

**AN ASSESSMENT OF THE POTENTIAL IMPACTS OF CLIMATE
VARIABILITY ON SUGARCANE PRODUCTION ACROSS SOUTHERN AFRICA**

SIMPHIWE I. NGCOBO

MSc (Hydrology)

**Submitted in partial fulfilment of the requirements
for the degree of PhD in Hydrology**

Discipline of Hydrology
Centre for Water Resources Research
School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal
Pietermaritzburg
November 2023

TABLE OF CONTENTS

	Page
LIST OF TABLES.....	I
LIST OF FIGURES.....	II
PREFACE	VI
DECLARATION 1: PLAGIARISM.....	VII
DECLARATION 2: PUBLICATIONS	VIII
ACKNOWLEDGEMENTS	V
DEDICATION	VI
ABSTRACT	VII
CHAPTER ONE	1
INTRODUCTION	1
1.1 Research Justification.....	9
1.3 Research Aim	11
1.4 Research Objectives	11
1.5 Thesis Outline.....	12
References	13
CHAPTER TWO.....	21
IMPACTS OF GLOBAL CHANGE ON SOUTHERN AFRICAN WATER RESOURCE SYSTEMS	21
2.1 Introduction	22
2.2 Vulnerability to Global Change.....	24
2.3 Aspects of Global Change	28
2.3.1 Climate Change	28
2.3.2 Land Use Change	29
2.3.3 Population Growth and Economic Development	32
2.4 Discussion and Conclusions	33
2.4.1 Science and Technology Lessons	35
2.4.2 Governance, Policy and Management Lessons	35
2.4.3 Socio-economic Lessons	35
Acknowledgements	36
References	36

CHAPTER THREE.....	46
MULTISCALE DRIVERS OF SUGARCANE EXPANSION AND IMPACTS ON WATER RESOURCES IN SOUTHERN AFRICA	46
Abstract.....	46
3.1 Introduction	47
3.2 Proximate and Ultimate Drivers of Sugarcane Expansion in southern Africa 53	
3.2.1 Sugarcane Expansion in southern Africa.....	53
3.3 Proximate and Ultimate Drivers	54
3.4 The Significance of Scale in Understanding Drivers and Impacts.....	55
3.5 Methods	57
3.5.1 Data Acquisition and Processing.....	57
3.5.2 Frequency Analysis of Proximate and Ultimate Drivers.....	59
3.6 Water Resources Impact Assessment.....	63
3.6.1 Sugarcane Production Growth Scenarios	63
3.6.2 Estimating Sugarcane Water Use	65
3.7 Results and Discussion	67
3.7.1 Drivers of Sugarcane Production across Spatial Scales	67
3.7.2 Drivers of Sugarcane Production across Temporal Scales.....	70
3.8 Water Resources Impacts	73
3.9 Conclusions	78
References	80
CHAPTER FOUR	87
A YIELD GAP ANALYSIS TO ASSESS VULNERABILITY OF COMMERCIAL SUGARCANE TO CLIMATIC EXTREMES IN SOUTHERN AFRICA	87
Abstract.....	89
4.1 Introduction	90
4.2 Study Sites	93
4.3 Methods	94
4.3.1 Introduction	94
4.3.2 Yield Gap Analysis.....	97
4.3.3 Input Data Acquisition and Processing	99
4.3.4 Model Description	101

4.3.5	Model Inputs.....	103
4.3.6	Conservative and Non-Conservative Parameters	103
4.3.7	Aquacrop File Setup and Simulation Procedures	103
4.3.8	Yield Estimation.....	107
4.3.9	Model Validation and Verification.....	108
4.4	Results and Discussion	112
4.4.1	Sugarcane Yield Trends and Yield Gaps.....	112
4.5	Drivers of Yield Gaps.....	118
4.6	Recommendations to Reduce Yield Gaps	120
4.7	Conclusions	123
	Acknowledgements	125
	References	125
	Appendix 4A: Observed and Supplementary Input Data	138
	CHAPTER FIVE	143
	AN ASSESSMENT OF THE VULNERABILITY AND ADAPTATION	
	POTENTIAL OF SUGARCANE PRODUCTION TO WATER STRESS	
	ACROSS SOUTHERN AFRICA.....	143
	Abstract.....	144
5.1	Introduction	145
5.2	Study Sites	149
5.3	Methods	151
5.3.1	Introduction	151
5.3.2	The AquaCrop Model.....	154
5.3.3	Data Sources and Availability	156
5.3.4	Simulation Procedures	158
5.3.5	Seasonal Sugarcane Water Use	161
5.3.6	Crop Productivity Ratio.....	162
5.4	Adaptation Spaces	163
5.5	Results and Discussion	166
5.5.1	Long Term Sugarcane Water Use	166
5.5.2	Sugarcane Yield and Water Use Relationships	169
5.5.3	Sugarcane Crop Productivity Ratio	174
5.6	Adaptation Spaces for Sugarcane Production	179
5.7	Adaptation Recommendations.....	182

5.8	Conclusions	183
	Acknowledgements	184
	References	184
	CHAPTER SIX	197
	SYNTHESIS	197
6.1	Research Challenges.....	202
6.2	The Way Forward.....	203
6.3	Contributions of Research to New Knowledge.....	204
	References	206
	CHAPTER SEVEN	209
	CONCLUSIONS	209

