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# A yield gap analysis to assess vulnerability of commercial sugarcane to climatic extremes in southern Africa

S.I. Ngcobo [a,*], T.R. Hill [c], G. Jewitt [a,d,e], E. Archer [b]

[a] Department of Hydrology, Centre for Water Resources Research, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg Campus, King Edward Avenue, Scottsville, 3209, Pietermaritzburg, South Africa
[b] Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Hatfield, 0028, South Africa
[c] Discipline of Geography, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg Campus, King Edward Avenue, Scottsville, Pietermaritzburg, 3209, South Africa
[d] Department Water Resources and Ecosystems, IHE Delft Institute for Water Education, PO Box 3015, 2601DA, Delft, the Netherlands
[e] Water Management, Civil Engineering & Geosciences, TU Delft, PO Box 5048, 2600 GA, Delft, the Netherlands

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ABSTRACT

Sugarcane yields have steadily declined across southern Africa for the past 25 years and, despite research into the causes, there has been limited progress in addressing these trends. This study developed a methodology of assessing yield declines and performed a yield gap analysis to assess and develop recommendations to assist in combating yield declines and offering potential safeguards for the sugarcane industry against climatic extremes. Mill areas from South Africa, eSwatini, Malawi and Tanzania were selected, providing a diversity of regional hydroclimatic conditions and sugarcane agronomic management approaches. Using the AquaCrop crop model, maximum potential yields and yield gaps were simulated based on observed climate and yield data spanning 25 years. Results show that yields are declining for the mill areas in South Africa, Malawi and Tanzania, resulting in increased yield gaps, whilst yields are stagnant in eSwatini resulting in relatively fixed yield gaps. Yield gaps remained high across all six mill areas, suggesting that they remain vulnerable and exposed to climatic extremes. Modelling results suggest that these yield trends, including yield gaps, are primarily attributed to existing crop management approaches as opposed to the climatic regimes in these areas. Recommendations include several solutions that could result in an immediate response and reduce yield gaps while increasing harvestable yields. Such measures include increasing technology transfer and agronomic management education to small-scale outgrowers, adopting drought-resistant, high-yielding sugarcane varieties, contouring and mulching, improving soil structural properties and minimizing in-field traffic. The study concludes that if sugarcane growers are to withstand the effects of extreme climatic events, they have to consider shifting crop management approaches and be proactively included in related research.

## 1. Introduction

The strategic importance of commercial sugarcane production as one of the primary sources of food, fodder and energy in southern Africa cannot be overstated. Sugarcane is an important commodity crop that not only supports millions of livelihoods [2–4], but also constitutes a significant proportion of the biofuels industry [5,6] which, if widely adopted, could contribute to the reduction of greenhouse gas emissions across the region [7,8]. Further, according to the World Bank, the commercial sugar industry in the SADC region generates an estimated average indirect income of over $7.15 billion per year [9,10]. Considering the importance of sugarcane production as a primary source of income for thousands of growers in this region, it is important to gain a more thorough insight into the factors which affect yields - particularly over the past 25 years which has witnessed a worrying decline [11].

In addition to its contribution to the economies of the region, the sugarcane industry assumes a vital role in education and training [12], agronomic research [13,14], science and technology and in ensuring environmental sustainability [15]. The strategic importance of this industry is reflected in the typical southern African sugarcane value chain, which spans a myriad of major industries including, *inter alia*, research, small and large-scale farms, mill-owned estates, mills and refineries,

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[*] Corresponding author.
*E-mail address:* ngcobos21@ukzn.ac.za (S.I. Ngcobo).

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export markets and consumers (Fig. 1) [18]. Despite the importance of this crop in the SADC region, it remains exposed and vulnerable to the effects of climatic extremes engendered by climate change [19,20]. This exposure is already undermining yields by increasing water deficits [21, 22], and by forcing changes in crop management which can threaten the long-term sustainability of the sugar industry in the region [23].

Sugarcane is a perennial C4 carbon-fixing perennial plant that is grown across a variety of hydroclimatic zones in southern Africa [24]. It is usually cultivated over a period of 18–24 months and during this period, access to adequate water resources (*i.e.* rainfall and/or irrigation), temperature (*i.e.* heat units), and nutrients are crucial in determining sugarcane yield and quality [25,26]. Typically, sugarcane requires an average of 1800 mm. annum$^{-1}$ of rainfall for a full canopy crop that, in this region, must often be supplemented with irrigation and requires an 'optimum' temperature range between 32° and 38 °C for successful germination, growth and senescence (N [27,28]. Continuous access to nutrients and the absence of pests and disease are primary factors that limit the successful cultivation of sugarcane [29], which has specific and narrow growing and management conditions that have to be met if sufficient yields are to be achieved. It is, however, becoming increasingly difficult to meet these conditions owing to competitive land-use change, pests, changes to climatic regimes and increases in illegal sugar imports from poorly regulated foreign markets [30,31].

An estimated 785 000 Ha is under sugarcane across southern Africa [17], and although sugarcane growth by area has been stagnant in the region, water use has been steadily increasing to meet the increasing water deficits caused, in part, by increases in temperature, total evaporation and increased competition for access to water resources [24,32]. As a consequence of these increases in water deficits, yields in the countries have correspondingly declined over the past 25 years [20,33]. There is considerable debate regarding these declines in yields, with some scholars suggesting water deficits as the main cause (N. G. [34], while others cite sub-optimum crop management driven by intensive monocropping [22,35] or suggesting a combination of nutrient management, variety selection and soil health [36]. It is, thus, necessary to understand the actual causes of the recent declines in sugarcane yields to arrest these concerning trends. The yield gap (YG) analysis suggested in this study provides a methodology for assessing and identifying the main factors affecting crop yields, and offers a potential tool for developing mitigation options.

At this point, it is important to note that, globally, there is a substantial body of work dedicated to the investigation of sugarcane yield declines and yield gaps [37–41]. However, there remains a dearth of similar studies in southern Africa. This is of concern since the sugar industry in the region is considered to be vulnerable not only to the impacts of climate change [19] but also to management-related factors that are currently transforming the global sugar industry [42]. If growers in this region are to remain internationally competitive and for livelihoods to be protected, it is key that the current yield gaps and yield declines are addressed.

As mentioned previously, climate change represents a significant threat to the productivity and the sustainability of the sugarcane industry across southern Africa [19,43]. By altering rainfall and temperature regimes, climatic changes projected for this region [43] have the potential to significantly undercut yields and, as demonstrated by the drought of 2014–2017, devastate livelihoods [44]. It is, thus, important to study the impacts of climatic extremes on sugarcane yields and offer potential adaptation measures that can assist in buffering the impacts of climate change on the sector. A yield gap (YG) analysis offers a methodology of identifying the main factors affecting sugarcane yields [45–48], and can be a useful tool for assessing the exposure of sugarcane to extreme climatic conditions, both present and future, and allows the determination of mitigation options.

Advances in technology resulting in the development of improved crop varieties and increasingly efficient irrigation techniques [35,49], combined with climatic conditions conducive to sugarcane production over the past 25 years [21] would intuitively suggest increases in yields however, as this study will show, this has not been the case. Indeed, a hydroclimatic environment ideal for sugarcane production is simultaneously ideal for the proliferation of pests and diseases such the *Eldana saccharina* stalk borer [50] and *Sporisorium scitamineum* or sugarcane smut [51–53]. In South Africa, for instance, yield declines are often a direct result of the effects of the *Eldana* stalk borer, increasingly forcing growers to forgo sugarcane production in favour of other equally high-value crops that are immune to the effects of this pest [54]. Growers in eSwatini are almost entirely reliant on irrigation, and the increase in the frequency of droughts over the past 20 years has resulted in significant declines in yields [55,56]. In Tanzania, increased competition for land as a resource, has led to stagnant yields, particularly for small-scale growers which constitute a substantial proportion of sugarcane production in this country [32]. Finally, in Malawi, government involvement in the sugar industry has led to yield declines by

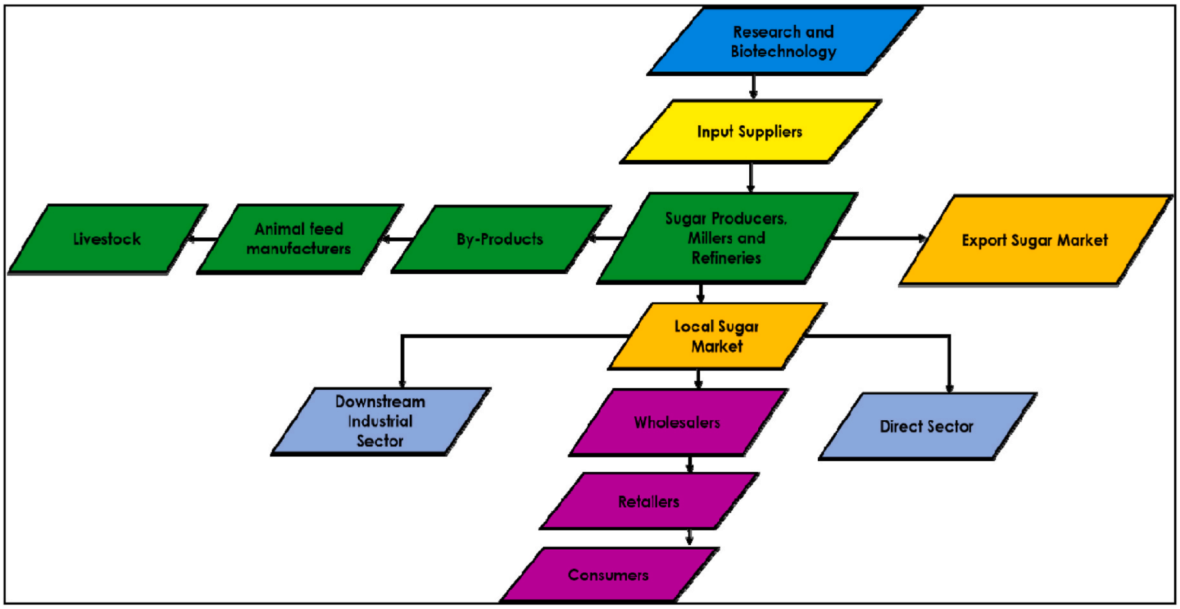

**Fig. 1.** A typical southern African sugarcane production value chain (Modified from [16,17]).

prioritising access to water resources for tea growers at the expense of sugarcane growers [30,57,58]. It is clear, therefore, that no single factor is the cause of these trends, and that each catchment or growing region requires site-specific diagnoses to address yield gaps and yield declines. This study, therefore, aimed to i) offer a methodology of quantifying yield declines and yield gaps as a result of climatic extremes and management interventions, and ii) offer recommendations to arrest these trends.

