected dryland and irrigated sugarcane yields (biomass, stalk dry mass, sucrose and ethanol) and water use for two cultivar types for potentially suitable areas in South Africa. Although a previous study by Schulze and Kunz (2010) also produced spatial data, our study used a more sophisticated and thoroughly tested crop model that incorporated recent knowledge on crop response to environmental factors for two sugarcane types. The spatial estimates of 1G and 2G ethanol yields produced in this study are a first for South Africa.

It is difficult to compare results obtained here with other studies, because of differences in current and projected future climate and water supply, and differences in research methodology.

Yield increases predicted for future climate in this study are generally lower than those predicted in studies for southern Africa by Knox et al (2010) and Jones et al (2015) for irrigated cane (5-16% and 10-12% respectively), and Schulze and Kunz (2010) for dryland cane (5-25%). Predicted yield responses to mid-century climate change for other parts of the world using a similar methodology (Biggs et al. 2013, Marin et al. 2013, Singels et al. 2014, Everingham et al. 2015 and Ruan et al.

2018) vary widely depending largely on assumed changes in future water supply (rainfall and/or irrigation), and whether a CO_2 fertilization effect on photosynthesis was assumed. We believe that the version of DSSAT-Canegro used in this study incorporates most recent knowledge regarding crop response to elevated temperatures and [CO_2] and that the sucrose and ethanol yield predictions are the best available for the given weather and soil input used.

Most comparable studies predict increased crop water use in future, given adequate water supply, due to increased evaporative demand and accelerated canopy development. Predicted increases in unstressed crop water use from studies using the Canegro model for the 2050s are around 7-11% (Singels et al., 2014; Jones et al., 2015) agreeing with the findings from our study. Knox et al. (2010) found a huge increase in crop water use of 26% for Swaziland.

It should be noted that future climate change impact results are heavily dependent on the projected changes in future rainfall. Rainfed crop water use and yields rely on rainfall, while irrigation requirements also depend on it. As pointed out the projected rainfall changes are quite uncertain, as is evident in the large variation in these predictions between the different GCMs used in this study. The latest rainfall projections by the Inter Governmental Panel on Climate Change (IPCC, 2021), published after our study was completed, suggest a decline in annual rainfall for the study area, contradicting the projected rainfall increases used in this study. A decline in future rainfall will undoubtedly have a negative effect on dryland yields and increase irrigation requirements.

Another aspect to remember is that for irrigated production scenarios adequate water supply was assumed. Indications are that streamflow in current irrigated sugarcane production areas could very well decline in future (Schulze and Taylor, 2016), which could reduce yields substantially (Singels and Jones, 2018).

Table 2 Simulated future long term median (LTM) annualised dry biomass yield, dry stalk yield and sucrose yield (t/ha/annum), first and second generation (1G, 2G) ethanol yield (kL/ha/annum), water use (mm/annum) and irrigation demand (mm/annum) for the high sucrose (HS) and high fibre (HF) cultivars for a representative catchment in each of the different agro-climatic regions of the industry. The expected long term mean increase (Δ in %) for each of these variables is also given. Numbers in brackets are corresponding data for the high-fibre cultivar.

Region	Harvest age (months)	Cultivar	Dry biomass yield		Dry stalk yield		Sucrose yield		1G ethanol yield		2G ethanol yield		Water use		Irrigation demand	
			LTM	Δ	LTM	Δ	LTM	Δ	LTM	Δ	LTM	Δ	LTM	Δ	LTM	Δ
Dryland																
Zululand	12	HS	24.9	10.9	15.8	12.3	6.3	12.2	4.4	12.9	5.0	10.0	747	8.7		
		HF	36.2	6.7	20.5	7.7	5.5	8.2	4.3	8.0	8.2	6.4	778	9.0		
North Coast	14	HS	31.1	10.1	18.3	14.1	8.8	16.1	5.7	15.4	6.0	8.0	734	8.5		
		HF	39.6	6.8	21.7	10.2	5.9	11.3	4.6	11.1	9.0	6.0	773	8.8		
Midlands	23	HS	25.6	14.9	15.8	18.8	8.4	20.8	5.2	20.4	4.8	12.2	622	10.6		
		HF	30.3	8.0	17.0	11.4	4.8	12.2	3.7	12.0	6.8	7.2	650	7.6		
South Coast	14	HS	26.4	10.3	16.2	13.4	7.1	14.6	4.9	13.9	5.2	8.8	654	10.0		
		HF	34.3	6.7	19.4	9.4	5.2	10.3	4.1	10.1	7.8	6.0	679	10.6		
Irrigated																
Mpumalanga	12	HS	57.4	0.4	35.8	1.1	18.3	-2.0	11.4	-0.9	10.7	1.2	1241	9.3	790	8.4
		HF	63.6	0.3	36.0	1.0	9.9	-0.2	7.7	0.1	14.3	0.4	1327	10.2	870	7.4
Pongola	12	HS	51.6	4.7	31.6	5.9	16.3	5.1	10.2	5.3	9.6	4.6	1172	8.3	700	5.4
		HF	60.5	3.7	33.8	4.8	9.4	4.7	7.3	4.7	13.6	3.5	1244	9.7	765	8.0
Zululand	12	HS	50.1	4.8	30.6	6.3	15.5	4.0	9.8	4.9	9.4	4.9	1000	9.6	375	8.0
		HF	56.6	4.0	31.9	5.4	8.8	5.0	6.9	5.1	12.8	3.8	1045	10.7	400	11.6
North Coast	12	HS	48.3	9.5	29.4	11.1	15.0	10.8	9.4	10.8	9.1	9.0	1068	9.8	460	10.3
		HF	56.1	8.5	31.3	9.7	8.6	10.0	6.7	9.9	12.7	8.2	1104	11.4	470	13.4
Midlands	12	HS	38.2	17.0	22.7	20.8	10.9	23.2	7.1	22.1	7.4	14.8	1002	8.7	370	11.9
		HF	49.0	11.7	27.0	14.3	7.3	15.1	5.7	14.9	11.1	11.1	1041	10.3	405	15.3
South Coast	12	HS	45.1	14.0	27.1	16.2	13.6	17.3	8.6	16.8	8.6	12.8	986	10.2	465	11.2
		HF	53.1	10.0	29.4	11.4	8.1	12.0	6.3	11.9	12.0	9.7	1012	11.7	485	13.1

CONCLUSIONS

The study has produced a spatial database of projected dryland and irrigated sugarcane yields (biomass, stalk dry mass, sucrose and ethanol) and water use for two cultivar types for potentially suitable areas in South Africa. The information may be used to assist decision-making for: (1) optimizing production and processing processes; and (2) the development of sustainable greenfield projects in South Africa.

Results suggest that high-fibre sugarcane genotypes could produce higher (15-35%) dryland biomass and ethanol yields (a larger proportion derived from second-generation sources) than sucrose sugarcane genotypes, but could also use slightly more (~4%) water. Climate change is likely to increase dryland yields for both cultivar types (8-19%), especially in current cool areas. Irrigated yields will not change much in current high potential areas (1-5%), given an adequate water supply, while yields could increase substantially in current cool areas (~20%). Water and irrigation requirements are expected to increase by 9-15% under a future climate. New areas could be become suitable for production such as northern Limpopo (irrigated), north-eastern parts of the Eastern Cape (dryland and irrigated) and high lying areas in KwaZulu-Natal and Mpumalanga.

The study highlighted some methodology weaknesses that need attention. These include the uncertainty of rainfall projections, limitations of the downscaling method and assumptions of adequate future irrigation supply. It will be important to keep abreast of climate projections and downscaling methods as they evolve in future.

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