LIST OF TABLES

Table 3.1	Hydrological indicators, estimated sugarcane water use and approximate harvested sugarcane area by country in the SADC region.	49
Table 3.2	Background information on case study catchments.	59
Table 3.3	Broad themes and variables which culminate in proximate and ultimate drivers for sugarcane production and the associated impacts on water resources.	62
Table 3.4	Current sugarcane production rates and prospective production scenarios.	65
Table 3.5	Spatial frequency of cases describing broad proximate and ultimate drivers across local catchment and regional scales.....	68
Table 3.6	Frequency of cases describing drivers of sugarcane production across various temporal scales.....	71
Table 3.7	Average sugarcane water use (wu) and ET_C estimates as functions of mean annual production rates (P) and crop coefficients (K_C) respectively, for the 2013/14 production cycle, for the various catchments under study.	74
Table 4.1	Information on sugarcane mills and parent catchments.	96
Table 4.2	Years excluded from the YG analysis including reasons for exclusion and actual data sources for rainfall, temperature and total evaporation.	100
Table 4.3	Non-conservative parameters adjusted in the AquaCrop to simulate yields*.....	105
Table 5.1	Information on selected sugarcane mill areas and parent catchments for the 1994-2019 period.....	151
Table 5.3	Data sources for rainfall, temperature and total evaporation used to simulate maximum potential sugarcane yields.....	155

LIST OF FIGURES

Figure 1.1	Mean annual precipitation (MAP) across southern Africa highlighting the high spatial variability of rainfall across the region. The global average of 860mm/yr is represented by the thick red line. 2
Figure 1.2	A typical southern African sugarcane production value chain. 6
Figure 2.1	Diagram building from the ‘kite’ concept indicating the various drivers of change unique to southern Africa across different spatial scales, but also illustrating the panarchy of changes ranging from rapid, small changes (‘revolt’) at local scales to large and slow changes (‘remember’) at larger scales. Rapid, small changes (revolt) can overwhelm larger and slower changes in the region (<i>e.g.</i> socio-political unrest related to poor public service delivery). The ‘remember’ progression of change represents the dissemination of wisdom accumulated from episodes of revolt to prevent further collapse of systems and, ideally, this wisdom cascades progressively from large to small scales. 24
Figure 2.2	Map indicating the contiguous nations of southern Africa, shared river basins and major reservoirs. 27
Figure 2.3	(a) Multi-model probabilistic forecasting for the likelihood of February-March-April 2011 rainfall totals exceeding the 85 th percentile (extremely wet, left panel) and 15 th percentile (extremely dry, right panel) percentiles of the climatological record and (b) projected changes (%) in austral summer (Dec-Feb) mean daily precipitation rates in each of the 5 climatic zones of Southern Africa generated from multi-model ensembles 29
Figure 2.4	Modified Environmental Kuznets Curve showing two possible environmental degradation trajectories (a, b) across various stages of economic development for South Africa: a) under the current limited implementation of environmental protection policies designed to limit environmental degradation; b) effective implementation of environmental protection policies (<i>e.g.</i> NWA and NWRS) and availability of capacity to facilitate implementation..... 32
Figure 3.1	Mean annual precipitation (MAP) across southern Africa highlighting the high spatial variability of rainfall across the region. The global average of 860mm/yr is represented by the thick red line. 50
Figure 3.2	Mean annual precipitation (MAP) and mean annual runoff (MAR) conversion ratios relative to various countries (a) and (b) MAR ranges across major shared basins in Southern Africa. The MAR: MAP conversion ratio across southern Africa is only 20%, at best. 51
Figure 3.3	Sugarcane harvested areas across southern Africa occupying an area of approximately 785 000 Ha. 52

Figure 3.4	Diagram building from the ‘kite’ concept indicating the dominance of various drivers of change applicable to Southern Africa across different spatial scales. The green arrows indicate changes in dominant drivers as scale is progressively increased and red arrows reflect changes as scales are reduced. This indicates that at large scales, ultimate drivers become increasingly dominant, whereas at smaller scales proximate drivers assume the dominant role.	56
Figure 3.5	Location of case study catchments in southern Africa.	58
Figure 3.6	Schematic representation of the methodological approach.	61
Figure 3.7	Spatial relative dominance of drivers at local catchment and regional scales also indicating the strength of the causal relationships between themes of drivers.	67
Figure 3.8	Actual and projected sugarcane yields (t) for the 2013/14-2019/20 cycles based on (a) low, (b) medium and (c) high production scenarios. Water use estimates (mm.a ⁻¹) are reported in direct relation to the projected sugarcane production rates.	77
Figure 4.1	A typical southern African sugarcane production value chain.	91
Figure 4.2	Mill locations within individual catchments and the spatial extent of the area under sugarcane across the region. 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, c) the Kilombero Catchment in Tanzania. d) the Shire Catchment in Malawi and e) the Mvoti, Umlaas and Mngeni Catchments in South Africa.	95
Figure 4.3	A conceptual framework describing the yield gap analysis and its components.	97
Figure 4.4	The AquaCrop calculation scheme indicating the various processes (indicated by the dotted lines) that are directly affected by water stress.	102
Figure 4.5	A summary of the modelling procedures in the AquaCrop model adopted in this study to determine yield gaps.	110
Figure 4.6	AquaCrop verification results based on average (<i>i.e.</i> combined) observed (Ya) and simulated (Yp) sugarcane yield data for the mill areas in South Africa.	111
Figure 4.7	AquaCrop verification results based on observed (Ya) and simulated (Yp) sugarcane yield data for the Big Bend mill area in the Ubombo catchment.	111