### 1.1. Study sites

The Yield Gap (YG) analysis was conducted at mill area level across six catchments located in four countries, using hydrological, climatic and sugarcane production data spanning 25 years (1994–2019). These catchments are the Mvoti, Umlaas and Mngeni Catchments in South Africa, the Ubombo Catchment in Swaziland, the Shire Catchment in Malawi and the Kilombero Catchment in Tanzania. Their six resident mill areas (Fig. 2) and catchment information are summarised (Table 1). The sites were selected owing to their varied hydroclimatic conditions, relatively high sugarcane production levels, distinctive management approaches, access to long-term climate and production data and for their strategic economic importance in their catchments and countries (Table 1). Each mill area was represented by a set of observed climatic, hydrological and production data that were used as input into the AquaCrop model to simulate maximum potential yields. The differences between observed average growing cycle yields (Ya), *simulated* maximum potential yields (Yp) and water-limited yields (Yw) represent the yield gaps (YG) for each mill (see Fig. 3). The yields gaps were used to isolate the effects of water deficits and agronomic management from those of climatic extremes [45,46,59,60].

## 2. Methods

### 2.1. Introduction

This study used a combination of the AquaCrop crop simulation model and average annual yields reported by primary and secondary sources to determine yield gaps [61–64], Illovo Malawi, 2018, [65,66]. The justification for this approach rests on the fact that crop simulation models such as DSSAT/CANEGRO [67], APSIM-Sugarcane [68], and AquaCrop [1] and many others, have shown good performance when simulating sugarcane yields in the selected study catchments [60]. Further, reliable data related to average annual yields can be difficult to obtain and verify independently for some of these catchments. It was thus considered imperative to consider both observed and simulated yields to determine yield gaps.

It is important to re-iterate that sugarcane is grown under a combination of rainfed and irrigated systems in these catchments (Table 1). This has significant implications for yields and yields gaps. Sugarcane yields have been declining across all four catchments under study over the past 25 years under all growing conditions and management approaches. The challenge, however, remains identifying the cause of this decline. According to Refs. [45,67]; crop simulation models provide the best chance of understanding current and future sugarcane production trends, and in separating the effects of climate change from those of management to understand yield gaps and define the causes of the recent declines in yields.

### 2.2. Yield gap analysis

Conducting a YG analysis requires information related to the following yield types: potential yield (Yp), potential water-limited yield (Yw) and observed long-term yield (Ya) per growing cycle [67,69] (Fig. 3). A growing cycle is the length in days the crop requires to reach senescence and maturity. Each of the aforementioned yield types assessed in this research are described below.

1. Potential yield (Yp in $t.ha^{-1}$) is the yield that would be achieved provided that there are no agronomic or management limitations to crop growth. This is the optimum yield that can be attained provided the crop is not affected by, *inter alia*, access to water, nutrients, sunshine and is grown under optimum management.

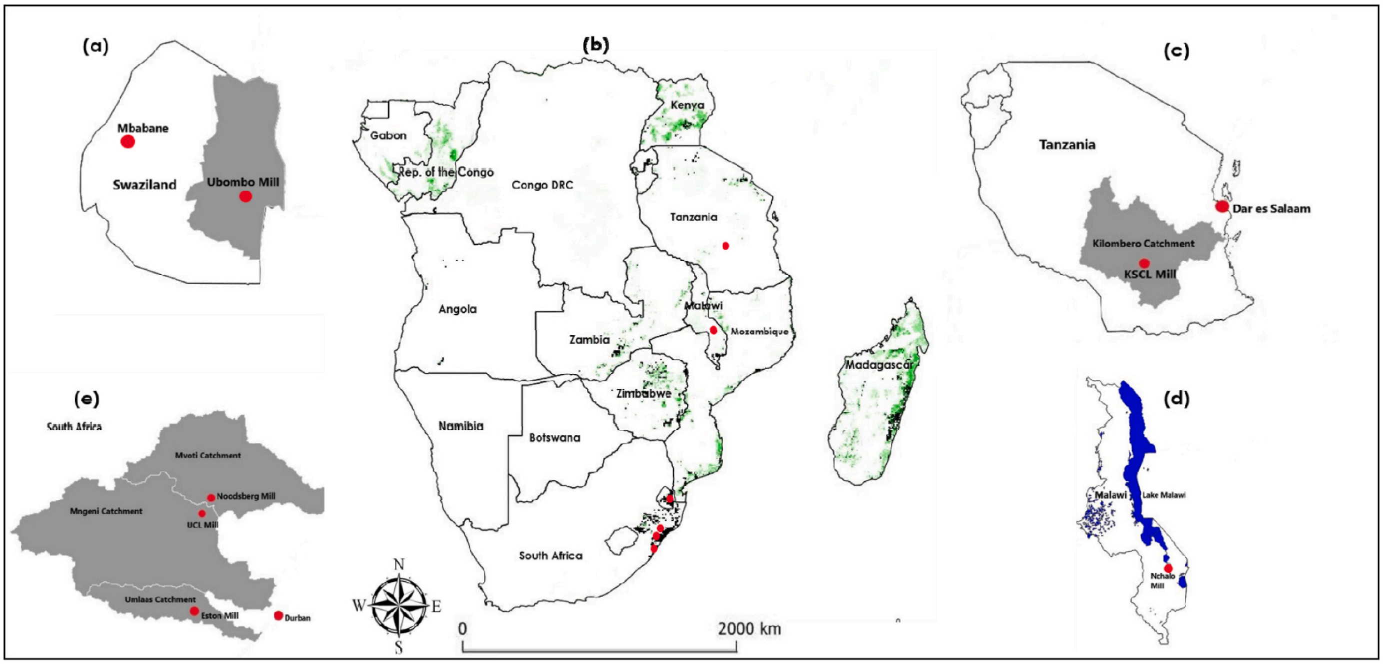

**Fig. 2.** Mill locations within individual catchments and the spatial extent of the area under sugarcane across the region [17]. Clockwise from top-left: **a)** the Ubombo Catchment in Swaziland, **b)** The approximate spatial distribution of sugarcane production areas across southern African based on modelled data [17], **c)** the Kilombero Catchment in Tanzania. **d)** the Shire Catchment in Malawi and **e)** the Mvoti, Umlaas and Mngeni Catchments in South Africa.

**Table 1**
Information on sugarcane mills and parent catchments (Sources: [61–64], Illovo Malawi, 2018, [65,66].

| Mill | Catchment | MAP (mm/annum) | Water Management | Area Under Sugarcane (Ha) | Observed Annual Output (t/annum) | Long-Term Average Yield (t/ha) | Agronomy | Growing Cycle Length (Months) |
|---|---|---|---|---|---|---|---|---|
| **Eston** | Umlaas (SA) | 833 | Irrigated and Rainfed | 36 728 | 1 124 488 | 76 | Advanced in-field, irrigation and processing technologies | 24 |
| **Noodsberg** | Mngeni (SA) | 787 | Rainfed | 29 917 | 1 326 214 | 62 | | 24 |
| **Union Cooperative Limited (UCL)** | Mvoti (SA) | 892 | Rainfed | 18 433 | 712 257 | 63 | | 24 |
| **Big Bend** | Ubombo (SWA) | 659 | Irrigated | 10 987 | 1 303 750 | 56 | Drought resistant N41 and N26 varieties | 12 |
| **Nchalo** | Shire (MAL) | 814 | Irrigated and Rainfed | 19 520 | 1 680 000 | 72 | Ratooning | 12 |
| **Kilombero Sugar Company (KSCL)** | Kilombero (TNZ) | 1223 | Irrigated and Rainfed | 21 800 | 1 200 000 | 113 | Ratooning | 12 |

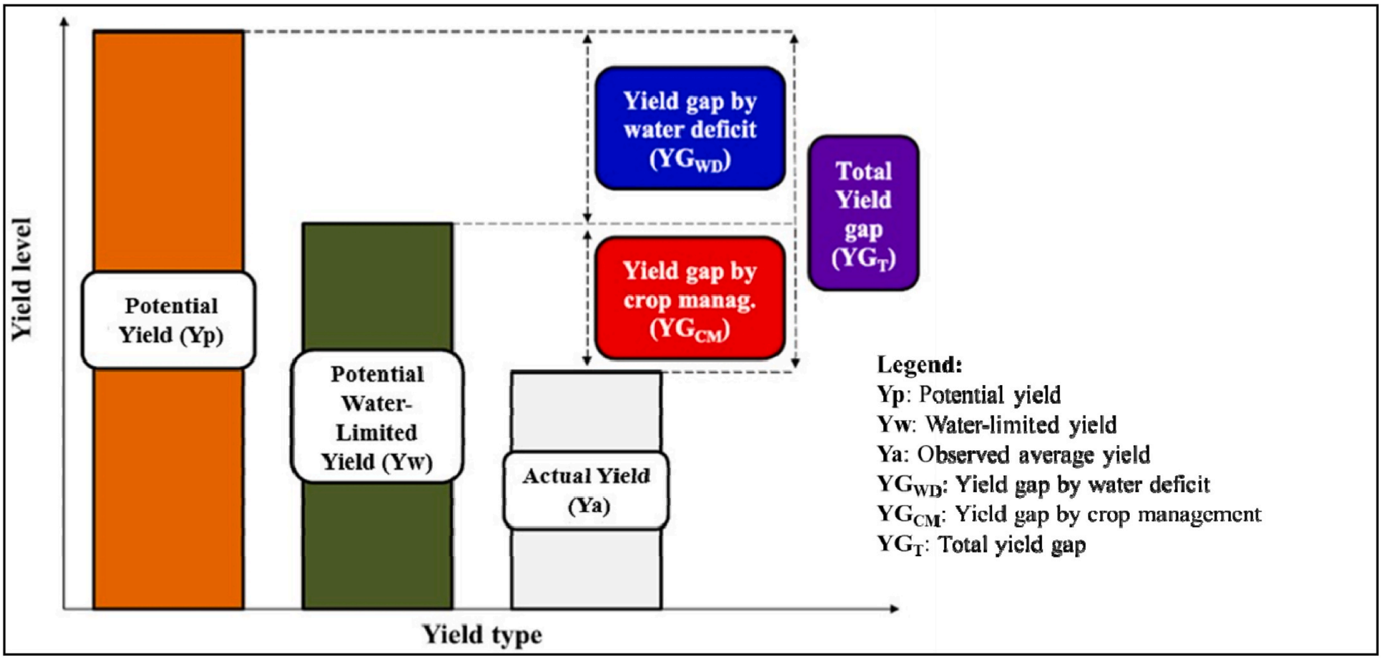

**Fig. 3.** A conceptual framework describing the yield gap analysis and its components (Modified from: [45].

2. Potential water-limited yield (Yw in t.ha$^{-1}$) is the yield that would be achieved provided the crop is not affected by access to water from rainfall, irrigation and soil moisture.
3. Observed yield (Ya in t.ha$^{-1}$) is the actual growing cycle yield and is reported as an accumulated annual value by the individual mills.

