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An assessment of the vulnerability and adaptation potential of sugarcane production to water stress, southern Africa

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ABSTRACT

The high spatial variability of precipitation, heightened frequency of droughts and concomitant increases in exposure to water stress across southern Africa due to climate change, presents significant challenges for sugarcane production and the regional sugarcane production value chain. While production has intensified in the past few decades, yields have declined due to increased climatic variability and agronomic management approaches. Increased precipitation variability has enhanced sugarcane vulnerability to water stress and is likely to negatively affect yields. Combining crop simulations and relationships between sugarcane water use and observed rainfall, we introduce a crop productivity ratio (CPR) which assesses sugarcane water stress for six sugarcane mills across southern Africa. The CPR and simulation results were used to assess the adaptation potential or 'space' for mill areas that have varying rates of exposure and abilities to adapt to water stress. Simulation results were used to determine the long-term adaption potential of mill areas and to surmise the causes of yield declines. The results were used to offer recommendations to reduce vulnerabilities and enhance adaptation to water stress. We conclude that the amplification of inter-annual precipitation variability will enhance the exposure of sugarcane to water stress and require adaptation interventions. Adapting to external shocks is a multifaceted exercise that requires a holistic approach that includes every aspect of the sugarcane value chain.

1. Introduction

Commercial and out-grower sugarcane production significantly contributes to economic and social wellbeing across southern Africa. The viability and sustainability of sugarcane production is, however, under threat due to the increased frequency of extreme hydrological events that include prolonged droughts and extreme floods [1]. The fifteen contiguous nations of southern Africa, belonging to the inter-governmental socio-economic development and trade organization known as the Southern African Development Community (SADC), produce approximately 58 % of the total African sugar production, exporting over 1.2 million tonnes of refined sugar annually and, in the 2021/2022 growing cycle, generated revenues in excess of $2.15 billion (SADC Sugar Digest, 2022; South African Sugar Research Institute, 2022). Between 2015 and 2021, the number of outgrowers and commercial sugarcane producers has increased by 7 % in southern Africa (Marais, 2022; Syngenta, 2022) creating thousands of indirect and direct employment opportunities (Dubb et al. [2]. Further, Dal Belo Leite et al. [3] note that regional sugar production accounts for approximately 11 % of total earnings from agricultural commodities, despite a consistent decline in global sugar demand and the increased frequency of interruptions in the sugarcane supply chain [4]. By building revenue into national economies and contributing to the socio-economic development of local communities, it is clear that sugarcane production is an important contributor to the wellbeing of southern Africa.

Sugarcane is harvested in approximately 785 000ha across southern Africa under complex hydrological, agronomic and socio-economic conditions [5–7]. In catchments where sugarcane is grown, the crop

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can consume as much as 40 % of available water resources [8–10]. The crop is cultivated under a highly variable hydroclimatic environment, characterised by high temperatures resulting in high evaporation rates and substantial water requirements punctuated by low rainfall-to-runoff conversion ratios and high evaporation rates [11–14]. Owing to these hydroclimatic dynamics, sugarcane is often exposed to water stress and, out of necessity, is grown under a combination of rainfed, supplementary and full irrigation regimes.

Further, sugarcane is a water use intensive crop, with mean annual crop water use/actual evapotranspiration (ET_C) rates ranging between 1100 and 1 800 mm.annum^{-1} for a full canopy crop [15], and requiring approximately 850 mm of water per growing cycle for sustainable rainfed production [16]. These water use estimates should be seen in the context of potential evapotranspiration (ET_O) rates ranging between 1610 and 2 800 mm.annum^{-1} across the region ([17]; FAO Aquastat, 2020; [14]). Considering the high sensitivity of sugarcane yields to water stress [18–21], these estimates have implications for the sustainability of both the sugar industry and for the severely pressured water resources across the region, particularly under an increasingly variable climate.

The current and projected changes to climatic patterns reported by the IPCC Special Report on Climate Change and Land (IPCC, 2019; IPCC, 2022) and Hennessy et al. [1] present unique challenges for the southern African sugar industry. The variability of precipitation and temperature is reported to be rapidly increasing owing to changing atmospheric patterns influenced by a changing climate. Such climatic changes are likely to amplify both inter- and intra-annual precipitation variability (IPCC, 2019), increase drought risks [22], undermine water availability [16] and increase the risks of diminished sugarcane yields [23–25]. By increasing the variability of an already highly variable hydroclimatic environment and impact upon the seasonality and availability of water resources, enhanced climate variability will negatively impact the sugar industry. Increased climate variability is already affecting runoff generation [26], total evaporation rates [27], nutrient retention [28], and is expected to increase the exposure of sugarcane to water stress and impact sugarcane yields [25,29]. Since all mill areas in this study adopt multiyear growing cycles spanning 18–24 months, the focus will be on inter-annual precipitation variability as the primary determining factor in the exposure of sugarcane to water stress and, ultimately, the viability and sustainability of rainfed and irrigated sugarcane production. Inter-annual precipitation patterns directly influence the generation of surface runoff, soil infiltration rates and consequently, the volume of plant available water (PAW). The magnitude of PAW deficits determines the severity of exposure of crops to water stress over a growing cycle [30].

Similarly, inter-annual precipitation variability serves as an important indicator of water stress by reflecting the relative severity and frequency of wet and dry periods (or seasons) across a region. Therefore, despite the relatively successful cultivation of sugarcane in the region [31], access to adequate amounts of water at the correct intervals, remains a major challenge. Given the variable nature of precipitation in southern Africa, regional sugarcane production is constantly exposed to water stress, and this can ultimately result in reduced yields [32].

Water stress of irrigated and rain-fed sugarcane is detrimental to above-ground biomass accumulation and yields [20,33]. A range of studies, *e.g.* Ref. [18,19,34,35], conclude that water stress can curtail crucial processes such as the rate of photosynthesis, nutrient uptake and structural growth leading to a decline in sugarcane yield quantity. Understanding the relationship between actual and potential water stress and sugarcane yields is critical not only for improving water use efficiency and increasing production (South African Sugarcane Research Institute, 2022), but for enhancing the adaptive capacity of outgrowers and commercial producers with the aim of improving agronomic management and planning.

As a consequence of their limitations related to access to finances, current climate data and information, crop modelling, climate forecasting tools and current sugarcane varieties, outgrowers in the region are historically more vulnerable to the impacts of climatic extremes compared to their large-scale commercial counterparts [36–39]. Although there are strong relationships between outgrowers and commercial producers, particularly in eSwatini and Tanzania, outgrowers remain vulnerable to any disturbances that may affect their sugarcane production value chain.

A range of studies including Knox et al. [25], Srivastava & Rai [40], Singels et al. [41], Adhikari et al. [42] and Linnenluecke et al. [43], have addressed the impacts of climate change on sugarcane production in the region; however, these studies are often limited to well-resourced countries where the potential impacts of climate change on agriculture are well-understood and are performed at small spatial and temporal scales. We lack a regional assessment of the vulnerability of sugarcane to inter-annual dry periods over sufficient temporal scales to understand the vulnerability and adaptation potential of sugarcane.

To address this research gap, this study assessed the vulnerability and adaptation potential of sugarcane production to climate and management-related water stress in selected mill areas across southern Africa, and recommends viable adaptation strategies to ensure the sustainability of sugarcane production. The objectives of this study were, i) to assess the long-term observed sugarcane water use with the purpose of defining the current and potential vulnerability of sugarcane production to water stress resulting from extended dry conditions, ii) to identify the hydrological parameters and agronomic management practices which may influence the vulnerability of sugarcane production to water stress caused by extended dry conditions, and iii) define the adaptation potential or adaptation 'space' for outgrowers and commercial sugarcane producers.

The results are intended to inform approaches for mitigating the vulnerability of sugarcane production systems to potential loss events such as seasonal droughts associated with increased climate variability.

2. Study sites

The study 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) (Fig. 1). These catchments were the uMvoti, uMlaas and uMngeni Catchments in South Africa, the Ubombo Catchment in Swaziland, the Shire Catchment in Malawi and the Kilombero Catchment in Tanzania. These catchments and their resident mill areas (Fig. 1) were selected due to their varied hydroclimatic conditions, relatively high sugarcane production levels, distinctive management approaches, access to long-term climate and production data (Table 1) and for their strategic economic importance. Each mill area was represented by a set of observed climatic, hydrological and production data that were used as input into a crop growth model to simulate maximum potential sugarcane yields. The relationships between sugarcane water use and observed rainfall for each growing cycle, observed yields, simulated maximum potential yields, and the potential exposure to water stress, provide an indication of the vulnerability of sugarcane in each mill area to climatic extremes, such as seasonal droughts.