Figure 4.8	(a) Observed (Y_a) and simulated (Y_p) 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 (Y_{GT}) per year are reported here indicating, on average, an increase in yield gaps over the 1996-2015 period and a subsequent decrease in yield gaps from 2016-2019. 114
Figure 4.9	Potential water-limited yield (Y_w) for the (a) South African and (b) Nchalo mill areas compared to observed (Y_a) and potential (Y_p) yields. Y_w for these mills area averaged 75.69t/ha over the course of the study as a result of lower water deficits. 115
Figure 4.10	Observed yield trends for all mill areas under study between 1994 and 2019..... 117
Figure 4.11	Access to water resources and crop management as the main causes of sugarcane yield gaps across the study catchments..... 121
Figure 4.12	Yield gap analysis results for the mill areas under study based on the conceptual framework..... 122
Figure 4A.7	Example of an observed climate data file (CLI) for the Eston Mill Area in South Africa for the year 1985. This climate file spanned 1984-2019. 141
Figure 5.1	Average sugarcane yields ($\times 000t/annum$) and mean annual precipitation. 147
Figure 5.2	Clockwise from top-left: a) the Ubombo Catchment in Swaziland, b) Spatial distribution of sugarcane production areas across Southern African based on modelled data, c) the Kilombero Catchment in Tanzania. d) the Shire Catchment in Malawi and e) the Mvoti, Umlaas and Mngeni Catchments in South Africa. Mill locations within individual catchments and the spatial extent of the area under sugarcane across the region are also reflected. 150
Figure 5.3	Examples of practical AquaCrop application. 156
Figure 5.4	A summary of the modelling procedures in the AquaCrop model adopted in this study to simulate maximum potential sugarcane yields. 160
Figure 5.5	Defining safe and unsafe adaptation spaces based on the CPR concept and observed and simulated yields. 165
Figure 5.6	Long-term mean (LTM) sugarcane water use (wu) in relation to mean annual precipitation (MAP) for individual mill areas..... 168
Figure 5.7	LTM observed and simulated yields for the South African mill areas and annualized water use per growing cycle. 170

Figure 5.8	LTM observed and simulated yields for the Big Bend mill area and annualized water use per growing cycle.	171
Figure 5.9	LTM observed and simulated yields for the Nchalo mill area and annualized water use per growing cycle.	172
Figure 5.10	LTM observed and simulated yields for the Kilombero mill area and annualized water use per growing cycle.	173
Figure 5.11	Long Term Mean (LTM) Crop Productivity Ratios (CPR) for a) South African, b) Big Bend, c) Nchalo and d) Kilombero mill areas relative to observed and simulated yields.	176

PREFACE

The research contained in this thesis was completed by the candidate while based at the Discipline of Hydrology, Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Centre for Water Resources Research and the Global Challenges Research Fund - Uncertainty Reduction in Models for Understanding Development Applications (GCRF-UMFULA) who are gratefully acknowledged.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed:



Simphiwe Innocent Ngcobo

Signed:

Professor Graham Jewitt



Signed:

Professor Trevor Hill

Signed:



Professor Emma Archer

DECLARATION 1: PLAGIARISM

I, *Simphiwe Innocent Ngcobo*, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work.

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university.

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been rewritten but the general information attributed to them has been referenced.

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.

(v) where I have used material for which publications followed, I have indicated in detail my role in the work.

(vi) this dissertation is primarily a collection of material, prepared by me, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included.

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

A large black rectangular redaction box covers the signature area, obscuring the name and any handwritten notes.

Signed:

Simphiwe Innocent Ngcobo

DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

Publication One: Chapter Two of this Thesis

Ngcobo, S.I *, Jewitt, G., Stuart-Hill, S., & Warburton, M. (2013). Impacts of global change on southern African water resources systems. *Current Opinion in Environmental Sustainability*, 5(6), 655–666. <https://doi.org/10.1016/j.cosust.2013.10.002>.

The research, data collection and analysis for this publication were conducted by S Ngcobo with writing and technical advice from G. Jewitt, M. Warburton and S. Stuart-Hill. The publication was written by S Ngcobo and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding paper structure and scientific content was provided by G. Jewitt, M. Warburton and S. Stuart-Hill.

Publication Two: Chapter Three of this Thesis

Ngcobo, S.I *, & Jewitt, G. (2017). Multiscale drivers of sugarcane expansion and impacts on water resources in Southern Africa. *Environmental Development*, 24, 63–76. <https://doi.org/10.1016/j.envdev.2017.07.004>.

The data collection, modelling and analysis for this publication were conducted by SI Ngcobo with writing and technical advice from G. Jewitt. The publication was written by SI Ngcobo and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding content and structure was provided by G. Jewitt.

Publication Three: Chapter Four of this Thesis

Ngcobo, S., Hill, T. R., Jewitt, G., & Archer, E. (2023). A yield gap analysis to assess vulnerability of commercial sugarcane to climatic extremes in southern Africa. *Journal of Agriculture and Food Research*, 14, 100734. <https://doi.org/10.1016/j.jafr.2023.100734>

The data collection, hydrological modelling, analysis and interpretation of results for this paper were conducted by SI Ngcobo with writing, technical advice and editing from T. Hill, G. Jewitt and E. Archer. The publication was written by SI Ngcobo and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding content and structure was provided by G. Jewitt, T. Hill and E. Archer.

A black rectangular box redacting the signature of the author.

Signed:

Simphiwe Innocent Ngcobo

ACKNOWLEDGEMENTS

This research would not have been possible without the input, guidance and support of numerous people and organisations that I am eternally indebted to. Special thanks to the following:

My family, Azania, Mpumi, Hlengiwe and Amanda for the love, encouragement, the jokes, the late-night chats, this would not have been possible without you. I love you and thank you!

Professor Graham Jewitt of the Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, South Africa and the Faculty of Civil Engineering and Geosciences, Technical University, Delft, The Netherlands for his patient supervision, encouragement, and guidance throughout the project. Thank you for not giving up on me.

Professor Trevor Hill of the Discipline of Geography, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa for his impeccable editing, scientific and technical writing advice and the wonderful coffee breaks.

Professor Emma Archer of the Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Hatfield, for the patient guidance and constant encouragement.

The South African Sugar Research Institute, Harvest-Choice, the South African Weather Service, the National Aeronautics and Space Administration and the University of KwaZulu-Natal Centre for Water Resources Research for supplying the long-term climatic data and valuable hydrological modelling advice.