**Table 2**
Years excluded from the YG analysis including reasons for exclusion and actual data sources for rainfall, temperature and total evaporation (**Sources**: University of KwaZulu-Natal Centre for Water Resources Research; SASRI WeatherWeb; NASA/POWER Climate Portal; World Bank Climate Change Knowledge Portal; University of Cape Town Climate System Analysis Group; Texas A&M University International Laboratory for High-Resolution Earth System Prediction; NASA Global Precipitation Measurement).

| Mill | Catchment | Period | Number of Years | Years Excluded from Analysis | Reason(s) for Exclusion | Data Sources |
|---|---|---|---|---|---|---|
| **Eston** | Umlaas (SA) | 1994–2019 | 25 | – | – | http://cwrr.ukzn.ac.za/resources<br>https://sasri.sasa.org.za/weatherweb_legacy/ |
| **Noodsberg** | Mngeni (SA) | 1994–2019 | 25 | – | – | https://sasri.sasa.org.za/rtwd/458/index.html |
| **Union Cooperative Limited (UCL)** | Mvoti (SA) | 1994–2019 | 25 | – | – | https://power.larc.nasa.gov/data-access-viewer/<br>https://climateknowledgeportal.worldbank.org/download-data |
| **Big Bend** | Ubombo (SWA) | 1996–2019 | 23 | 1994 and 1995 | Ya data reliability | https://www.csag.uct.ac.za/climate-services/cip/ |
| **Nchalo** | Shire (MAL) | 2000–2019 | 19 | 1994 and 1999 | Climate and Ya data reliability | https://cip.csag.uct.ac.za/webclient2/app/<br>https://texasclimate.tamu.edu/research/data/index.html |
| **Kilombero Sugar Company (KSCL)** | Kilombero (TNZ) | 2000–2019 | 19 | 1994 and 1999 | Climate and Ya data reliability | https://ihesp.github.io/archive/products/ds_archive/Datasets.html#regional-datasets<br>https://gpm.nasa.gov/data |

The difference between Yp and Yw results in the YG caused by water deficit or $YG_{WD}$, while the difference between Yw and Ya results in the YG caused by crop management or $YG_{CM}$ (Fig. 3). The sum of $YG_{WD}$ and $YG_{CM}$ yields the total yield gap or $YG_T$. This study was concerned with assessing $YG_{WD}$, $YG_{CM}$ and $YG_T$. For purposes of this study, the YG analysis was conducted for all mill areas for a period of 25 years ranging from 1994 to 2019 (Table 2). These analyses were performed only for years where observed yields (Ya) and long-term climatic and crop management data were available. In instances where one or more of these datasets were missing, an assumption was made that yields resembled the average yields reported in the years either preceding or succeeding the 'missing' growing cycle. Years with a significant proportion of missing climatic data were omitted from the exercise, as any simulation results could not be accurately or reliably reconciled with the reported Ya. The KSCL and Nchalo mills, were missing nine and eight years of Ya records, respectively (Table 2). This limitation was recorded in the modelling study and considered in the interpretation of the results. Regardless, several authors (*e.g.* Ref. [25]; van Ittersum et al., 2013; Fischer et al., 2015) recommend a minimum of 15 years of Ya and climate data for low-yielding areas, and at least 5 years for high-yielding areas for performing a YG study. In this study, the average Ya data spanned an average of 19 years, while the climate data averaged 15 years. The majority of the mill areas were considered to be high-yielding and met the minimum of 15 years of data to permit the YG analysis.

To calculate the $YG_T$, $YG_{WD}$ and $YG_{CM}$ were simulated for individual mill areas using the AquaCrop model. The exception to this approach were the UCL and Noodsberg mill areas in South Africa which, being within a 12 km radius of each other, tend to operate and report yields as a single mill depending on seasonal conditions (seasonal production rates, availability of labour, pest outbreaks, fuel prices *etc.*), and on where individual growers choose to send their harvests in any given growing cycle. Thus, yields for all mill areas were simulated based on their own unique climate conditions, management approach, length of the growing cycle, area under sugarcane, irrigation status and planting density.

### *2.3. Input data acquisition and processing*

Observed average annual yield (Ya) data were obtained from FAOSTAT (2019), the South African Canegrowers Association (SACGA) yearbooks, the South African Sugarcane Research Institute (SASRI), the UCL Company, the Swaziland Sugar Association, Kasinthula Canegrowers Association, Illovo Sugar Africa, Illovo Malawi, the University of KwaZulu-Natal, Harvest-Choice and the Kilombero Sugar Company (KSCL) (Table 2). South Africa (1994–2019) and eSwatini (1996–2019) had the longest observed yield records. The bulk of observed sugarcane yield data from Malawi and Tanzania was estimated from the total annual output and area under sugarcane as reported by the mills, as there were either no known or reliable records prior to 2000. A limitation with datasets from Malawi and Tanzania was the lack of independent verification; therefore, it was necessary to back-calculate the Ya from available area and mill crush/production data to create a synthetic yield record from secondary sources. Ultimately, these estimated yields prior to 2000 were excluded from the YG exercises, as there was no reliable method of validating their accuracy.

Where necessary, the records were checked for errors using data profiling, identifying outliers, double-mass plots, and using the ACRU-based Time Series Analysis [70] tool to find and correct errors. Following this exercise, records were considered to be robust enough for use in the crop yield modelling exercise. Missing daily climate data was infilled using data from weather stations closest to the mills. Some missing parameter values that could not be infilled, quality controlled or sourced from veritable sources were defaulted to the standard as per the AquaCrop model guidelines. This default value can be changed in the model as and when data becomes available. The AquaCrop model was used to generate $ET_O$ data from observed temperature records using the $ET_O$ calculator embedded within the model which is based on the FAO Penman-Monteith equation [71]. The primary limitation of this approach was related to scale. Climate data from mills are only representative of the mills themselves, and not the entire mill area. Therefore, an assumption was made that climate data from mill areas are representative of so-called 'homogeneous climate zones' that span the mill area [25]. The results were a continuous set of daily and monthly climate records ranging from 1994 to 2019 for each mill area.

The remaining datasets, including soils and management data, were based on Best Management Practices for sugarcane production as suggested by researchers (*e.g.* Refs. [39,72,73] and the USDA and the FAO-AGRIS databases.

### *2.4. Model inputs and simulation procedures*

The AquaCrop model (version 6.1 released in 2018) was set up for individual mill areas and simulations were performed iteratively for 25 years between 1994 and 2019. AquaCrop is a water-driven model that requires climate, crop, field and irrigation management and soils data to simulate above-ground biomass and, ultimately, yields. In the case of this study, simulated yields were represented by Yp, Yw and $YG_{WD}$ and $YG_{CM}$. This section describes the modules within the AquaCrop model and the procedures which were followed to simulate sugarcane yields (Fig. 6).

#### *2.4.1. Conservative and non-conservative parameters*

The AquaCrop model uses both conservative and non-conservative parameters to simulate crop yields. Conservative parameters are not affected by location, crop and soil management, time and field management and, thus, were kept constant throughout the simulations. These conservative parameters primarily are coefficients which govern *inter alia*, canopy cover, canopy growth and development, flowering and yields, root deepening, soil water depletion, flowering and stomatal opening and closure, aeration stress, salinity and fertility, crop coefficients for total evaporation and atmospheric $CO_2$ concentration. Since these simulations were concerned with only the sugarcane crop, these conservative coefficients were fixed for all mill areas and throughout the simulation periods. Additional conservative parameters which remained constant for all mill areas under study included soil water retention, hydraulic conductivity, stoniness and penetrability characteristics and soil type. It is important to note that these parameters can be adjusted as and when required to improve simulations; however, this was kept to a minimum. All remaining parameters were considered to be non-conservative (*i.e.* parameters that require adjustment for individual mill areas), and these are described in the following section and summarised in Table 3.

#### *2.4.2. Simulation procedures*

The AquaCrop model requires daily observed rainfall, minimum and maximum temperature, $ET_O$ and atmospheric $CO_2$ concentration as input. The climate module was set up for individual mill areas with the exception of the Noodsberg and UCL mills, which (as mentioned

**Table 3**
Non-conservative parameters used in the AquaCrop to simulate yields.

| Parameter | Unit |
|---|---|
| Crop Water Productivity (WP) | g. $m^{-2}$ |
| Rainfall | mm |
| Temperature | $^{O}C$ |
| $ET_O$ | mm.$day^{-1}$ |
| Plant Density | plants. $ha^{-1}$ |
| Soil water depletion coefficient | dimensionless |
| Leaf growth stress coefficient | dimensionless |
| Stomata stress coefficient | dimensionless |
| Days from sowing to senescence and harvesting | days |
| Harvest Index | dimensionless |

previously) were treated as a single mill owing to their proclivity to operate as one mill. Once the climate data were correctly formatted, quality controlled and reliable records of sufficient length were established for each mill area, and used as input into the model.