3. Methods

3.1. Introduction

The vulnerability of sugarcane to extended dry conditions can be determined by correlating observed yield data with annual sugarcane water use [8,24,44]. Sustained reductions in plant-available water (PAW) resulting from low rainfall and high total evaporation rates can potentially lead to reduced yields and enhance the vulnerability of sugarcane to water stress. Crop simulation models such as the AquaCrop model ([45]; Raes et al., 2009; Raes et al., 2012; [46]) are applied to simulate the variables to determine the vulnerability of sugarcane to

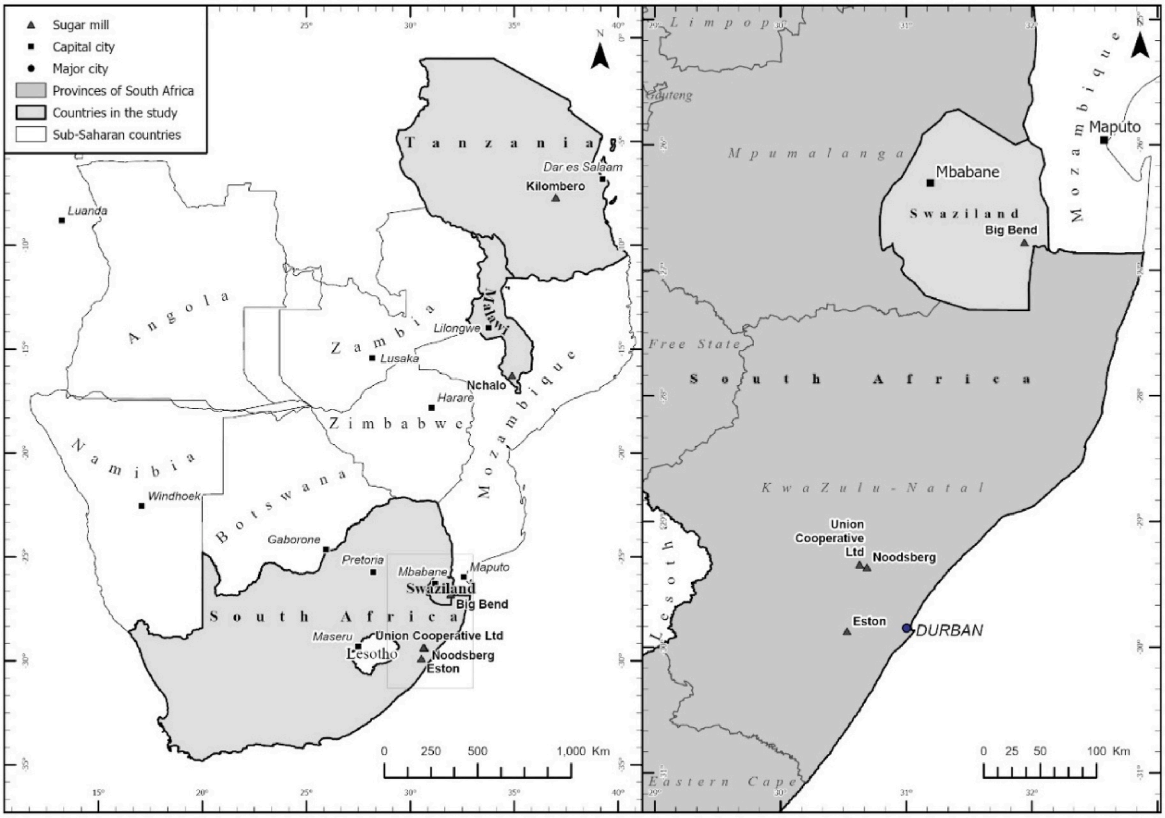

Fig. 1. Situation of the study sites within southern Africa.

Table 1
Information on selected sugarcane mill areas and parent catchments for the 1994–2019 period (Sources: SA Canegrowers Association, 2019; Harvest-Choice, 2019; Illovo Sugar Africa, 2020).

Mill	Catchment	MAP (mm/annum)	MAE Range (mm/annum)	Water Management	Approx. Area Under Cane (ha)	Mean Annual Output (t/annum)
Eston	Mngeni (SA)	833	1570–1740	Rainfed	36 728	1 124 488
Noodsberg	Mngeni (SA)	787	1570–1740	Rainfed	29 917	1 326 214
Union Cooperative Limited (UCL)	Mngeni (SA)	893	1570–1740	Rainfed	18 433	712 257
Big Bend	Ubombo (SWA)	659	2000–2200	Irrigated	10 987	1 303 750
Nchalo	Shire (MAL)	814	1500- 1800	Irrigated and Rainfed	19 520	1 680 000
Kilombero	Morogoro (TNZ)	1223	1600–1800	Irrigated and Rainfed	21 800	1 200 000

water stress instigated by extreme climatic conditions.

This study used a combination of the AquaCrop model and average observed sugarcane yields reported to determine maximum potential sugarcane yields. Both the observed and simulated maximum potential yields were correlated to estimates of sugarcane water use over 19 to 25 growing cycles to determine a 'Crop Productivity Ratio' and, thus, define the vulnerability of sugarcane to water stress, define adaptation spaces for the selected mill areas, and offer mitigation strategies that could be applied to the southern African sugarcane production industry. To effectively address the objectives of this study, the following methodological approach was adopted:

1) Apply the AquaCrop model to simulate the maximum potential yields that would be achieved under ideal agronomic growing conditions for each mill area,
2) Use observed sugarcane yields from the selected mill areas to determine the annualized actual sugarcane water use following the Thompson (1976) and Bezuidenhout et al., (2006) empirical water use equations,
3) Derive an annualized '*Crop Productivity Ratio*' (CPR) based on the relationship between annualized sugarcane water use and observed rainfall to assess potential water stress during individual growing cycles, and,
4) Perform a qualitative assessment that relates the proposed CPR with simulated and observed yields to ascertain the positioning of each mill area within a particular adaptation space.

Sugarcane vulnerability to water stress can be linked to an increase in the variability of specific hydrological parameters. For instance, if PAW deficits cause transpiration rates to drop below the critical threshold of 6 mm.day^{-1} required for phenological development [47], the induced stress can reduce above-ground biomass by up to 8 % [44, 48,49], thus necessitating increases in supplementary irrigation. Similarly, if rainfall or irrigation over a growing cycle does not exceed the critical threshold required to prevent water stress, total yields may be compromised, which can undermine the viability of sugarcane production (Jangprommа et al., 2012). Furthermore, the outbreak of pests as a consequence of high maximum temperatures, weather changes, and the absence of pest control measures can enhance vulnerability and potentially suppress yields [20]. Overall, it is possible to compare the inter-annual variability of hydrological parameters such as rainfall, potential evaporation (ET_O), and cumulative PAW to actual yield variability over a growing cycle and infer the vulnerability of sugarcane to water stress stemming from extended dry conditions [30,50,51].

This study uses observed yields to determine actual sugarcane water use based on an empirical relationship proposed by Thompson (1976) and updated by Bezuidenhout et al., (2006). The relationships between observed and simulated yields and annual sugarcane water use define the “space” for adaptation. In addition to these biophysical drivers, this space fluctuates as a function of three factors: i) the magnitude of inputs required to produce maximum yields, ii) the flexibility of agronomic management and iii) the favourability of the sugarcane production landscape with respect to legislation governing agricultural production. A sugarcane production system that is able to produce maximum yields while using the least inputs, uses efficient agronomic approaches and can access foreign markets with minimal interruptions would have a lower need for adaptation. Conversely, there would be a greater requirement for adaptation in systems that expend more resources such as water, land and finances, with no corresponding increases in yields.

3.2. The AquaCrop model

Developed by the United Nations Food and Agriculture Organization, AquaCrop is a water-driven daily time-step model that simulates crop, soil, and atmospheric interactions under rainfed, supplemental and full irrigation conditions and various field management practices [45,46,52]. Based on the main components of the soil-plant-atmosphere continuum, the model uses the interactions between crop transpiration, soil evaporation and canopy growth to simulate attainable above-ground biomass and harvestable yields. In this study, the product of above-ground biomass and the harvest index (*HI*) [46] was used to simulate maximum potential yields for sugarcane provided the crop experiences minimal climatic, agronomic, and water-related limitations over 19 to 25 growing cycles for each mill area (Table 2).

The model was run in calendar days spanning the lengths of growing cycles for individual mill areas. The model uses climate data to simulate daily crop growth and development based on four factors that determine crop responses to water stress. These factors *viz.,* canopy expansion, stomatal control, canopy senescence and *HI* ultimately determine the amount of water transpired by the crop and thus the amount of above-ground biomass produced. Due to its relatively low input data requirements, the AquaCrop model has been used extensively by agronomists and hydrologists for a range of applications including irrigation planning, climate change studies, crop yield projections, yield gap analyses and water use efficiency assessments. The model has been calibrated and verified in a number of studies conducted in Brazil [53,54], southern China [55,56], India [57,58] and in South Africa [59–61].