The National Research Foundation, Water Research Commission, the Centre for Water Resources Research and the Global Challenges Research Fund for their financial assistance.

DEDICATION

For my late mother. Forever my hero. Thank you for everything.



ABSTRACT

The scale and extent of changes to demographic, economic and environmental systems exacerbated by human activities have been rapid and pervasive enough that it has been established that a new geologic era termed the Anthropocene has already begun. One of the most critical and challenging consequences of the Anthropocene has been the accelerated release of greenhouse gases leading to global warming and, consequently, climate change (CC), which has impacted hydrological responses and available water resources by increasing surface temperatures and altering precipitation patterns across spatio-temporal scales. These changes have exacerbated the vulnerability of various systems that sustain livelihoods, placing them at high risk of collapse. One of these systems is sugarcane production, which is a crucially important agricultural activity in many parts of the world, including southern Africa.

There is a consensus that as a region, southern Africa will be subjected to amplified hydrological impacts which will affect the sugarcane production landscape. Further the expansion and intensification of sugarcane production across southern Africa is highly likely due, in part, to the recognition of the economic and social importance of this activity for supporting livelihoods. Sugarcane yields have been declining over the past 25 years in the region because of the increased frequency of climatic extremes. Literature reviews showed that by amplifying precipitation variability, climate change will increase the exposure and vulnerability of sugarcane to water stress and will have a devastating impact on yields. However, knowledge gaps remain regarding climate change impacts on water resources and sugarcane yields. Further, few studies have addressed the vulnerability and adaptation potential of sugarcane production at sufficient spatio-temporal scales. To address these knowledge gaps, an initial review was conducted to understand the dynamics between global change and water resources across southern Africa. The review showed that although global drivers are intricately related, their water resources impacts are highly complex, indirectly coupled and spatially and temporally sensitive.

Having established a general perspective of the impacts of global change in southern Africa, the multi-scale drivers of sugarcane production were analysed using of a frequency analysis.

This approach allowed the determination of proximate and ultimate drivers in the uMngeni, uMlaas, and Umvoti catchments in South Africa, the Ubombo catchment in eSwatini, the Shire catchment in Malawi and the Kilombero catchment in Tanzania. The frequency analysis provided quantitative descriptions of the water resource impacts of sugarcane production across southern Africa. Applying a relationship between observed sugarcane yields and future low, medium, and high production scenarios, this study developed water use estimates for sugarcane over multiple growing cycles. Results indicated that ultimate drivers play the most dominant role in the expansion of sugarcane production within each catchment. Drawing from this analysis, a methodology of assessing yield declines was developed based on a yield gap analysis using the AquaCrop crop growth model. The results were used to develop recommendations to mitigate yield declines by offering safeguards for the sugarcane industry against climatic extremes. Modelling results suggested that yield trends can be attributed to existing crop management approaches instead of prevailing hydroclimatic regimes. The importance of recognising the vulnerability and adaptation potential in sugarcane production was highlighted in this study. It was concluded that if sugarcane growers are to adapt to the effects of extreme climatic events, they must consider shifting crop management approaches and be proactively included in related research. This research highlighted the importance of addressing the interactions between activities that drive land use change, such as sugarcane production, and the current impacts of climatic extremes on water resources. This is important in rapidly developing regions and climate change hotspots such as southern Africa. The development of innovative adaptation policies that will safeguard the already-pressured water resources and secure the sustainability of sugarcane production will become increasingly important under an altered climate.

CHAPTER ONE

INTRODUCTION

The ability of humanity to alter their habitats to access, secure and cultivate important resources such as water, food, fodder, fibre, and fuel dates back to the First Agricultural Revolution around 7500BC (Braidwood, 1960; Kerridge, 2013). Since then, and particularly following the Industrial Revolution in the 18th century, the scale and extent of changes to a host of socio-ecological systems driven by human activities have been rapid and pervasive enough that it has been suggested that a new geologic era termed the ‘*Anthropocene*’ has already begun (Crutzen, 2006; Ruddiman, 2013; Steffen et al., 2011) This is a geologic era dominated by humanity, and one in which anthropogenic activities have become the main change agents to global climates and ecosystems. Humanity has been exceptionally successful at extracting and processing natural resources, often with unintended and unpredictable consequences. The successful exploitation of these resources has come at significant environmental and human costs, particularly in low-income regions such as southern Africa (Parnell and Walawege, 2011; Vincent, 2011).

Perhaps the most pervasive and challenging consequence of the Anthropocene has been the accelerated release of greenhouse gases (GHGs) which has led to global warming (Houghton, 2005) and, consequently, climate change (IPCC, 2019; Hennessy et al., 2022; Houghton et al., 1990) which has impacted hydrological responses and available water resources by increasing surface temperatures (Kaufmann et al., 2011), accelerating evaporation rates (Dai et al., 2018) and altering precipitation patterns over a range of spatial and temporal scales (Knapp et al., 2017; O’Gorman, 2015) particularly in southern Africa (Engelbrecht, 2017; Theron et al., 2022). This region is often severely impacted by climate change, despite contributing a small fraction to global greenhouse gas emissions (M. I. Tongwane & Moeletsi, 2018). This is a result of the high vulnerability and low resilience of various important systems such as water resources that render the region highly susceptible to collapse as a consequence of climate change. While the drivers of climate change are often local in scale, their impacts tend to be expressed across regional and global scales (Ngcobo et al., 2013). An example of this dynamic is extensive land use change (LUC) (Musakwa & Niekerk, 2013; Schulze, 2000; Warburton Toucher et al., 2010) which, despite being a local phenomenon, can potentially and significantly alter the hydrological cycle by disrupting

critical processes and fluxes such as total evaporation, convection, precipitation and surface runoff.