The model was run with the assumption that a full set of crop development and production parameters was available. In reality, some of these parameters had to be estimated from observed records as obtained from agronomy annual reports published annually by individual mills. The model was run in calendar days spanning the length of the growing cycle, as opposed to growing degree days, which only consider heat units required by the crop to reach senescence. The sowing dates were based on actual dates as reported by individual mills assuming direct sowing as the preferred planting method. Since this was the planting method selected, canopy cover was assumed to be initially small, progressively increasing until maximum canopy cover was reached. Plant densities varied between mill areas with each mill area averaging 350 000 plants per hectare based on interrow spacings of 1.00 m and plant spacings of 0.05 m [73,74]. Plant density estimates are a crucial component that directly influence overall above-ground biomass and thus yields, and these estimates were based on planting and seeding densities recommended by SASRI (2018), the [73,75]. In some instances, plant densities had to be adjusted according to the prevailing seasonal conditions. For instance, during droughts, the number of plants per hectare was reduced to offset the effects of water stress on overall yields.

Days to reach emergence, maximum canopy cover, senescence and maturity were determined based on calendar days and growing cycle length for each mill area. For instance, the Ubombo mill area adopts a 12-month growing cycle, with days to senescence and maturity of 105 and 127 days, respectively. The South African mill areas follow a 24-month growing cycle with days to senescence and maturity of 582 and 604 days, respectively. The days to senescence, maturity and harvest are important as they, together with plant densities, directly influence the harvest index and overall yields generated by the AquaCrop model. Accepting that sugarcane is extremely sensitive to water stress, it was specified in the model that the crop is extremely sensitive to soil water stress, air temperature or $ET_O$ stress, soil salinity and fertility stress. Non-conservative coefficients related to $ET_O$, crop water productivity and *HI* were kept constant.

Field management parameters were adjusted according to the soil surface and water management approaches adopted at each mill area. For instance, the Eston mill area adopts a hybrid of irrigation and rainfed regimes. In this instance, the net irrigation requirement option was invoked in AquaCrop. This option ensures that at no point does the crop experience water stress, as the allowable root zone depletion is set at a maximum of 50% of the readily available water (RAW). It was assumed that once RAW reached 50%, irrigation would be activated to return the soil profile to field capacity. The irrigation option was not invoked for mill areas that are exclusively rainfed such as the Noodsberg and UCL mills. The Ubombo mill area is exclusively irrigated and the irrigation option was invoked assuming surface irrigation with an allowable RAW depletion of 10% to return the soil profile to field capacity.

Field management parameters such as soil fertility, mulching, runoff reduction practices and weed management were assumed to be non-limiting such that sugarcane in each mill area was produced under the best possible management practices. Once all the modules were compiled, the model was run on a growing cycle basis for 24 years and for all 6 mill areas.

### 2.5. Yield estimation

The AquaCrop model simulates potential yields (Yp) as a function of total evaporation ($ET_O$). The model translates $ET_O$ into above-ground biomass (B) using conservative and non-conservative crop parameters, crop water productivity (WP) and daily crop transpiration ($T_r$) using Equation (4.1):

$$B = WP \text{ x} \sum_{i=0}^{n} \left( \frac{T_r}{ET_o} \right) \tag{Eq. 4.1}$$

where:

B is the above-ground biomass ($t.ha^{-1}$), $T_{ri}$ is the daily crop transpiration ($mm.day^{-1}$), $ET_O$ is the daily total evaporation ($mm.day^{-1}$), and WP is the crop water productivity normalized for daily total evaporation or atmospheric evaporative demand ($ET_O$). WP is normalized for the local climate (*i.e.* $ET_O$) and is nearly constant for a crop provided no limitations related to water and soil nutrients are present. The normalization for the local climate is calculated from the quotient of $T_r$ and $ET_O$.

The AquaCrop model estimates potential yields from the product of above-ground biomass and the harvest index using Equation (4.2):

$$Yp = HI \text{ } x \text{ } B \tag{Eq. 4.2}$$

where:

Yp is the potential yield ($t.ha^{-1}$) that would be achieved provided that there are no agronomic or management limitations to crop growth, HI is the harvest index which is the fraction of biomass that is harvestable product and B is the above-ground biomass ($t.ha^{-1}$). The harvest index is influenced by the degree of water stress a crop is subjected to throughout the growing cycle and can vary from cycle to cycle. Potential water-limited yield (Yw) is the yield that would be achieved provided the crop is not affected by access to water from rainfall, irrigation and soil moisture. Yw was simulated by specifying no water stress, regardless of prevailing rainfall and irrigation conditions. $YG_{WD}$ and $YG_{CM}$ were not simulated directly in the model. $YG_{WD}$ was calculated as the difference between Yp and Y (*i.e.* Yp – Yw) and $YG_{CM}$ was calculated from the difference between Yw and Ya (*i.e.* Yw – Ya).

### 2.6. Model validation and verification

To ensure that the AquaCrop model adequately represented the observed (*i.e.* historical) yields as reported by individual mills, verification studies were performed over a 15-year period ranging from 2004 to 2019. This period was selected as it covers the most complete and easily verifiable sugarcane records for the mill areas in the catchments. Model simulations were verified against observed sugarcane yield data from the three South African mill areas and the Ubombo mill area in eSwatini, and results from these exercises indicated that the model was closely representing reported observed yields.

Mill areas in South Africa and in the Ubombo catchment were considered in the verification exercise, as they have sufficiently long observed climate data and sugarcane yield records to permit an appropriate verification study. The model was verified for rainfed and irrigated conditions assuming 24-month growth cycles at the mill areas of concern. Results from those exercises (Figs. 4 and 6), show that the model was able to consistently reproduce sugarcane yields satisfactorily across the verification period.

To account for the 24-month growing cycle, observed (Ya), simulated (Yp) yields and total yield gaps ($YG_T$) are as 2-year moving averages for the verification period. Comparisons between observed and simulated sugarcane yields for the South African and Ubombo catchments respectively indicated strong statistical correlations in terms of precision (RMSE), correlation coefficient ($R^2$) and mean absolute percentage error (MAPE). Based on simulation results, mill areas in South Africa collectively reported an RMSE of 0.88, an $R^2$ of 0.96 and an MAPE of 5.74. Mill areas in the Ubombo catchment reported an RMSE of 0.98, an $R^2$ of 0.61 and an MAPE of 14.76. In this regard, the AquaCrop model was considered to be adequate for simulating sugarcane yields in the remainder of selected catchments.