In these geographically diverse studies, the model provided a sufficient level of precision to allow confidence in its use in predicting sugarcane yields under varied climatic conditions and agronomic management regimes. Crucially, the model is able to simulate the effects of irrigation on crop growth using its net irrigation, irrigation scheduling and deficit irrigation modules. This ensures that a clear distinction can be made between yields obtained from rainfed mills, irrigated mills and mills which use a combination of both approaches (see Table 1).

3.2.1. Simulation procedures

The AquaCrop model was run with the assumption that the full set of crop development and production parameters were available (Fig. 2). Some of these parameters had to be estimated from observed records as obtained from agronomy and annual reports published annually by individual mills. The model was run in calendar days spanning the length of growing cycles unique to each mill area (*e.g.* 24 months in South African mill areas *vs.* 18 months in Tanzanian mill areas). 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 low and progressively growing until maximum canopy cover was reached over the growing cycle.

Plant densities varied between mill areas, averaging between 350 000 and 475 000 plants per hectare based on interrow spacings of 1m and plant spacings of 0.05m (HarvestChoice, 2020; SASRI, 2018; SASRI, 2019; SA Canegrowers Association, 2019). In some instances, plant densities had to be adjusted according to the prevailing seasonal conditions. For instance, during seasonal droughts, the number of plants per hectare was reduced to offset the effects of water stress on overall yields. 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 harvestable yields generated by the AquaCrop model. Accepting that sugarcane is sensitive to water stress, it was specified in the model that the crop is also sensitive soil water stress, total evaporation stress, and fertility stress. Non-conservative coefficients related to ET_O, crop water productivity and harvest index 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 applied in AquaCrop. This option ensures that at no point does the crop

Table 2
Data sources for rainfall, temperature and total evaporation used to simulate maximum potential sugarcane yields (**Sources**: SASRI WeatherWeb; NASA POWER Project; 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).

Mill	Catchment	Period	Number Of Growing Cycles	Data Sources
Eston	Umlaas (RSA)	1994–2019	25	https://sasri.sasa.org.za/weatherweb_legacy/, Accessed: August 2019 https://sasri.sasa.org.za/rtwd/458/index.html, Accessed: August 2019
Noodsberg	Mngeni (RSA)	1994–2019	25	https://power.larc.nasa.gov/data-access-viewer/, Accessed: October 2021
Union Cooperative Limited (UCL)	Mvoti (RSA)	1994–2019	25	https://climateknowledgeportal.worldbank.org/download-data, Accessed: November 2020
Big Bend	Ubombo (SwZ)	1996–2019	23	https://www.csag.uct.ac.za/climate-services/cip/, Accessed: October 2021
Nchalo	Shire (MAL)	2000–2019	19	https://cip.csag.uct.ac.za/webclient2/app/, Accessed: October 2021 https://texasclimate.tamu.edu/research/data/index.html, Accessed: June 2022
Kilombero Sugar Company (KSCL)	Kilombero (TZA)	2000–2019	19	https://ihesp.github.io/archive/products/ds_archive/Datasets.html#regional-datasets, Accessed: June 2022 https://gpm.nasa.gov/data, Accessed: June 2022

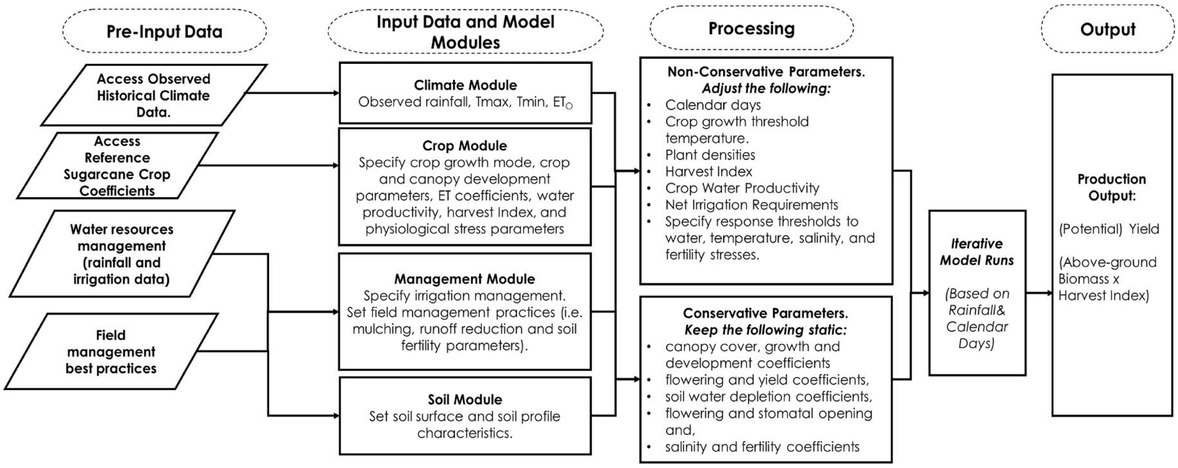

Fig. 2. A summary of the modelling procedures in the AquaCrop model adopted in this study to simulate maximum potential sugarcane yields.

experience water stress as the allowable root zone depletion is set at a maximum of 50 % of PAW. It was assumed that once PAW reached or dropped below 50 %, irrigation would be activated to return the soil profile to field capacity. No soil restrictions were specified with regard to root deepening. Field management parameters including soil fertility, mulching, runoff reduction practices and weed management were assumed to be non-limiting such that the sugarcane in each mill area was produced under the best possible management practices. Once all the modules were compiled, the model was run for individual growing cycles for all 6 mill areas spanning the length of the available data records (*i.e.* for 19 to 25 growing cycles).

3.2.2. *Seasonal sugarcane water use*

Thompson (1976), Bakker [62] and Bezuidenhout et al. (2006) developed an empirical relationship which correlated sugarcane yields and ET_C based on extensive field-based studies conducted for southern African growing conditions. These studies yielded the approximation indicated in Equation (1), thus:

$$Yield = 9.53\,\frac{\Sigma\,ETc}{100} - 2.36 \tag{1}$$

Where *Yield* is the annualized observed sugarcane yield (t. ha^{-1}. $annum^{-1}$) and ET_C is the actual total evaporation ($mm.day^{-1}$). The derivations from studies conducted by Thompson (1976), and the updates by Ref. [62] and Bezuidenhout et al. (2006), were able to derive a relationship between annualized actual sugarcane water use, *wu* (mm. $annum^{-1}$) and observed sugarcane yields. While it is acknowledged that both outgrowers and commercial farmers often grow sugarcane for longer than 12 months, mill areas report observed yields as 2-year moving averages that reflect the complete growing cycles. In other words, while yields are reported on an *annual* basis by the mills, these actually reflect the preceding 18–24 month growing cycles for each mill area. The *wu* estimates are, therefore, a reflection of these 2-year moving averages presented as annualized estimates.

The relationship between *wu* and *Yield* is presented in Equation (2):

$$wu = \frac{100\,(Yield + 2.36)}{9.53} \tag{2}$$

Note that *wu* and thus *Yield* as reflected in Equation (2) includes contributions from irrigation (Bezuidenhout et al., 2006) since most, if not all, mill areas engage in some form of supplementary irrigation over the course of the growing cycle. Since one of the objectives of this study was to define the vulnerability of sugarcane to water stress, understanding the relationship between observed yields, actual sugarcane water use and observed rainfall is critical. This relationship is expressed as the proposed 'Crop Productivity Ratio' and reflects the efficiency of water use in growing sugarcane over a growing cycle.

3.2.3. *Crop productivity ratio*

The *Crop Productivity Ratio* (hereafter the CPR) assists in identifying mill areas which have the greatest need or 'space' for adaptation and thus in need of intervention to limit yield declines. The CPR relates actual sugarcane water use with observed rainfall and serves as an indicator of the volume of water that would be required to produce sugarcane over a single growing cycle and can be represented by Equation (3) thus:

$$Crop\ Productivity\ Ratio = \frac{Actual\ Water\ Use\ (wu)}{Annualised\ Observed\ Rainfall\ (P)} \tag{3}$$

In instances where actual sugarcane water use (*wu* in mm. $annum^{-1}$) consistently exceeds observed rainfall (*P* in mm. $annum^{-1}$), it may be concluded that sugarcane is using the maximum available water from both rainfall and supplementary irrigation and, thus, the potential for water stress is diminished. This would be reflected by a CPR >1. Conversely, sugarcane water use that is consistently below observed rainfall throughout a growing cycle would imply inefficient water use from irrigation and/or a relatively dry growing cycle, which would increase the likelihood of water stress and would be reflected by a CPR <1.

The adaptation space can be determined based on the long-term yield performance of a mill area in relation to the CPR. While the CPR is not a direct estimation of water stress, it reflects the actual annualized water use relative to observed rainfall over a growing cycle and can be indicative of the dependence of each mill area to irrigation. A CPR >1 implies high actual sugarcane water use relative to observed rainfall which implies the intervention of irrigation for that growing cycle to prevent water stress and thus maintain, increase or prevent a decline in yields. In that sense, a CPR >1 implies relatively low rainfall that is insufficient to sustain rainfed sugarcane production and thus implies that sugarcane was potentially exposed to water stress, thus the requirement for irrigation. A CPR <1 would result in reduced yields which would be the consequence of water stress or, potentially, poor agronomic management. Further, a CPR <1 may reflect a growing cycle with below average rainfall that would further expose sugarcane to water stress and require increased irrigation to prevent yield losses.