In southern Africa, a region already subject to high hydroclimatic variability (Hennessy et al., 2022) (**Figure 1.1**), the amplification of the intensity of these processes tends to be cumulative and can lead to high-impact ‘natural’ disasters such as extensive floods (Dube et al., 2023; Kalantari et al., 2018; Smithers et al., 2018) and the high frequency of droughts and heatwaves (Engelbrecht, 2017; Theron et al., 2022).

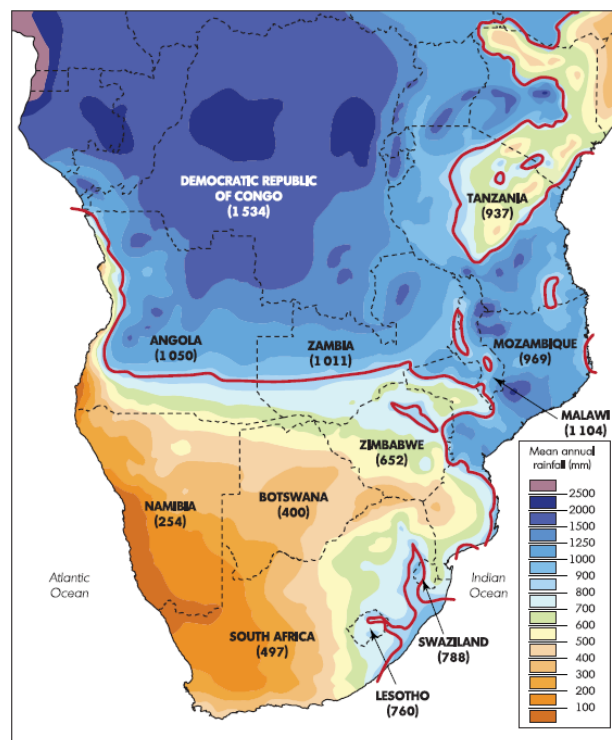


Figure 1.1 Mean annual precipitation (MAP) across southern Africa highlighting the high spatial variability of rainfall across the region. The global average of 860mm/yr is represented by the thick red line (Data Sources: Hewitson et al., 2005; Turton, 2008).

In many parts of the world, LUC is a well-understood process and its consequences have been widely studied (Aleman et al., 2016; Fischer & Hajdu, 2015; Forsell et al., 2016; German et al., 2020; Meyfroidt et al., 2013; Veldkamp & Lambin, 2001); however, significant knowledge gaps related to LUC dynamics remain across southern Africa. The region is made up of developing nations and emerging economies where the drivers of LUC are particularly unique and are geared specifically towards social and economic

development, and these drivers of LUC often generate non-linear impacts (Deressa et al., 2005; Dubb, 2015). Commercial agriculture, for instance, is a necessary and economically important form of LUC that in many instances (although not always) disregards environmental and hydrological impacts such as biodiversity loss and soil degradation. Despite their long-term significance, these negative impacts are often overlooked in favour of the socio-economic development benefits associated with commercial agriculture (German et al., 2020; Gasparatos et al., 2021).

While the 2014/2017 drought and the 2020/2021 pandemic resulted in the decline in productivity for a plethora of commercial agriculture enterprises (Nchanji & Lutomia, 2021), the extent and significance of the impacts of anthropogenic LUC borne from commercial agriculture has not diminished (Odebiri et al., 2023). In fact, it may be argued that the pace of LUC has regained its momentum to recoup the economic losses incurred during the 2014/2017 drought and the unexpected pause in production triggered by the COVID-19 pandemic. The inherent dynamism of LUC in southern Africa has been investigated by numerous scholars in the region including Odebiri et al., (2023), German et al., (2020), Gasparatos et al., (2021), Mararakanye et al., (2022) and more broadly by the IPCC Special Report on Climate Change and Land (IPCC, 2019). A few common themes emerged from the results generated by these studies and these include, *inter alia*, the central role of land as a source and sink of GHGs and an important medium in the exchange of water and energy (IPCC, 2019), the importance of land in providing important ecosystem goods and services (Odebiri et al., 2023; Akpoti et al., 2022) and the role of land as a key determinant of the extent and intensity of the negative impacts of climate change (Mararakanye et al., 2022). While LUC has supported increased food, fodder and fibre production in the region, it has also affected the regional climate by increasing the release of GHGs, particularly CO₂, N₂O and CH₄ (Atedhor, 2023; Tongwane & Moeletsi, 2018; Tongwane et al., 2016) ultimately leading to the increased frequency and intensity of extreme hydrological events such as droughts, heatwaves and extreme rainfall. These observations are supported by Meque et al., (2022) who note that the spatial and temporal variability of heatwave characteristics have increased significantly in southern Africa as a result of the El Niño Southern Oscillation (ENSO) climate pattern, the effect of which, as Akpoti et al., (2022) conclude, has resulted in significant losses of suitable agricultural land owing to high day/night temperature oscillations.

These climatic and hydrological changes are-or should be-a major concern across Southern Africa considering that this is a region currently undergoing major land use changes that are influenced by economic transformation and agricultural expansion (Conradie et al., 2019; Musakwa & Niekerk, 2013; Alcamo *et al.*, 2011). While necessary to alleviate the crippling endemic poverty, the long-term consequences of these activities are often poorly understood. The combination of LUC and climate change has enhanced the vulnerability of numerous systems that are important in sustaining livelihoods - and combating poverty - and placed them at high risk of collapse (Hennessy et al., 2022; Ishtiaque et al., 2022). The IPCC Special Report on Climate Change and Land (IPCC, 2019) presented substantive evidence to suggest that commercial agriculture is a significant contributor to regional climate change and acts as a stressor to biophysical systems, particularly water resources (German et al., 2020). Concurrently, however, commercial agriculture is an invaluable and indispensable activity that is the cornerstone of multiple economies in the region (du Preez & van Huyssteen, 2020; Ncoyini et al., 2022). The effect of this “double-edged sword” state of affairs necessitates a detailed study of both the drivers and impacts of LUC on important biotic and abiotic resources but also of the effects of climate variability on LUC.