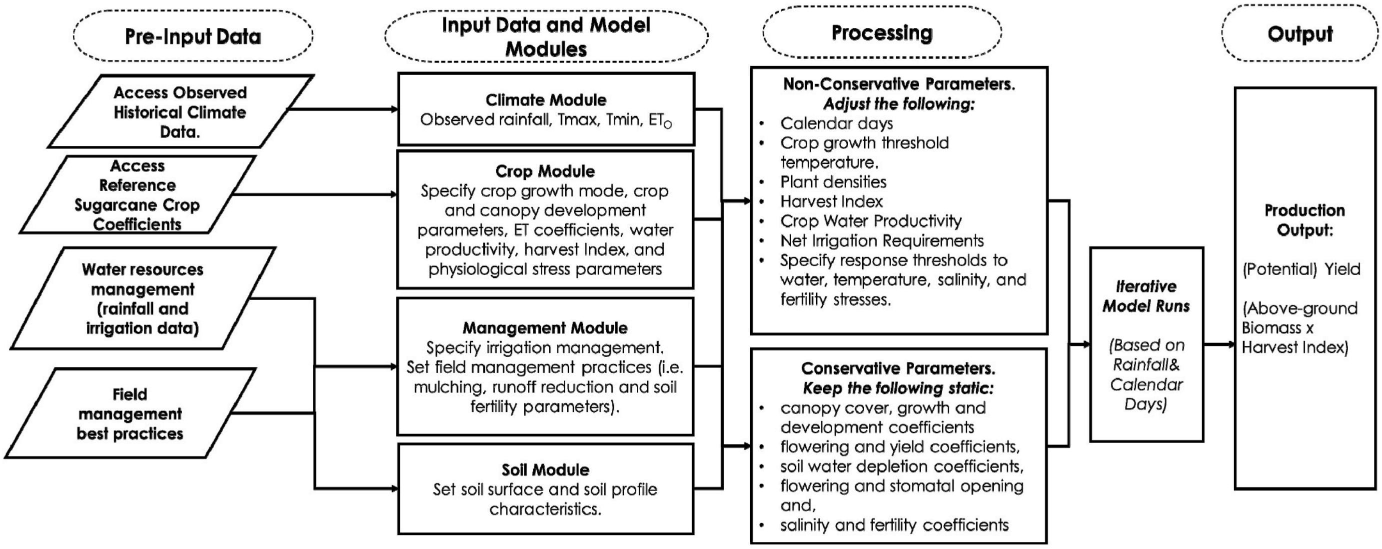

**Fig. 4.** A summary of the modelling procedures in the AquaCrop model adopted in this study to determine yield gaps.

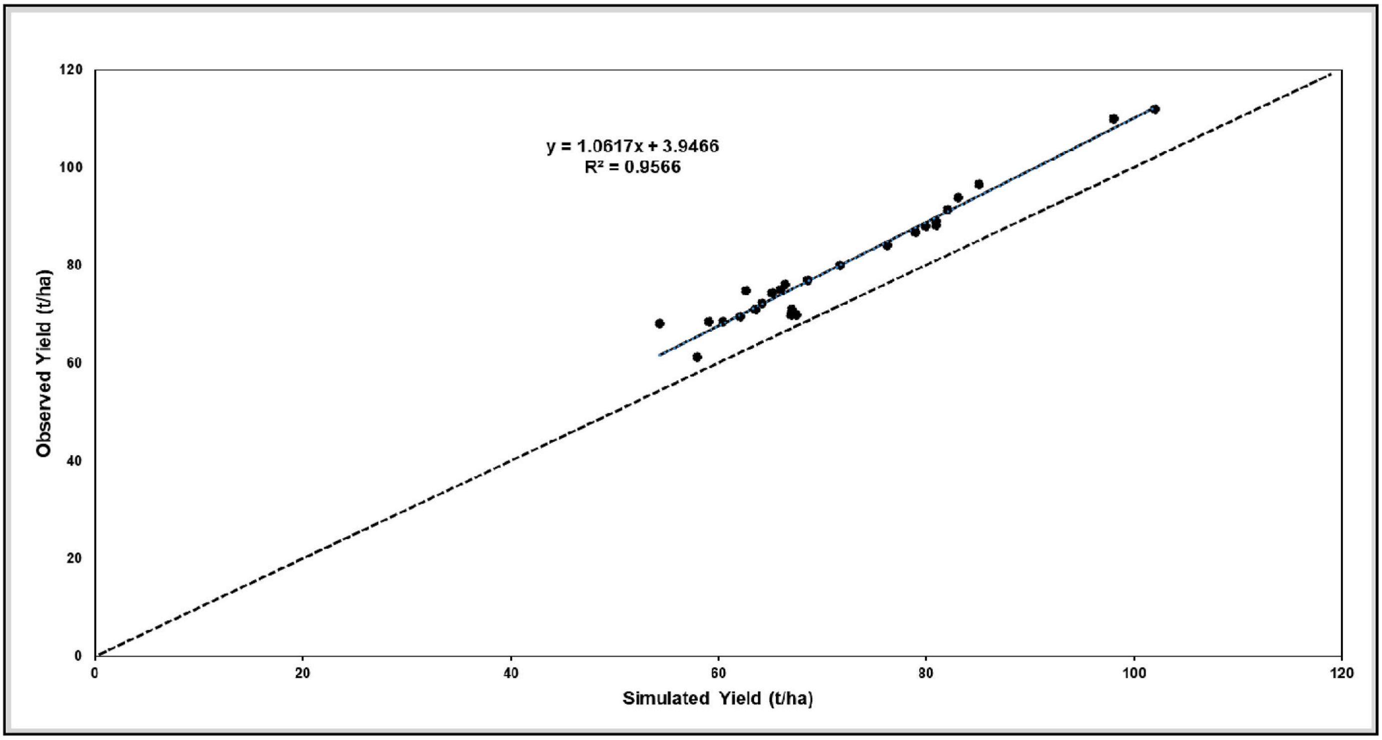

**Fig. 5.** AquaCrop verification results based on average (*i.e.* combined) observed (Ya) and simulated (Yp) sugarcane yield data for the mill areas in South Africa.

## 3. Results and discussion

### 3.1. Sugarcane yield trends and yield gaps

The average Ya simulated by AquaCrop for mills in South Africa, the Ubombo Catchment, the Shire Catchment and the Kilombero Catchment were, respectively, 71.95 t/ha, 46.50 t/ha, 71.48 t/ha and 113.09 t/ha over the study period. It is important to note that although the yields presented are reported as annual yields, they are in fact, moving averages of growing cycle yields. Therefore, regardless of whether mills adopted 12-month or 24-month growing cycles, the yields reflect a 2-year moving average to provide comparable annual yields. In the irrigated Big Bend mill area in the Ubombo catchment, Ya consistently increased for the period 1996–2004, remained almost constant for the period 2005–2015, and subsequently increased in the post-drought 2016–2019 period. These trends can be attributed to the fact that sugarcane is almost exclusively irrigated in this mill area which consequently buffers and limits yield declines. The reported near-constant Ya trend during the 2005–2015 period was considered to because for further investigation. Yields during this period changed by less than 1% per annum, and this was considered to be unlikely.

This unlikely trend was attributed to either under-reporting of Ya by the mill or, potentially, the diversion of harvested sugarcane to nearby mills for processing (SASRI, 2018). In any case, Yp in this mill area was consistently higher than Ya by at least 10% per annum. This was because no limitations regarding crop growth parameters were invoked for this

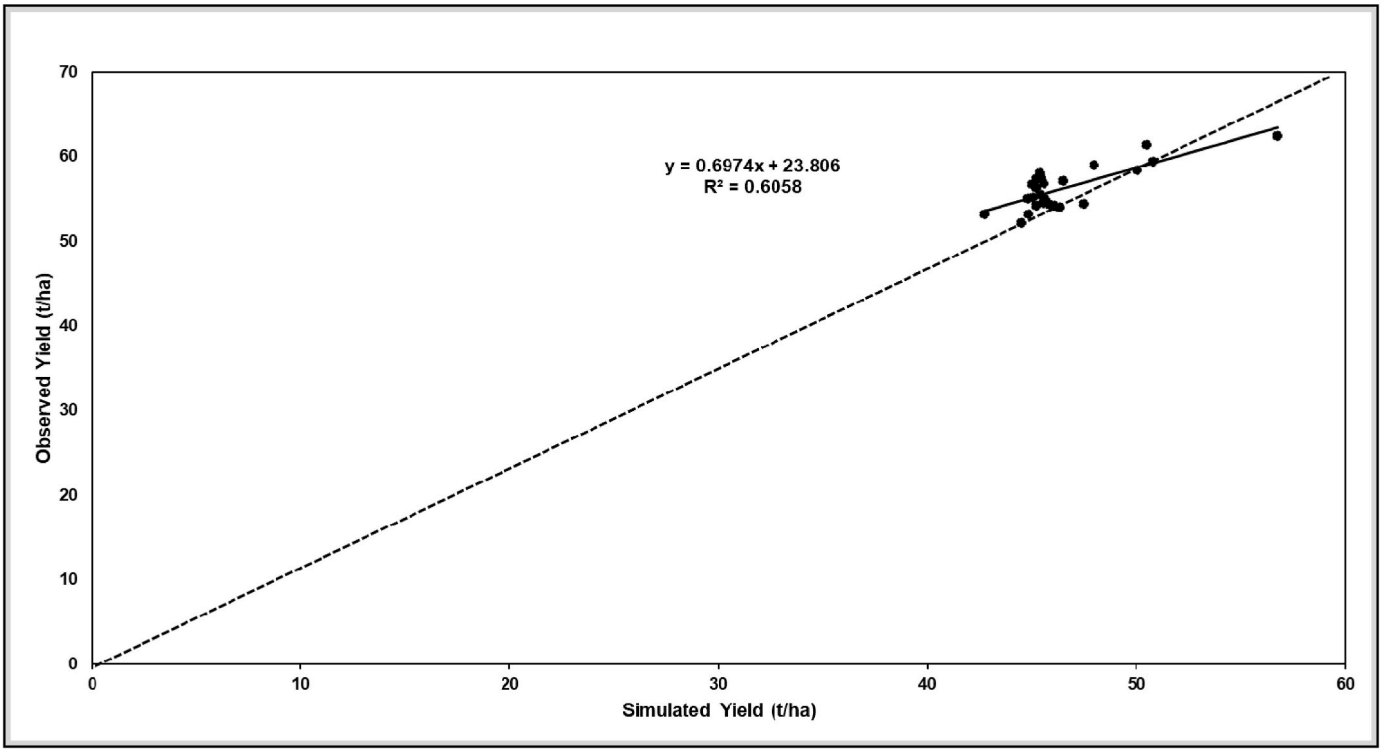

**Fig. 6.** AquaCrop verification results based on observed (Ya) and simulated (Yp) sugarcane yield data for the Big Bend mill area in the Ubombo catchment.

mill area in the simulations, and it was noted that rainfall has been steadily increasing in this mill area for the 1996–2019 period. However, despite the consistently higher Yp relative to Ya, Ubombo had the lowest average Yp of all the mill areas in the study. This, again, was attributed to widespread irrigation and the use of the drought resistant N41 and N26 varieties which, in part, prevented yield declines and kept yields fairly constant [64] (Fig. 7a). The implication of the constant Yp implies that the maximum possible yields are already being produced in this mill area and any crop management interventions are unlikely to result in increased yields - unless there is a considerable increase in the area under sugarcane or the adoption of an alternate high-yielding sugarcane variety. Consequently, the average $YG_T$ for this mill area averaged 9.83 t/ha and consistently increased for the period under study. This suggests that without major agronomic management changes, yields will likely remain constant for the foreseeable future in this catchment which can potentially enhance yield gaps.

The KSCL mill area had the highest average potential yield (Yp) of all the mill areas due to, in part, the limitations that growers in this catchment face related to high cloud cover, short sunshine duration and the high rainfall seasonality over the growing cycle (Fig. 7b). This suggests that, despite the reported increases in Ya, sugarcane growers in this mill area can still benefit from investments such as drought-resistant sugarcane cultivars and supplementary irrigation during the dry periods, which would significantly improve yields and reduce water deficits. $YG_T$ in this mill was observed to be in decline, particularly in the 2009–2019 period as a result of (reportedly) increases in the area under sugarcane in this catchment and increased contributions by outgrowers to the KSCL mill (Kilombero Sugar Company, 2019). Outgrowers are defined here as small-scale sugarcane producers that primarily grow sugarcane from smallholdings to supply larger commercial growers through binding contractual agreements [58,76]. Regardless of the increases in contributions from outgrowers, commercial growers still constitute the bulk of sugarcane yields in this mill area. It is clear that yields are, in fact, increasing for this mill area despite the fact that the Yp remains high.

The three mill areas in South Africa consistently indicated declining yield trends for the 2002–2017 period, and a slight improvement for 2019 (Fig. 8a). Ya and Yp for these mill areas averaged 71.95 t/ha and 80.34 t/ha respectively for the period under study. The relatively high average Yp in these mills is a result of declining yields resulting from climatic variations (Singels et al., 2013), increased pest outbreaks (Naude, 2015), increased competition for access to water resources and reductions in areas under sugarcane [60]. Further, these high Yp estimates suggest that there remains a requirement for improved agronomic performance by growers in these areas, despite having access to advanced irrigation and in-field mechanisation technologies.

The Nchalo mill area indicated a slight increase in Ya for the 2000–2006 period and minor, yet consistent Ya declines over the 2007–2019 period (Fig. 8b). As minor as these yield declines may be, they potentially represent a significant proportion of yield for outgrowers in this mill area as they already produce proportionally smaller yields compared to the commercial growers. Ya and Yp were estimated at 71.48 t/ha and 82.53 t/ha respectively. The implication is that growers in this catchment can also benefit from enhanced irrigation and even increases in area under sugarcane. However, sugarcane growers in this catchment face intense competition from other commodity crops, particularly tea growers. $YG_T$ was increasing for the 2001–2007 period but had since been steadily decreasing for the 2007–2019 period.