3.2.4. *Adaptation spaces*

Adaptation may be defined as the process of adjustment to actual or expected climatic stimuli and their effects to alleviate adverse impacts of change or take advantage of new opportunities (IPCC, 2001 [63]; Robinson, 2020). For a system to adapt, it has to build adaptive capacity and transform that capacity into action. Further, a system has to anticipate and attempt to minimize its exposure to expected disturbances such as extended dry periods caused by climatic extremes in the case of sugarcane production. For purposes of this study, the adaptation 'space' for sugarcane production may be defined as the ability of a mill area to anticipate disturbances and accumulate the necessary adaptive capacity that will allow it to respond to adverse conditions to minimize impacts to the value chain. Each mill area can occupy a particular adaptation space depending on its ability to respond to external disturbances. This space can either be an unsafe or 'high-risk' adaptation space or a safe or 'low-risk' adaptation space (Fig. 3). A mill area would occupy an unsafe adaptation space in instances where the requisite adaptive capacity such as access to irrigation or advanced in-field mechanization is limited or nonexistent.

To ascertain the positioning of each mill area in the adaptation space, it was necessary to relate both observed and simulated yields with annualized sugarcane water use for all growing cycles. The adaptation space is determined by the relationships between water use over an annualized growing cycle with observed and simulated yields (Fig. 3). To minimize vulnerability and maximize adaptability, each mill area should ideally remain in the safe or low-risk adaptation space. While remaining in the safe adaptation space for extended periods is not always possible, particularly during prolonged dry conditions, mill areas can transition to the safe adaptation space, provided they consider sugarcane production policies, potential climatic changes, and advances in production technologies.

A critical aspect related to adaptation spaces are the barriers to adaptation that may be encountered when a mill area is attempting to transition from an unsafe to a safe position. Reducing water stress would require access to irrigation and above average rainfall to sustain break-even yields and retain a CPR close to or above 1. Growers, particularly small-scale outgrowers, may be unable to adapt quick enough to water stress and may remain in the unsafe space. It should be noted that if a mill area remains consistently in the unsafe or 'high-risk' adaptation space, it does not necessarily reflect poor agronomic management. It could, however, suggest that the mill area can make improvements that can significantly bolster its adaptation and reduce its vulnerability to climatic extremes and water stress. While this study focuses exclusively on sugarcane water use as a key determinant of adaptation potential, there are a multitude of factors across the sugarcane production value chain that can affect the adaptation status of a mill area. Sugarcane is a water-use intensive crop - therefore, any discussions regarding adaptation have to consider existing management strategies that seek to maximize water use efficiency and reduce unnecessary losses.

4. Results and discussion

4.1. Long term sugarcane water use

The South African mill areas, Eston, Noodsberg and UCL have the advantage of being in catchments that experience relatively high mean annual precipitation (MAP) averaging 838mm/annum, and can supplement their water supply with irrigation schemes (Fig. 4). Sugarcane water use in the South African catchments averages 730mm/growing cycle and long-term water use by sugarcane remains disproportionately high compared to other comparative crops (Jarmain et al., 2014). Therefore, despite being one of the most well-managed and successfully cultivated crops in South Africa, this high water use means sugarcane is vulnerable to the impacts of climatic extremes.

Owing to the inherently high sugarcane water use relative to MAP, the Big Bend mill area of eSwatini require sustained irrigation to achieve viable yields. The Ubombo catchment, in which the Big Bend mill area is situated, receives a relatively low MAP of approximately 659mm/annum. However, with a long-term mean (LTM) water use approximating 1270mm/growing cycle (Fig. 4), irrigation is imperative for the successful cultivation of sugarcane. Growers supplying the Big Bend mill are considered to be using the maximum available water resources in the Ubombo catchment [25] suggesting high potential exposure to water stress and a strong need for adaptation to climatic extremes in this mill area.

Despite LTM water use averaging 780 mm per growing cycle against an MAP of 814 mm (Fig. 4), the Nchalo mill area of Malawi requires irrigation owing to the high rainfall seasonality in the Shire catchment. This catchment is characterised by a hot wet season, which lasts from early November to late May, and a cool dry season which lasts from late May to early October. This high seasonality or 'two-season' rainfall distribution cycle means sugarcane cannot be cultivated successfully without irrigation during the lengthy dry season. Thus, both Nchalo and Big Bend mill areas are vulnerable to climatic extremes and water stress as a consequence of their hydroclimatology. This conclusion is supported by the reduced yields resulting from reduced MAP during the dry seasons.

Similar to the Nchalo mill area, the Kilombero (KSCL) mill area of Tanzania experiences high rainfall seasonality, with high MAP estimates averaging 1200 mm during the rainy seasons and 990 mm during the dry seasons [64] (Fig. 4). Sugarcane water use averages 602mm/growing cycle in this mill area. Despite the relatively high MAP estimates and

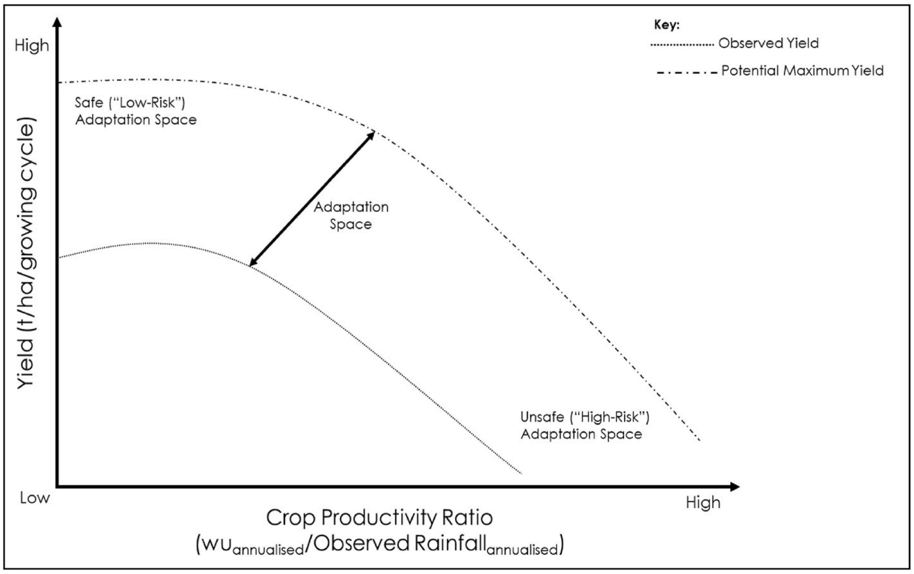

Fig. 3. Defining safe and unsafe adaptation spaces based on the CPR concept and observed and simulated yields.

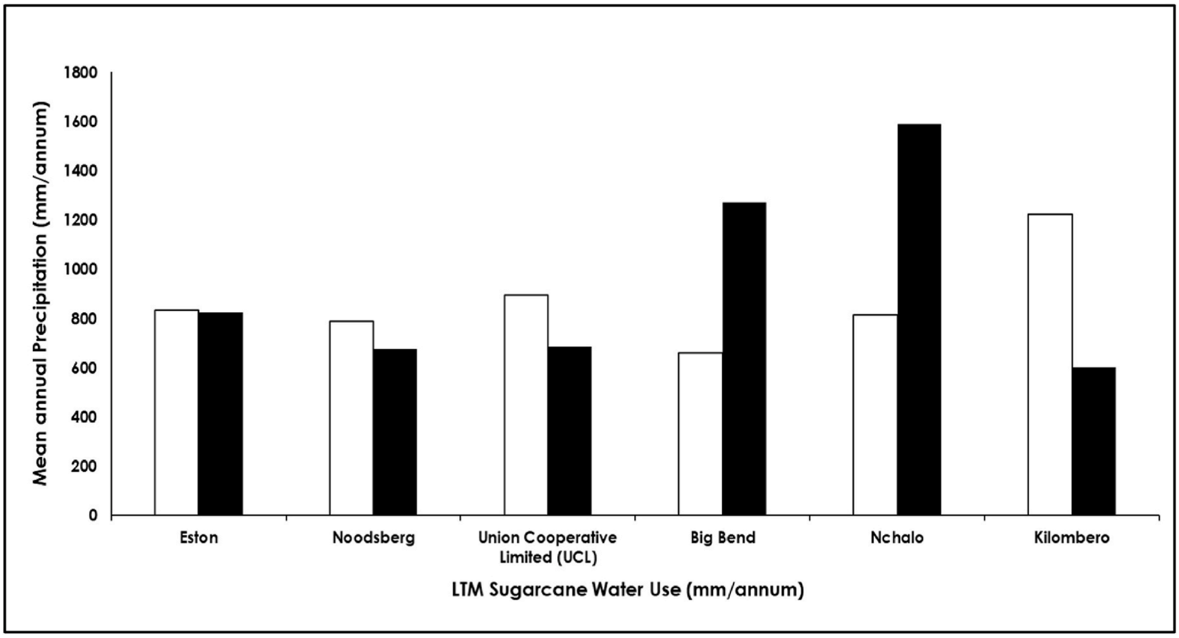

Fig. 4. Long-term mean (LTM) sugarcane water use (*wu*) in relation to mean annual precipitation (MAP) for individual mill areas.

relatively low water use by sugarcane, yields in this mill area remain below their potential. This is due to the limited access to irrigation during the dry seasons, and the geography of the Kilombero catchment which limits the area under sugarcane. While sugarcane is not necessarily vulnerable to water stress, such limitations can potentially increase the vulnerability of sugarcane particularly during the lengthy dry seasons. The main limiting factor in this mill area is the high rainfall seasonality suggesting that sugarcane will remain exposed to the effects of climatic extremes.