This study addresses LUC instigated by commercial agriculture through the lens of sugarcane production. For purposes of this study, ‘sugarcane production’ relates to both commercial and small-scale outgrowers. Outgrowers are defined as small-scale on smallholdings that supply larger commercial growers through binding long-term contractual agreements (Wendimu et al., 2016; Sulle, 2017; von Maltitz et al., 2019). The inclusion of outgrowers is important because they represent a highly significant component of the sugarcane production value chain and, being small-scale growers, are often highly vulnerable to the impacts of climate variability. As one of the most important agricultural activities in southern Africa, sugarcane production supports millions of livelihoods and contributes significantly to the economies of this region particularly in South Africa, Tanzania and eSwatini (Deressa et al., 2005; Hess et al., 2016; German et al., 2020). However, sugarcane production is under severe pressure to maintain and/or increase yields under challenging natural hydroclimatic and international economic conditions. This pressure will be amplified by the ongoing and projected expansion and intensification of sugarcane production that will cause significant impacts and responses on regional water resources and introduce added complexity to agronomic management (**cf.** Chapter Three for a detailed discourse on these impacts) (Dubb, 2015).

Sugarcane production is particularly vulnerable to climate variability as a result of the effects of changes in temperature and precipitation (Zinyengere et al., 2013; IPCC, 2019; Christina et al., 2021; Verma et al., 2023). This vulnerability may be expected to be enhanced in countries that rely heavily on rainfed agriculture and have limited access to irrigation systems (Jones et al., 2015a; Singels et al., 2019).

Further, the now-confirmed and already in-progress increases in the frequency of extreme events (*i.e.* droughts, heatwaves and extreme rainfall) (Hennessy et al., 2022; Meque et al., 2022) are introducing novel challenges to the production and management of sugarcane and will undoubtedly introduce additional complexities and vulnerabilities to sugarcane production. A review by Chandiposha (2013) on the potential negative impacts of climate change on sugarcane production in Zimbabwe showed that production trends often resemble the fluctuations in extreme climate events, and this illustrates the sensitivity of sugarcane production to climate variability. Similarly, the work by Knox et al., (2010) in Eswatini suggested that changes to rainfall instigated by climate change can result in yield declines unless irrigation is implemented on a continuous basis. Further, in a study in South Africa, Jones and Singels (2015a,b) also showed that yields may be compromised as a result of droughts leading to the increased frequency of soil water deficits. While these studies provided comprehensive assessments of the potential impacts of climate variability and change on sugarcane production, they were limited in scope and spatiotemporal scale since they considered sugarcane production in individual countries. It thus remains necessary to develop a regional assessment of the effects of climate variability on sugarcane production in order to capture the connectivity of the southern African sugarcane industry and the overarching effects of climate variability in this region.

Over the past 15 years, the sugarcane production industry has experienced significant changes to the entire production value chain. The typical southern African sugarcane production value chain includes numerous important industries, which include research, small and large-scale farms, sugar estates, mills and refineries, export markets, retailers, and consumers (**Figure 1.2**). This value chain has been changed -and continues to be changed- by a variety of factors, including increased competition for critical resources such as land and water, changes to rainfall seasonality leading to changes in planting dates, improved production and processing technologies, advances in biotechnology research leading to improved sugarcane varieties, increased pest outbreaks, increased illegal imports of sugar,

and policies which support (McKay et al., 2016) or undermine (James & Woodhouse, 2017) sugarcane production.

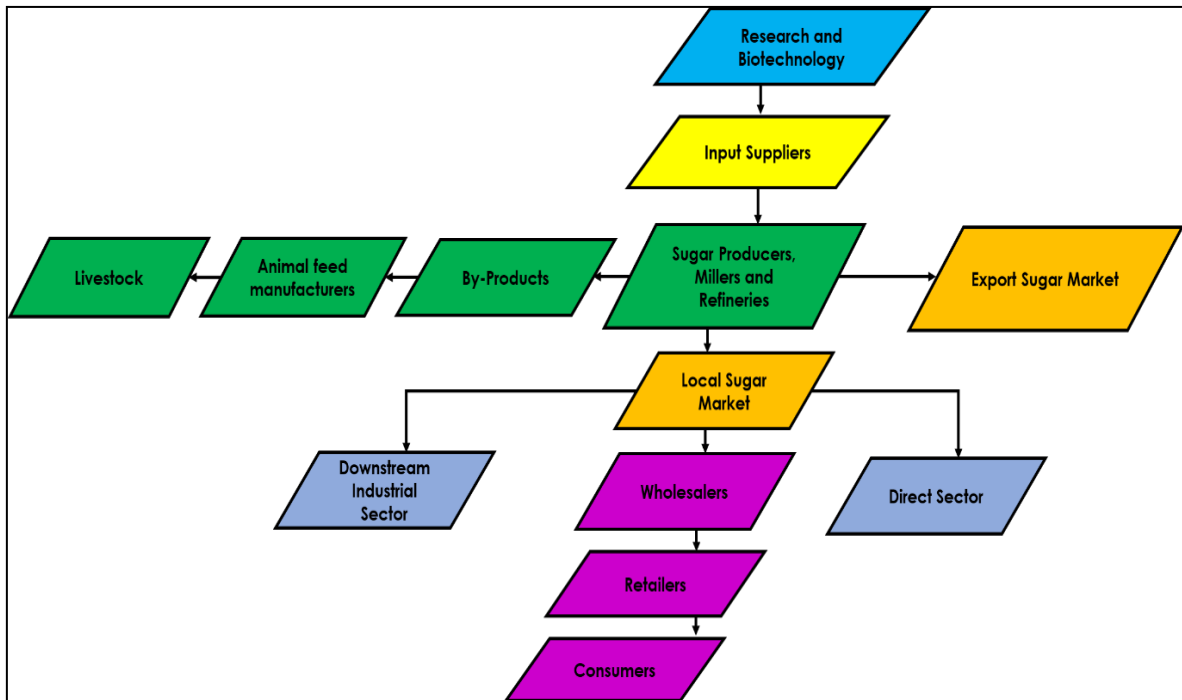


Figure 1.2 A typical southern African sugarcane production value chain (Modified from: (Booyesen et al., 2017 ; Harvest-Choice, 2019).