The KSCL mill area had the highest average water-limited yield (Yw) of 123.3 t/ha owing to the high overall MAP and low water deficits during the wet seasons. This, however, masks the significant impact of high rainfall seasonality and a lack of supplementary irrigation during the dry months on overall yields in this catchment. Mill areas in South Africa and Shire catchments also presented high average Yw yields of 75.69 t/ha and 73.00 t/ha respectively owing to lower water deficits as a result of limited irrigation, relatively high MAP and the use of high-yielding sugarcane cultivars. The Big Bend mill had the lowest average Yw at 47.92 t/ha due to higher water deficits caused by lower MAP and high temperatures. This demonstrates the need for continuous irrigation for the growing regions in this catchment.

The overall average Ya as reported by the individual mills and various sources averaged 71.95 t/ha for the South African mills, 46.50 t/

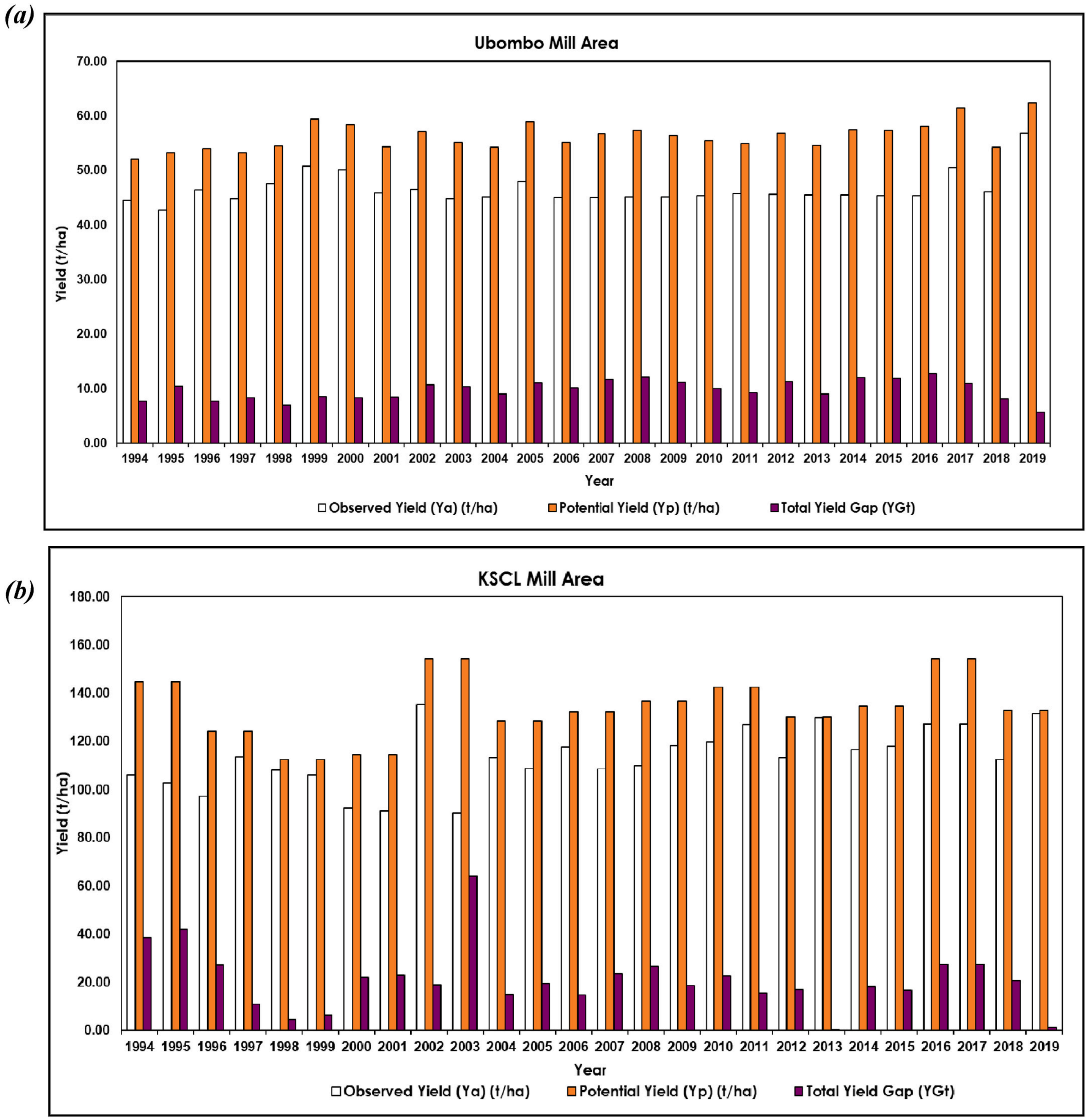

**Fig. 7.** **(a)** Observed (Ya) and simulated (Yp) yield for the irrigated Big Bend mill in the Ubombo catchment and **(b)** the KSCL mill area in the Kilombero catchment. The total yield gaps ($YG_T$) per year are also reported here indicating, on average, an increase in yield gaps over the 1996–2015 period and a subsequent decrease in yield gaps from 2016 to 2019.

ha for the Big Bend mill, 71.48 t/ha for the Nchalo mill and 113.09 t/ha for KSCL mill. On average, observed yields are declining for mills in the Mngeni and Shire catchments and increasing for mills in the Ubombo and Kilombero catchments, particularly after 2003 (Fig. 9). These differences in Ya can be attributed to, *inter alia*, recent variations in rainfall and temperature [73,77], access to supplementary irrigation [78], changes in areas under sugarcane and changes in agronomic management (particularly the use of drought and pest-resistant sugarcane cultivars) [79]; SASRI, 2018). It is important to note that the yield trends and yield gap simulations did not consider improvements in production technology, changes in sugarcane production policies and the development of improved cultivars - simply because there are currently no options in the AquaCrop model to factor in these possibilities. All these parameters and/or possibilities would have, potentially, resulted in increased potential yields (Yp) and reductions in $YG_T$ [60] (see Figs. 10 and 11).

### 3.2. *Drivers of yield gaps*

Yield gaps are primarily driven by access to water resources ($YG_{WD}$)

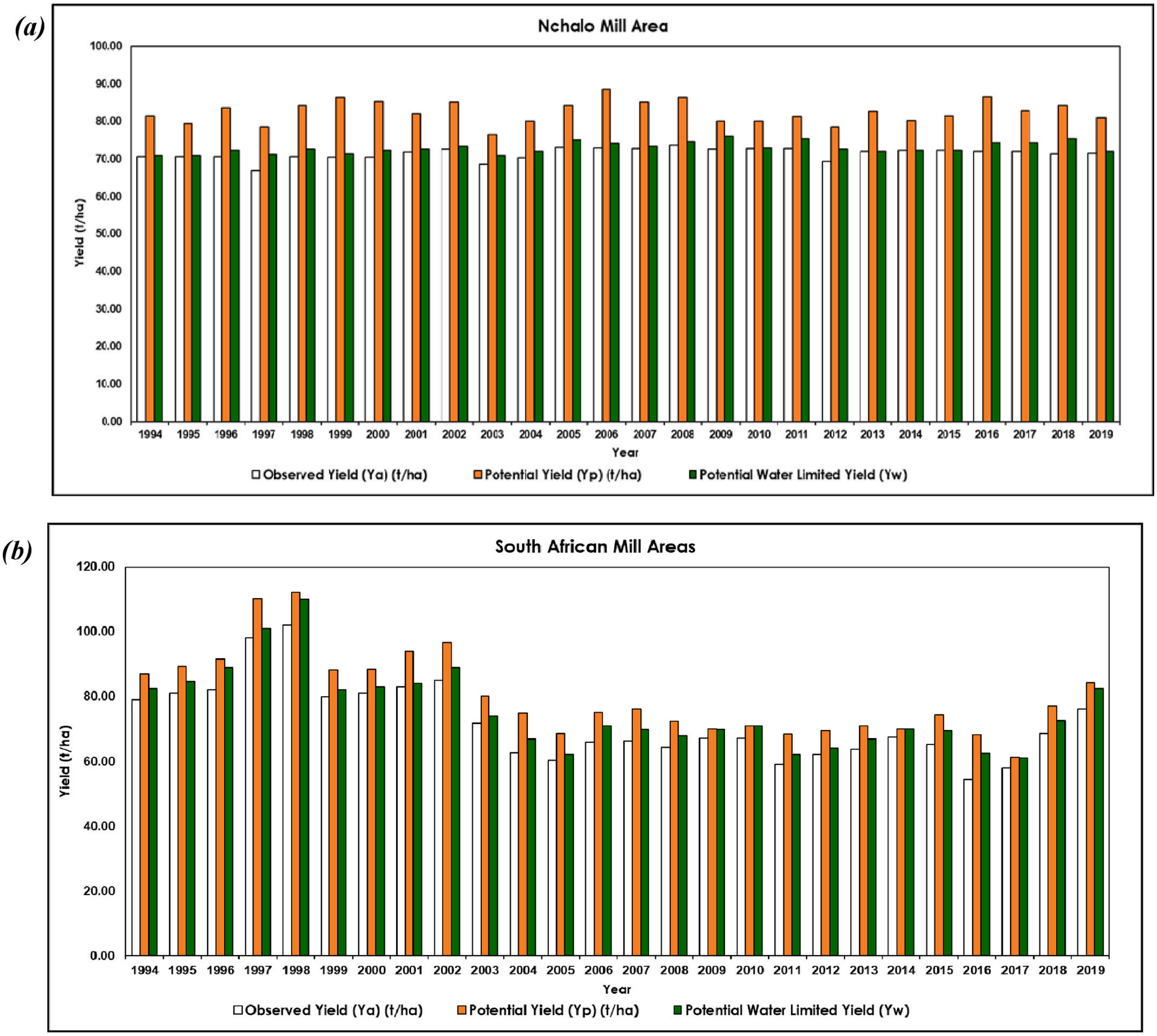

**Fig. 8.** Potential water-limited yield (Yw) for the **(a)** South African and **(b)** Nchalo mill areas compared to observed (Ya) and potential (Yp) yields. Yw for these mills area averaged 75.69 t/ha over the course of the study as a result of lower water deficits.

and approaches to crop management ($YG_{CM}$). For mill areas in the studied catchments, access to water resources remains a significant challenge, as is growing sugarcane under optimum crop management conditions. Unlike in countries such as Brazil or India, the hydroclimatic environment for most of southern Africa does not necessarily support the industrial-scale production of sugarcane [13,50]. However, as a result of improvements in agronomic management and the development of adaptive cultivars and improvements in the sugarcane supply chain, the crop has seen significant success in the past 50 years. Results from this study, however, suggest that a substantive change in both water resources management and management approaches for both rainfed and irrigated mill areas has occurred in the past 25 years. This is indicated by the significant changes in yields across all mill areas. While it is tempting to suggest that climate change prompted these changes, and is thus the main antagonist of Yp and $YG_{T}$, it is important to remember that crop management assumes an equally, if not more important role in the production of sugarcane.