4.2. Sugarcane yield and water use relationships

Contributions by outgrowers were included in this exercise, as although there are no known yield records for outgrowers across the study sites, the assumption that the yields reported by mills include contributions from outgrowers was reasonable, since they are contractually obligated to supply mills with sugarcane. The observed LTM yields as reported by the individual mills, averaged 71.95 t/ha/growing cycle for the South African mill areas *combined* (Fig. 5), 46.50 t/ha/growing cycle for the Big Bend mill area (Fig. 6), 71.48 t/ha/growing cycle for the Nchalo mill area (Fig. 7) and 113.09 t/ha/growing cycle for Kilombero mill area (Fig. 8).

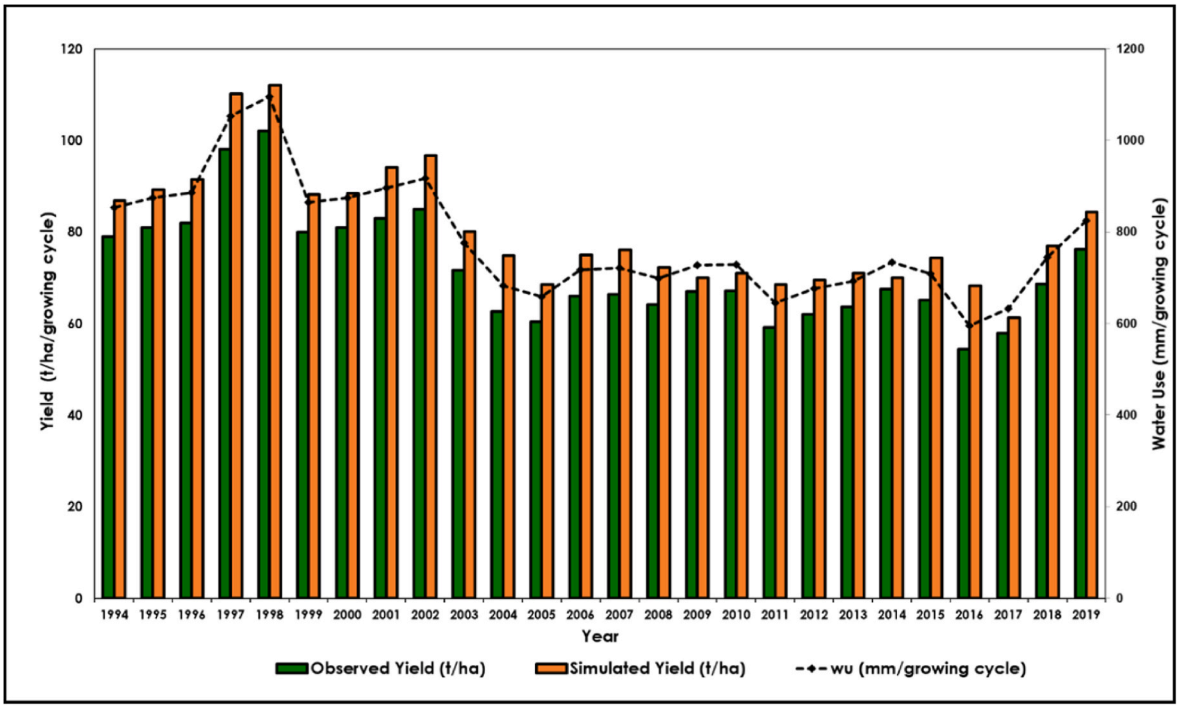

Fig. 5. LTM observed and simulated yields for the South African mill areas and annualized water use per growing cycle.

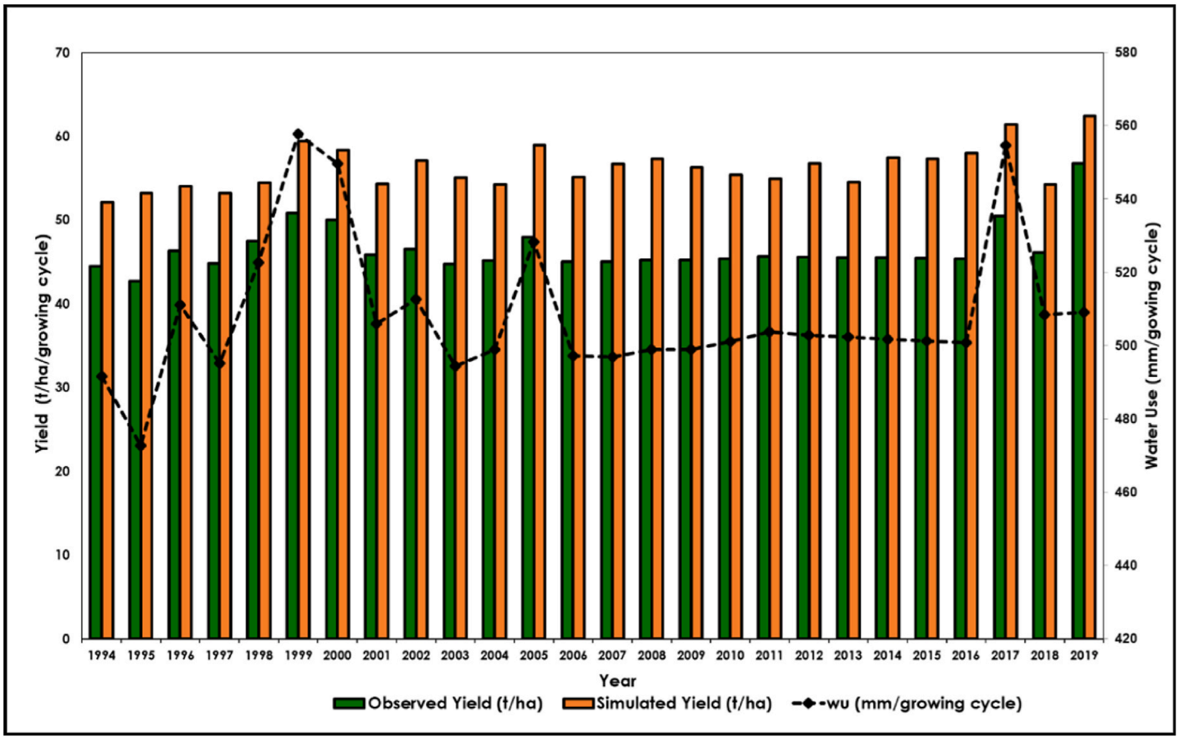

Fig. 6. LTM observed and simulated yields for the Big Bend mill area and annualized water use per growing cycle.