These changes have either been internal to ensure that growers remain internationally competitive (Meyer & Antwerpen, 2021; Zulu et al., 2019) or external as a result of stressors such as a climate change and, more often, myopic economic policies that suppress the progress of the sugar industry (Gasparatos et al., 2021). The drivers, impacts and feedbacks of these changes, however, remain poorly understood in this region. In the context of sugarcane production, while some relatively technologically advanced countries such as South Africa and eSwatini have begun to develop an understanding of the impacts of climate change on sugarcane production (Jones et al., 2015a; Singels et al., 2014), the same cannot be said for other major sugar producing countries in southern Africa. In fact, there are no known studies that have attempted to quantify the impacts of climate change on sugarcane over sufficient spatial and temporal scales in this region.

Despite a generally well-understood production environment (**Figure 1.2**), sugarcane yields remain far below their potential and there are still significant variations yields between different sugar producing countries in southern Africa. This is often a consequence of climate variations, particularly rainfall and temperature (Christina et al., 2021), high vulnerability to extreme climate events and pest outbreaks (Cockburn et al., 2014; Kasambala Donga & Eklo, 2018), poor forecasting systems (Muller et al., 2020; Ncoyini et al., 2022) and a macroeconomic landscape typified by high production costs and illegal cheap sugar imports (Chinsinga, 2017; Fundira & Henley, 2017) all of which undermine the successful cultivation of sugarcane and limit the global competitiveness of the regional sugar industry. The combination of these factors implies that there are significant gaps in knowledge that require greater scrutiny in order to create a production environment that can withstand current and future impacts of increased climate variability and reduce vulnerabilities across the production value chain.

Interrogating and understanding the impacts of climate variability on sugarcane production requires the consideration of the full spectrum of factors which determine the exposure and vulnerability of the crop to climatic extremes. This, as acknowledged by various scholars, includes a thorough assessment of the socioeconomic (Gasparatos et al., 2021), environmental (Conradie et al., 2019) and political (Dubb et al., 2017) factors which determine and influence the long-term sustainability of sugarcane production. For instance, Yang et al., (2022) and Desalegn et al., (2023) note that while it is important to increase productivity and profitability, this has to be achieved without compromising water, land and human resources upon which the enterprise depends. Further, as argued in Chapter 4 of this study and supported by Narimoto & Camarotto (2018), new technologies such as drought and pest-resistant cultivars and efficient irrigation systems need to be transferred to commercial and small-scale outgrowers at a faster pace to circumvent the effects of climatic extremes and minimise vulnerabilities across the production chain. Additionally, Coelho and Goldemberg (2019) highlight the importance of balancing the requirements for improved yields with meeting environmental regulations particularly in a rapidly changing region. Finally, Herrmann et al., (2018) and Silalertruksa & Gheewala (2020) suggest that the apparent increased competition between energy and food production is already enhancing the complexity of an already complex Water-Energy-Food Nexus (Hoff, 2011; Biggs et al., 2013; Albrecht et al., 2018) by limiting the availability of land and water resources which will undoubtedly compromise the continuity of sugarcane production across the region. It is

clear from the arguments presented above that sugarcane production is facing a multitude of challenges that will be compounded by a changing climate. It is thus imperative that the ideal of quantifying exposure, reducing vulnerabilities, and enhancing adaptation potential be supported by regional studies that seek to understand and quantify the effects of increased climate variability on sugarcane production.

The impacts of a changing climate are no longer speculative or confined to climate projections which have often been subjected to undue criticism and scepticism. The frequency of droughts, heatwaves and floods across southern Africa has visibly increased dramatically over the past 10 years (Ekolu et al., 2022; Gannon et al., 2018; Gizaw & Gan, 2017; Johnson et al., 2021; Lottering et al., 2021; Omotoso et al., 2023; Ramlall & Smithers, 2023; Ward et al., 2020) often with dramatic impacts. Sugarcane production, and agriculture in general, has experienced a variety of impacts stemming from increased climate variability which include increased water stress and pest outbreaks. While the regional sugar industry has responded effectively to these impacts by developing and adopting improved sugarcane varieties (Olivier and Singels, 2015) and changing agronomic management practices, these responses are still confined to the relatively technologically advanced countries such as South Africa and Eswatini. Other important sugar producing countries such as Malawi and Tanzania still lag far behind in the adoption of these mitigation strategies. This limits the overall competitiveness of the regional sugar industry and leaves it exposed to potential economic exploitation from other major global sugar producers.

Sugarcane production in southern Africa is an especially complex activity that involves multiple actors and a diverse array of biophysical, hydroclimatic and even sociopolitical landscapes. The sugar industry is domiciled in a region that is unfavourable to the production of this crop and, in many cases, was established out of necessity rather than design. The global sugar shortage of the 1970s led to high import costs which prompted many countries in the region to start cultivating sugarcane locally despite the high hydroclimatic variability that does not lend itself to the production of a water-use intensive crop such as sugarcane (Lewis, 1990; Dubb et al., 2017; Zhou, 2013) (**Figure 1.1**). Further, the now well-accepted vulnerability of this region to climate change implies that the viability and sustainability of sugarcane production will remain under threat as a direct consequence of the impacts of climate change (IPCC, 2019; Hennessy et al., 2022).