In the irrigated Big Bend mill, $YG_{WD}$ (*i.e.* the difference between Yp and Yw) was increasing at an average of 8.20 t/ha/annum between 1996 and 2014, and declined to an average of 8.13 t/ha/annum between 2015 and 2019. Although this does not represent a significant decrease in $YG_{WD}$, it is potentially a result of improvements in water resources management through increased irrigation and water conservation. Further, irrigation by commercial growers supplying the Big Bend mill are considered to be using the maximum available water resources in the Ubombo catchment [56], which implies that there is limited scope for improving $YG_{WD}$. $YG_{CM}$ (*i.e.* the difference between Yw and Ya) also declined from an average of 1.46 t/ha/annum between 1994 and 2006 to 1.12 t/ha/annum between 2007 and 2019. Decreases in both $YG_{WD}$ and $YG_{CM}$ in this mill can be attributed to, among other factors, increases in irrigation rates, the use of improved cultivars like the N41 and N26 variants [64], and, in some cases, increases in areas under sugarcane [80]. It is, therefore, apparent that access to water resources (*i.e.* $YG_{WD}$) assumes a more important role than $YG_{CM}$ in the $YG_{T}$ for this mill area.

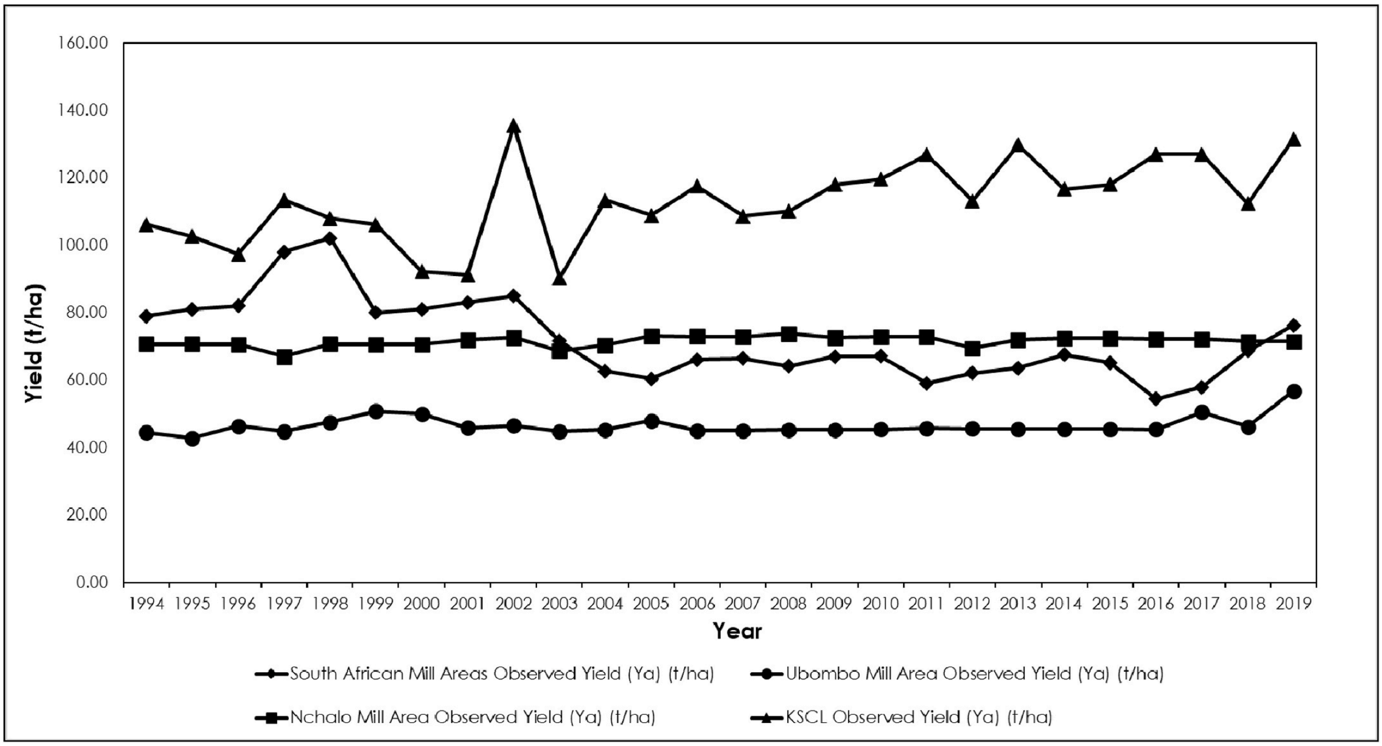

**Fig. 9.** Observed yield trends for all mill areas under study between 1994 and 2019.

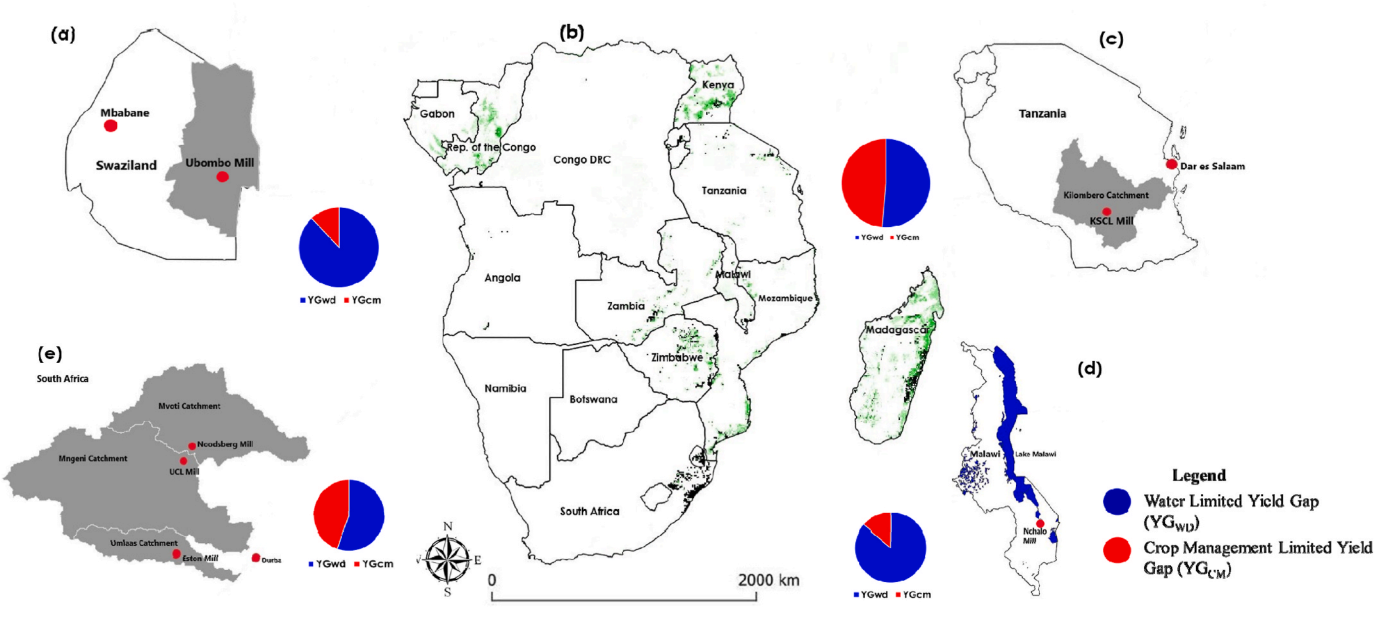

**Fig. 10.** Access to water resources and crop management as the main causes of sugarcane yield gaps across the study catchments.

Further, Ya and Yp increased between 2014 and 2019, which suggests some improvements in crop and water resource management by growers supplying this mill leading to increased yields.