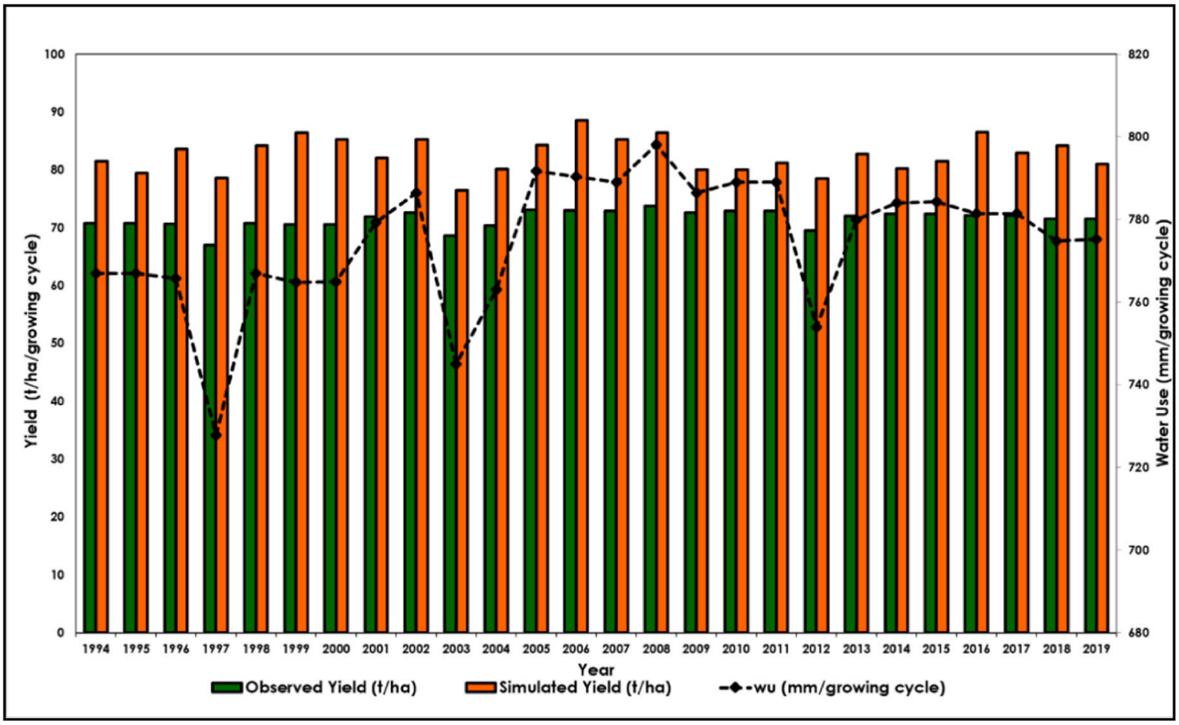

Fig. 7. LTM observed and simulated yields for the Nchalo mill area and annualized water use per growing cycle.

LTM observed yields are declining for mills in the Eston, Noodsberg, UCL and Nchalo mill areas, and increasing in the Big Bend and Kilombero mill areas. The simulated LTM yields indicated declines consistent with observed yield trends in the South African mill areas. These declines were evident despite specifying no limitations to crop growth parameters in the AquaCrop model. Such a finding confirms that the reported decline in observed yields is factual, and is directly linked to agronomic and water resources management. Simulated yields, since they were under no restrictions, are reflecting the prevailing water resource access and management conditions in the mill areas. While other factors may contribute to these yield declines, access to water resources by sugarcane is the primary cause of these declines.

Average water use per growing cycle in all mill areas calculated based on Equation (2), was consistently below observed rainfall for the

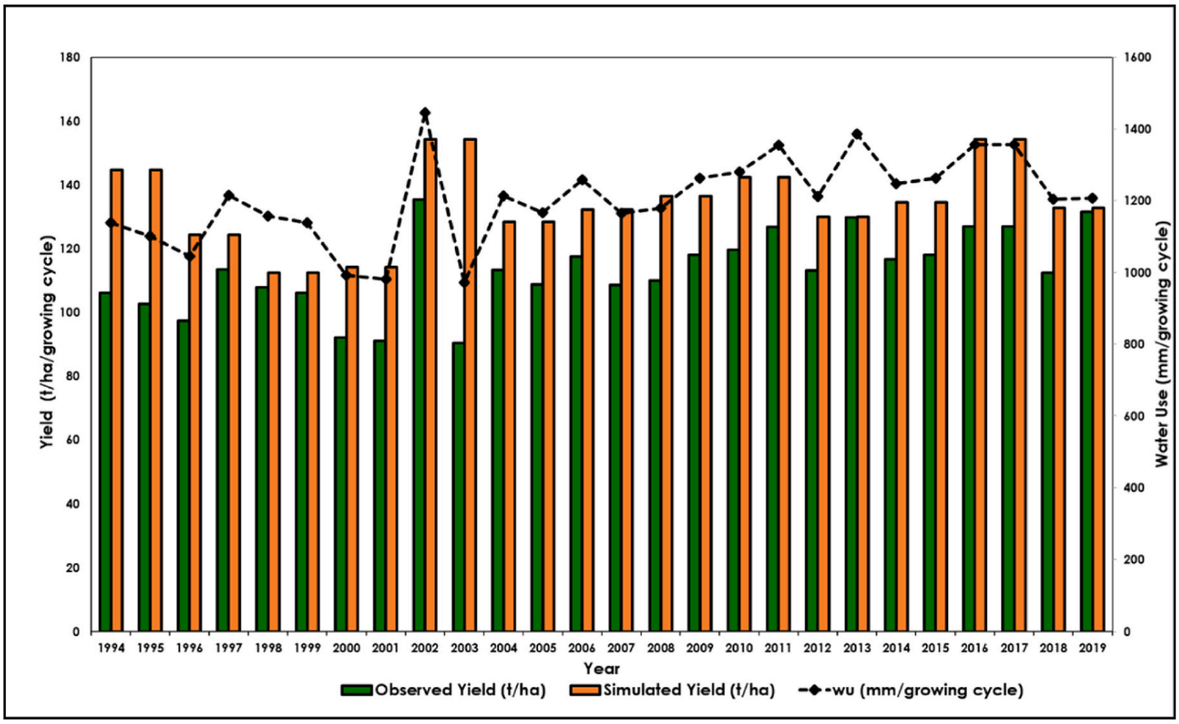

Fig. 8. LTM observed and simulated yields for the Kilombero mill area and annualized water use per growing cycle.

duration of the study period (Fig. 5). The exception to this was during the 2014–2016 period when most South African catchments were experiencing a 1 in 50-year drought [65]. Despite being located in catchments that have some of South Africa's highest MAP, sugarcane water use from rainfall and irrigation remains consistently high for sugarcane.

Further, while the designation of sugarcane as a 'Streamflow Reduction Activity' remains open to interpretation, the fact remains that the South African mill areas are vulnerable to water stress as they are already using the majority of the proportion of water allocated to sugarcane production. Although the vulnerability of these mill areas is lower than the other mill areas in this study, they are still operating under a challenging water resources management environment and therefore, adaptation to climatic extremes will remain important in these mill areas. In the irrigated Big Bend mill area, LTM observed yields consistently increased for the period 1996–2004, remained nearly constant for the period 2005–2015, and subsequently increased in the post-drought 2016–2019 (Fig. 6). This can be attributed to sugarcane being almost exclusively irrigated in this mill area which buffers and limits yield declines.

Of concern here is that yields during this period changed by less than 1 % per growing cycle, and this was considered to be an unlikely trend. This was attributed to either under-reporting of observed by the mill or, potentially, the diversion of harvested sugarcane to alternative mills for processing. The LTM simulated yields were consistently higher than observed yields. This was a direct result of the invocation of the net irrigation requirement option in AquaCrop, which assumes that irrigation is initiated once the soil plant available water (PAW) drops below 50 %. Owing to this invocation, the LTM simulated yields were consistently higher than the observed yields as water was not a limiting factor.

As rainfall in the area is not sufficient to meet the requirements of commercial or small-scale sugarcane production, and the catchment is prone to intense, short-term droughts, irrigation is an essential requirement for sugarcane production in this catchment, and it makes a significant difference in averting the effects of water stress and maintaining yields. However, despite the efficient irrigation systems in the mill area, the exclusive reliance on irrigation makes it clear that sugarcane production is extremely vulnerable to climatic extremes.

The Nchalo mill area witnessed an increase in observed LTM observed yields for the 2000–2006 period, and consistent yield declines over the 2007–2019 period (Fig. 7). Sugarcane production often assumes a lower priority compared to other bulk commodity crops such as tea, tobacco and maize in this mill area. The yield declines may thus not necessarily reflect poor agronomic or water resources management, but rather constantly shifting economic priorities. Regardless, sugarcane production is under increased pressure to access water resources, and this is suppressing yields. The decision to grow sugarcane appears to be contingent on the availability of resources such as water and labour, and on the prevailing sugarcane selling price for every growing cycle. As the pressures of climate change become more apparent and sugarcane production becomes more resource-intensive and less economically viable, the continued decline in sugarcane yields can be expected. As recently as May 2022, sugarcane production across Malawi has been critically low, which led to the Malawian government temporarily banning the export of sugar until production was restored and local sugar demands met (Nzangaya, 2022). This was a result of extreme events such as Cyclone Ana (International Federation of the Red Cross, 2022) that disrupted the sugarcane value chain. The relatively high water use coupled with low rates of irrigation and rainfall seasonality imply that this mill area is vulnerable to water stress, and will increasingly rely on supplementary irrigation.

The LTM observed yields for the Kilombero mill area were 113.09 t/ha/growing cycle over the study period as a result of increase rainfall rates, which appear to have favoured increased sugarcane productivity (Fig. 8). It should be noted that the actual observed yields for the period between 1994 and 2000 could not be independently verified, therefore the yields for this specific period are estimations based on yields reported by secondary sources (Table 1).

Sugarcane production in the KSCL mill faces a multitude of problems including access to irrigation, high rainfall seasonality 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, average yields have been steadily increasing as a result of an increase in the number of outgrowers subsidised by the Tanzanian government.