The KSCL mill area witnessed increases in Ya and Yp for the verifiable 2004–2019 period as a result of increased rainfall rates, which appears to have favoured increased sugarcane productivity. A consistent decline in $YG_{WD}$ and $YG_{CM}$ resulted in increased Yp. It should be noted that the actual Ya for the period between 1994 and 2000 could not be independently verified, therefore the yield trends reported for this *specific* period are all estimations. Sugarcane production in the KSCL mill faces a range of challenges, including access to irrigation, the physical geography of the Kilombero catchment which limits the area under cane and limited sunshine hours caused by high cloud cover, which contribute to a lower sucrose content of sugarcane. Despite these limitations, $YG_{WD}$ and $YG_{CM}$ and, therefore, $YG_T$ have been consistently declining. This is possible due to two main reasons: i) the Kilombero catchment has high rainfall seasonality (MAP averages 1200 mm during the rainy seasons and 990 mm during the dry seasons), and growers in this catchment have been investing in water conservation structures such as small-scale dams to preserve water and create sustainable water

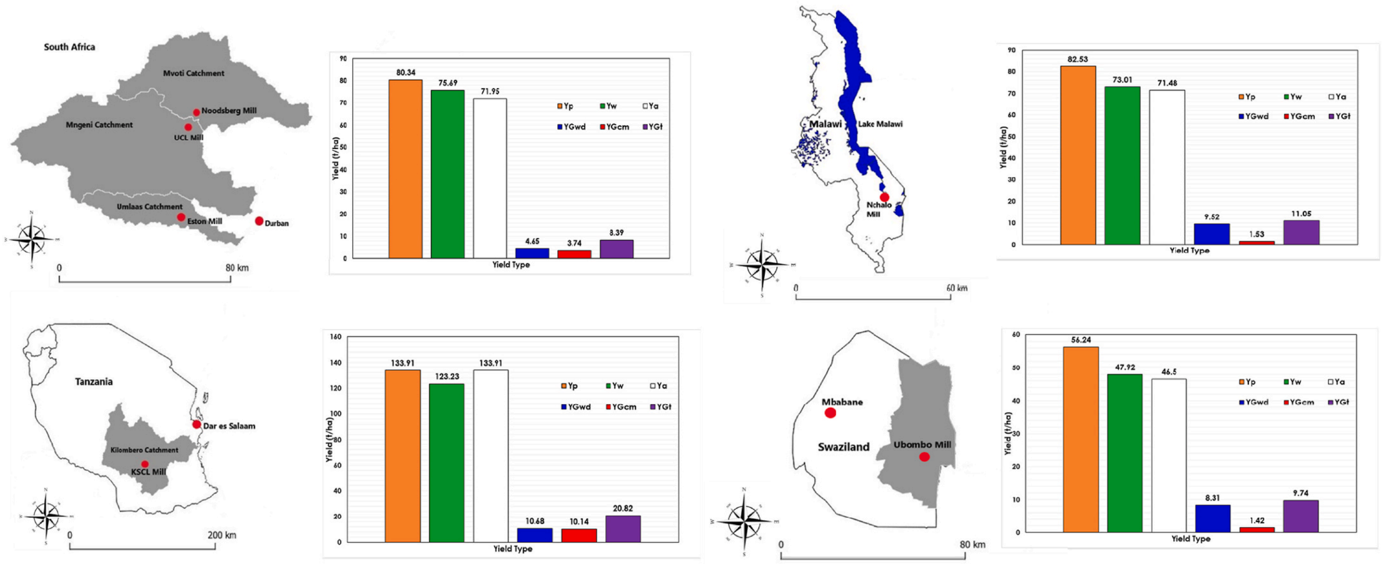

**Fig. 11.** Yield gap analysis results for the mill areas under study based on the conceptual framework.

sources for irrigation; and ii) an increase in the number of small-scale growers subsidised by the Tanzanian government and yield contributions from these growers would result in an increase in reported Ya.

The three mill areas in South Africa have experienced consistent declines in yields over the past 25 years. For these mills, Ya and Yp have been in decline since the early 2000s. However, $YG_{WD}$ has been in decline since the 2001–2002, suggesting that water resources management has been improving over the past 25 years in these mill areas, a fact that is at odds with observed yield declines. This suggests that access to water resources is not, in fact, a limiting factor to sugarcane production in these mill areas, and that yield declines are being driven by a different set of factors. Considering the general increase in $YG_{CM}$ over the 2001–2019 period, it is evident that there is a facet of crop management that is the key driver of yield declines in these mill areas. Since this study did not conduct a stakeholder survey, it would be difficult to suggest the actual crop management related cause of these yield declines. However [59], conducted a similar survey for the South African sugar industry, and the growers who participated suggested a number of crop management factors which they perceived to be the key drivers of yield declines. These included, *inter alia*, soil degradation, increased soil compaction as a result of high in-field traffic, increasing pest and weed pressures, declining age at harvest and climate change [77]. It is clear, therefore, that if these trends are to be stopped, growers in these mill areas require novel approaches and interventions to sugarcane production that can reduce soil degradation, enhance water holding capacities and safeguard sugarcane from pest outbreaks.

Yields in the Nchalo mill area have been in decline since 2006. $YG_{WD}$ was declining for the 2000–2003 and for the 2006–2012 periods due to rapid expansion in irrigation by large-scale growers during the period. However, yields continued to decline since the 2006–2012 period. $YG_{WD}$ then rose sharply between the 2013–2016 period and again for the 2018–2019 period. This suggests that sugarcane production in this mill area is under increased pressure to access water resources, and this is increasingly suppressing yields. $YG_{CM}$ indicated no consistency during the study period. This was attributed to the fact that sugarcane production in this mill area is more of an alternative than a primary agricultural activity [58], and growers only actively engage in it if they have access to the requisite resources. This implies that sugarcane yields are likely to keep declining as the pressures of climate change become more apparent.

### 3.3. Recommendations to reduce yield gaps

We suggest that yield gaps can either increase or decrease depending on the management and hydroclimatic conditions unique to each mill area. In instances where yield gaps are currently, or will be, driven by access to water resources, the continuous improvement of efficient irrigation techniques in conjunction with the development and adoption of water-use efficient high-yielding sugarcane varieties and improvements in in-field crop management is imperative [74,81]. While it is noted that access to capital to invest in irrigation systems, reservoirs and other water conservation technologies is often a challenge in certain of the mill areas (*e.g.* the Nchalo mill area) [82] it is nonetheless important that innovative solutions are developed to increase yields whilst not increasing water use. Some low-cost approaches can include mulching and contouring which can minimize surface runoff and improve infiltration and improve rooting depths [27]. Mulching can assist in minimizing soil surface evaporation and overall decrease total evaporation which will result in lower crop transpiration rates.

The adoption of drought-resistant and high-yielding varieties that, while expensive to develop in the short-term, will undoubtedly increase yields without the need of increasing the area under sugarcane for the mill areas [83]. Finally, retaining post-harvest crop residues can increase effective rainfall by increasing soil moisture through increased infiltration [84] Minimizing in-field traffic, such as is being undertaken in the Noodsberg and UCL mill areas of South Africa [61], can reduce soil compaction, thus improving infiltration rates and increasing soil organic matter during the tilling and harvesting phases. This will enhance the soil nutrient status and improve growth rates and the accumulation of biomass. Further, soil compaction can be reduced by opting for hand-cutting sugarcane as opposed to machine harvesting. The management of the soil physicochemical well-being is a consistent challenge, growers in the study sites often grapple with (SASRI, 2018). There is a range of approaches to achieve and maintain healthy soils which include (but are not limited to) crop cycling, using ameliorants such as gypsum to reduce soil acidity, fallowing (although unpopular among growers for economic reasons) and, where possible, minimizing tillage.

Frequently overlooked interventions include; increasing technology transfer and agronomic management education to small-scale outgrowers who otherwise may not be privy to up-to-date knowledge that can assist in improving yields. Small scale growers make-up a significant proportion of sugarcane supply in mill areas such Eston, Nchalo and

KSCL and if yields are to be improved, these growers should be included in the research and development processes, including feedback as to what types of information might be most useful.

## 4. Conclusions

The AquaCrop model was used to perform a YG analysis based on observed climate and sugarcane yield data for six mill areas located in four countries across southern Africa. The difference between simulated yields and water limited yields result in $YG_{WD}$, while the difference between water limited yields and observed yields resulted in the $YG_{CM}$. The sum of $YG_{WD}$ and $YG_{CM}$ defined the total yield gap or $YG_T$ for each mill area. A key aspect of this methodology was the use of observed sugarcane yield data to simulate maximum potential yield at mill area level. Results indicated that yields are declining for the mill areas in South Africa and Malawi, stagnant in eSwatini and increasing in Tanzania. These trends were the results of the unique approaches and growing conditions that are adopted by both large and small-scale growers in each mill area. In South Africa, for instance, yield declines were not caused by access to water resources but, instead, by approaches to soil management and by the pressures of pests and disease. Yield declines in the Nchalo mill area in Malawi were the result of inadequate access to water resources and on the fact that sugarcane is not cultivated as a priority crop in this mill area. The Big Bend mill has seen stagnation in yields as a result of a lack of space to cultivate sugarcane. The KSCL mill area actually indicated increases in yields over the past 15 years, a trend which was attributed to the increased investments in irrigation and state-sponsored subsidies in the national sugarcane industry.

It should be noted that yield gaps remain a cause for concern in these mill areas, since they appear to be increasing. Growers thus remain exposed to climatic extremes, and current management approaches may not be adequate to manage or respond to these conditions. Solutions to reduce yield gaps were recommended in this study and these were considered be applicable to most, if not all, mill areas under study. Further, while sugarcane production remains a viable enterprise in the region, it remains under significant pressure to minimize resource use (land, water, and costs), while remaining internationally competitive. The recommendations to address yield gaps suggested in this study can potentially increase yields and reduce yield gaps while minimizing resource inputs.

A strength of this study was the development of a methodology which used both long-term yield and observed climate data to simulate maximum potential yields by taking into consideration limitations related to crop management and access to water resources. Granted, observed records were not always comparable because in some instances (*e.g.* KSCL and Nchalo observed yields for the 1994–2000 period) data was simply not available. The verification of the AquaCrop for simulating sugarcane production was considered to be a unique and useful exercise that demonstrated the adequacy of using a simple but robust model to simulate sugarcane growth in southern Africa. The simulations in most cases compared favourably to observed yields.

A limitation of this study was that a single model was used to simulate yields. The study could have benefited from the use of ensemble models to simulate sugarcane growth. A further cause for concern was that a stakeholder survey into the actual drivers of sugarcane yield declines could not be conducted. This would have assisted in understanding the underlying dynamics which influence sugarcane production across the mill areas, and would have provided useful insights into the most useful and relevant strategies to reduce yield declines and reduce yield gaps.

Although sugarcane growers cannot directly address the impacts of climate change on yields and yield gaps, they can create production systems that can be more resilient to extreme events by adopting what is now so-called ‘climate-proofing’. One way of achieving this would be to have a system that allows small and large-scale growers free access to easily understandable and interpreted current climate forecasting data that extends at least 5–10 years into the future. This will, with additional interpretation and (essentially) appropriate support, enable them to respond rapidly to any sudden climatic shocks such as floods, droughts, heat waves and even shifting hydrological patterns. A grower who has access to current knowledge regarding the impacts of climate change on sugarcane production would be at an advantage and will be able to sufficiently prepare for the short and long terms effects of extreme climatic conditions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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