Sugarcane water use is relatively high in the Kilombero mill area - averaging 1206mm/annum, against a MAP of 1220mm/annum. Despite the high MAP, the water deficit ratio was high, averaging 0.94 over the study period, which can be explained by the high seasonality which necessitates high rates of irrigation during the dry seasons. Regardless, the Kilombero mill area is successful at producing sugarcane. However, owing to the high rainfall seasonality and the strong dependence on irrigation, the Kilombero mill area is vulnerable to effects of water stress and climatic extremes.

4.3. Sugarcane crop productivity ratio

The CPR was used to define the adaptation potential or ‘space’ for individual mill areas. The results are intended to mitigate the vulnerability of sugarcane production systems to current and future ‘loss events’ associated with water stress resulting from extreme events (Fig. 9). A CPR above 1 denotes that the maximum amount of water available to the crop was utilised and, conversely, a CPR below 1 implies that there are inefficiencies in supplying the crop with enough water to prevent water stress.

Regardless of the location of a mill area, sugarcane water use consistently exceeded observed rainfall for the majority of the study period. For instance, the CPR for the South African mill areas (Fig. 9a) averaged 0.97 based on observed yields indicating that sugarcane water use consistently exceeded rainfall and that supplementary irrigation was necessary to limit water stress and safeguard yields. While irrigation systems are efficient in these mill areas, they still have to contend with the reality of below average rainfall that would otherwise not permit or sustain rainfed sugarcane production. In relatively dry growing cycles such as in 2014, 2015 and 2016, the CPR exceeded 1, which indicates that all the available water from rainfall and irrigation was used to prevent water stress. The CPR for South African mill areas is consistently below 1, suggesting that droughts can place the sugarcane crop at risk of water stress. However, while it is true that the frequency of droughts is increasing in South Africa [66–69] and LTM yields are steadily declining, the advanced irrigation schemes, coupled with large investments into research to create drought-tolerant varieties, will serve to reduce the vulnerability of sugarcane to water stress. This CPR from simulated yields suggests that yield declines are not only caused by water stress but that other factors, such as pest outbreaks and increasing production costs, are playing a role in the reported yield declines in the South African mill areas.

Sugarcane production would not be possible in the Big Bend mill area without irrigation. This was evidenced by the LTM CPR which averaged 0.80, indicating that the below average rainfall is consistently exposing sugarcane to water stress and that irrigation is imperative to counter the risk of exposure to water stress (Fig. 9b). The CPR highlights the central role that irrigation plays in this mill area, and, further, that this mill area is in the unsafe adaptation space as a result of the over-reliance on irrigation. Any interruption to this system would potentially be catastrophic for sugarcane production, which highlights the significant role that irrigation assumes and underscores the high vulnerability to water stress that sugarcane is subjected to.

Similar to the South African mill areas, the Nchalo mill area of Malawi has a CPR of 0.97 over the study period (Fig. 9c). This was attributed to the high rainfall seasonality in the Shire catchment which, over the dry seasons, results in prolonged dry spells that can induce water stress, thus necessitating irrigation. Although irrigation is not entirely necessary during the wet seasons, the risk posed to sugarcane production during the dry season is substantial. The CPR increased to above 1 during the relatively dry growing cycles and correspondingly yields declined during abnormally long dry seasons. Despite not being a high-priority crop in the Shire catchment, sugarcane is highly vulnerable to climatic extremes. In fact, it may be argued that as it is not a priority, the vulnerability of the sugarcane crop can be amplified as during extreme events, water and other resources may be diverted to more economically important crops.

The LTM CPR estimates for the Kilombero mill area were considered

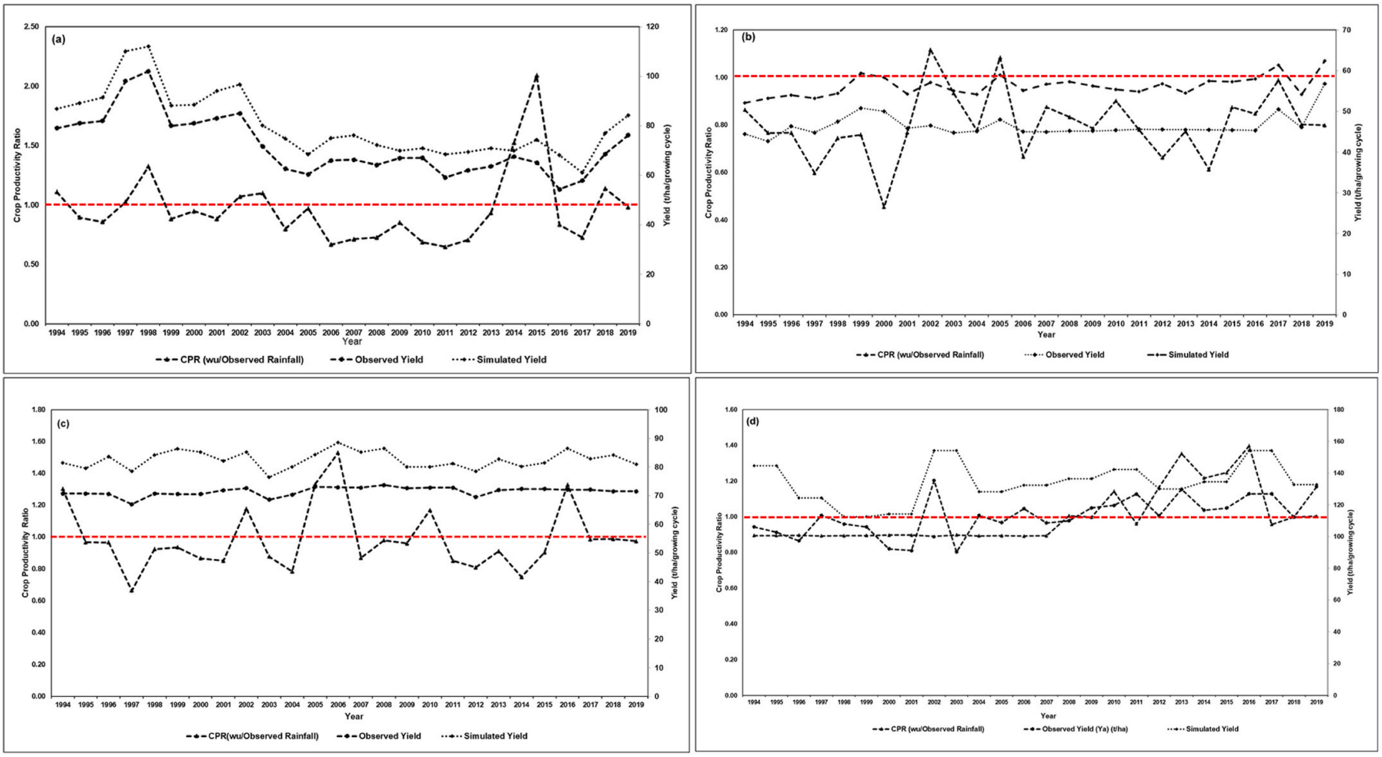

Fig. 9. Long Term Mean (LTM) Crop Productivity Ratios (CPR) for a) South Africa, b) Big Bend, c) Nchalo and d) Kilombero mill areas relative to observed and simulated yields. A CPR = 1 is the benchmark and differs for each mill area.

anomalous owing to poor and unverifiable data records between 1994 and 2006, which resulted in the use of secondary estimates that lacked reliability. Regardless, the records from 2007 to 2019 provided an adequate indication of the sugarcane water use and rainfall dynamics. The Kilombero mill area averaged LTM CPR of 1.13 between 2007 and 2019, suggesting that all the available water is being used in this mill area and that irrigation, similar to all the other mill areas, is an important facet of sugarcane production (Fig. 9d). Sugarcane water use is higher than observed rainfall, and this helps reduce water stress and sustain high yields. However, there is a risk that the high seasonality in this catchment can induce water stress and undermine yields. Despite this, the Kilombero mill area has a substantial irrigation network and relatively high rainfall rates that, despite the equally high seasonality, serve to support and sustain high yields. This implies that the mill area is (for now) in the safe adaptation space. Whilst rainfall is high, sugarcane production is a risky venture owing to the high rainfall seasonality, and this implies that the safe adaptation space can rapidly change should any disruptions be experienced in the sugarcane value chain.

4.4. Adaptation spaces for sugarcane production

The potential for adaptation is limited by the degree to which a system is vulnerable to external disturbances [63]. This potential for adaptation or 'adaptive capacity' is, in turn, defined by the magnitude of resources a system has access to and thus, on how well insulated a system is to unexpected disturbances. In the case of sugarcane production, the vulnerability of a mill area to water stress engendered by climatic extremes was determined based on the scale and extent of resources that the individual mill area can access. The discussion concerning adaptation potential will be based on the concept of adaptation spaces. To prevent speculation regarding the vulnerability of sugarcane production in mill areas, this study based its conclusions on the actual sugarcane water use and observed and simulated yields (Fig. 9), and on the actual interventions that are currently being employed by individual mill areas to safeguard the sugarcane production enterprise.

According to the IPCC (2022), the regional variability of precipitation and temperature across southern Africa is increasing owing to shifting atmospheric patterns influenced by a changing climate. This implies that, despite the range of interventions to limit yield losses, the sugarcane production industry will remain vulnerable to water stress and climatic extremes, albeit to varying degrees. The South African mill areas are the most technologically advanced and are supported by a robust research and development environment; factors which place these mill areas in the *safe adaptation space* (Fig. 9a). The long-term relationships between observed and simulated yields indicate that these mill areas are operating optimally, and their observed yield closely resemble their potential maximum yields. While improvements can be made in increasing yields or at least reducing losses, these mill areas are well insulated against water stress and, thus, have high adaptive capacity. It can therefore, be concluded that the South African mill areas are in the safe adaptation space, despite the reported yield declines.

This is not, however, to suggest that these mill areas are immune to water stress - rather that they are operating with a strong focus on interventions that will limit the vulnerability of sugarcane to future extreme events. Water use in these mill areas remains high as indicated by the LTM CPR of 0.97, despite sugarcane production being a closely regulated activity - these mill areas consistently produce proportionally high yields which suggests a more optimal operating space.

Contrary to the South African mill areas, the Big Bend mill area was considered to be operating in the *unsafe adaptation space* (Fig. 9b). There were consistently large differences between observed and simulated yields, suggesting that improvements need to be made to ensure that this mill area can produce maximum yields and thus transition into the safe adaptation space. Further, the over-reliance on irrigation places this mill area in the unsafe adaptation space. The fact that sugarcane is irrigated implies vulnerability to water stress; however, that can only be minimised by ongoing research into drought resistant sugarcane varieties and highly efficient irrigation systems. With increases in the frequency of extremes, a proportionally increase in resources would be required to achieve economically viable breakeven yields. While the Big Bend mill area is heavily subsidised by the eSwatini government and has substantial support from commercial growers, it remains in the unsafe adaptation, at least for the short to medium term.

High rainfall seasonality and heavy reliance on irrigation are major risk factors in the Nchalo and Kilombero mill areas. Both these mill areas follow a hybrid of rainfed and irrigation approaches. Sugarcane production is relatively successful in both mill areas despite the challenging hydroclimatic conditions, and the limited input related to research and development. In the Nchalo mill area, for instance, sugarcane is produced as a secondary crop and, therefore, limited attention is paid to this crop during dry spells. The risk-to-reward proportionality remains too high in this mill area due to high rainfall seasonality and irrigation limitations. In fact, during dry spells, outgrowers and commercial producers often switch to less water resource intensive and more financially rewarding crops. By way of an example, during the drought of 2014 and 2016, most growers ceased sugarcane production due to the inability to access irrigation. The Nchalo mill area is thus considered to be highly vulnerable and operating in the *unsafe adaptation space* (Fig. 9c). If sugarcane production is to remain viable, significant resources must be allocated to the sugarcane industry and considering the current sugarcane production environment specifically in the Shire catchment, this is unlikely to materialize.

Despite the challenging hydrological and geographic environment, sugarcane production in the Kilombero mill area has demonstrated significant increases yields in the past few growing cycles (Fig. 9d). This is a direct result of the prioritization of sugarcane production by the Tanzanian government and policies which support exports of high-quality processed sugar. Significant financial incentives and access to current research have been made available to both outgrowers and commercial growers. There exist strong (and legally binding) relationships between commercial growers, outgrowers and the agricultural ministry in Tanzania, the purpose of which is to safeguard and ensure the continuity of the highly vulnerable sugarcane industry. Although in its infancy, these relationships have yielded positive results. This is evidenced by increasing yields under a highly seasonal hydroclimate, and an increase in the area under sugarcane across the Kilombero catchment (Fig. 9d). While there are significant differences between observed and simulated yields, suggesting that the mill area is operating below its actual potential, there is still a significant increase in observed yields. Therefore, based on the LTM CPR of 1.13 and continuously high observed yields, it may be concluded that the mill area is operating within a *safe adaptation space*. This is despite the disproportionally high reliance on irrigation and high rates of illegal imports of sugar into Tanzania. Coupled with high seasonality, which is likely to be enhanced in the future, sugarcane production will be under increased pressure, and will most likely shift into the unsafe adaptation space if no agronomic and water resources management interventions are implemented.

Despite the current relatively successful cultivation of sugarcane production in the mill areas under study, they are all still vulnerable to water stress and there is significant scope for adaptation. This is particularly true under the projected climatic changes (IPCC, 2022) which will undoubtedly increase the exposure and vulnerability of sugarcane production to water stress. Mill areas such as Big Bend and Nchalo are under perpetual threat of collapse due to their over-reliance on irrigation. The projected climatic changes present unique challenges to sugarcane production in this region and if the enterprise is to survive, adaptation strategies will require more consideration than is currently the case. The need for adaptation will not be diminished across southern African mill areas, regardless of the differences in the urgency with which adaptation interventions will be required. As has been shown in this study, adaptation is a highly complex process that requires changes at every level in the sugarcane production value chain - and not just in water resources management.

4.5. Adaptation recommendations

The results from this study have yielded key lessons that were transferrable not only for the mill areas under study, but for other mill areas in the region. These lessons are intended to offer recommendations that can potentially reduce vulnerability and enhance adaptation to water stress, including:

1. Improving the understanding of the impacts of climatic extremes across the sugarcane value chain, *i.e.* from planting to cultivation to processing and retail.
2. Sharing (updated) research outputs regarding drought and pest-resistant sugarcane varieties particularly with outgrowers.
3. Growing multiple sugarcane varieties within a single mill area to create a 'yield buffer' to negate the effects of water stress during prolonged dry periods.
4. Exploring the use of biotechnology (*i.e.* genetically modified hybrid sugarcane varieties) to limit the exposure of sugarcane to biotic and abiotic stresses.
5. Increasing investments in efficient irrigation technologies that use limited volumes of existing water resources to increase yields.
6. Engaging in multi-cropping to increase soil organic matter which can potentially increase the water holding capacity of soil thus enhancing plant available water for every season.
7. Reversing stigmatizing policies that relegate sugarcane production to a secondary crop or a crop that threatens national water resources (*e.g.* the SFRA law in South Africa). While this position may have been true once, significant progress has been made in improving water use efficiency in the industry. These policies need to be revised to reflect the current status of sugarcane production.
8. Considering changes to cropping dates to limit the impact of increasing rainfall seasonality particularly in the Nchalo and Kilombero mill areas.
9. Improving in-field technologies that reduce soil degradation and enhance water holding capacities.
10. Reducing practices such as burning prior to harvesting and burning sugarcane trash which increase the emission of greenhouse which ultimately exacerbate climate change. While burning enables hand-cutting which creates seasonal employment, self-trashing varieties can limit the need for burning while not compromising livelihoods.

4.6. Conclusions

We introduce a crop productivity ratio based on actual sugarcane water use in relation to actual observed rainfall over a growing cycle. Findings suggest that despite the inherent vulnerabilities to water stress there remains scope for adaptation. The ability of each mill area to adapt varies according to the extent of resources dedicated to limit the exposure of sugarcane to the effects of water stress. Critical factors such as supplementary irrigation and research and development that encompasses the entire sugarcane production value chain, are invaluable in reducing the present and future vulnerability of sugarcane to water stress. While the CPR excluded factors that affect the exposure of sugarcane to water stress, it still provided useful insights into the current vulnerability of sugarcane. It was observed that the adaptation space of individual mill areas is a function of current agronomic practices, and of the present and projected changes to regional climatic extremes. While it is true that mill areas rely on direct rainfall, the requirement for irrigation will become increasingly important in the near future. Further, it is becoming an inescapable reality that the use of drought-resistant varieties is becoming central in the sustainable cultivation of sugarcane in the region.

Except for Kilombero, the mill areas selected in this study are subject to declining yields, despite several interventions to limit these trends. Growers, both outgrowers and commercial, remain exposed to climatic extremes, and current management approaches may not be adequate to manage or respond to conditions. The adaptation options recommended in this study were considered applicable to most, if not all, mill areas under study. While sugarcane production remains a viable enterprise in southern Africa, it remains under significant pressure to minimize resource use (land, water, and labor costs to name a few), while remaining internationally competitive. The adaptation options suggested in this study can potentially minimize current and future vulnerabilities, increase yields while minimizing resource inputs.

Adapting to a changing climate is a multifaceted exercise, requiring a holistic approach that includes every aspect of the sugarcane value chain. Studies such as this provide an initial view into the vulnerability of individual mill areas. By addressing water stress, this study highlighted the importance of understanding the exposure of sugarcane to climatic extremes and the need of developing more inclusive adaptation strategies.

CRediT authorship contribution statement

S. Ngcobo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Jewitt:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **T.R. Hill:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **E. Archer:** Writing – review & editing, Writing – original draft, Supervision.

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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