Despite the importance of this crop in southern Africa, it remains exposed and vulnerable to the effects of climatic extremes caused by climate change (Knox et al., 2010a; Jones et al., 2015b). This exposure is already undermining yields by increasing water deficits (Jones et al., 2019; Dias & Sentelhas, 2021), and by forcing changes in crop management which can threaten the long-term sustainability of the sugar industry (Biggs et al., 2013). There is a consensus that southern Africa will experience amplified hydrological impacts which will affect the sugarcane production landscape (Jones et al., 2015; Sulle, 2017; von Maltitz et al., 2019). It has been noted (*e.g.* Dubb et al., 2017; James et al., 2017; Ngcobo and Jewitt, 2017; Zulu et al., 2019) that the future expansion and intensification of sugarcane production across southern Africa is highly likely due, in part, to the recognition of the economic and social importance of this activity for supporting livelihoods. Knowledge gaps remain, however, regarding climate change impacts on water resources and sugarcane yields. By amplifying precipitation variability, climate change will increase the vulnerability of sugarcane to water stress and is likely to have a potentially devastating impact on sugarcane yields. To date, relatively few studies have addressed the vulnerability and adaptation potential of sugarcane production at sufficient spatial and temporal scales in this region. In fact, it is clear that sugarcane production will continue to be directly and indirectly affected by increases in climate variability and will require the continuous updating of adaptation strategies to offset the negative effects of extreme climatic events. This study, and other like it, seeks to understanding the drivers of sugarcane production and also assess the impacts of climate variability on this important commodity crop.

1.1 Research Justification

Sugarcane is one of the most important commodity crops on par with maize, cassava, sorghum, and sweet potatoes and supports millions of livelihoods in the region (Deressa et al., 2005; Hess et al., 2016; German et al., 2020). The importance of this crop cannot be overstated: the number of outgrowers and commercial producers grew by nearly 7% between 2015 and 2020 and over the same period, sugarcane accounted for approximately 11% of total earnings from all agricultural commodities. In addition, in the 2018/2019 growing cycle, the southern African sugar industry exported approximately 1.2 million tonnes of refined sugar and generated over \$2.15 billion in revenue. However, sugarcane requires an average of 1 800mm.annum⁻¹ of rainfall for a full canopy crop to achieve break-even yields consumes over 40% of available water resources in catchments where it is cultivated (Knox

et al., 2010a; Singels et al., 2014; Jones et al., 2015b). Sugarcane is grown in over 785 000Ha across southern Africa and in many catchments requires almost continuous irrigation which necessitates significant investments in technology, agronomic and financial resources. This is one of the main reasons sugarcane is a high-impact and high-benefit crop (Hess *et al.*, 2016).

Despite being an evidently important commodity crop, sugarcane production remains one of the most challenging agricultural activities in the region (Carr and Knox, 2011; Eksteen *et al.*, 2014). This is a result of three factors, namely, i) the hydroclimatic environment, ii) the magnitude of resources required to produce adequate yields and iii) the favourability of the sugarcane production landscape with respect to policies governing the production of the crop. As a result of a combination of increased hydroclimatic variability influenced by climatic change and global economic downturns, these factors have, in recent years, undermined the sustainability of sugarcane production in southern Africa. Coupled with significant competition for resources, sugarcane production will, for the foreseeable future, remain under severe pressure.

Climate change represents a significant threat to the sustainability of sugarcane production in southern Africa. However, there are currently no known studies that have addressed the impacts of this phenomenon on outgrowers and commercial producers in the region over sufficient temporal and spatial scales. The limiting hydroclimatic, agronomic and political conditions across this region, however, are not necessarily conducive to the large-scale production of sugarcane. Therefore, the sugar industry must adopt unique production techniques and be as adaptive as possible to allow for the successful cultivation of this crop.

The works presented by Hess et al., (2016); Knox et al., (2010); Xiong et al., (2023) have highlighted the need for regional studies that highlight the diversity of sugarcane production regimes across southern Africa. Such studies can generate useful data and knowledge based on the unique experiences of growers across the major sugar producing countries. Not only will these studies contribute towards mitigating the impacts of increasing climate variability on sugarcane, but they will also assist in sustaining communities that rely solely on this crop for their livelihoods (Cockburn et al., 2014; Manda et al., 2020; Mbabazi et al., 2023; Ndlela & Worth, 2021). It should be noted with concern that while such regional studies exist for crops such as maize and cassava for instance, the same is not true for sugarcane. This is even

further concerning considering the land and water resources required for sugarcane production.

As mentioned earlier, the effects of climate change are already being experienced across the sugarcane value chain and considering the pressure that the sugar industry is under to maintain and/or increase yields, there is a clear need to assess, understand and quantify the impacts of climate change on sugarcane production and offer realistic adaptation strategies that will buffer the sugar industry against climatic extremes in southern Africa.

1.2 Research Aim

To assess the potential impacts of climate change on sugarcane production in six catchments and six mill areas across southern Africa. Using a combination of crop modelling, yield gap analyses, frequency analyses and a water stress index, this study assesses the impact of climate change on water resources and consequently sugarcane yields. Climate change will amplify precipitation variability and thus increase the exposure and vulnerability of sugarcane to water stress which will ultimately compromise sugarcane yields. A secondary research aim was to address the vulnerability and adaptation potential of sugarcane production. Finally, this study recommends adaptation strategies that are applicable within the southern African sugarcane production industry.

1.3 Research Objectives

The specific research objectives of this study were to:

- Review the dynamics between global change and water resources across southern Africa. The purpose of this review was to frame the current understanding of the dynamics between global change and water resources and assess how they relate to local change (**Chapter Two, Paper One**).
- Conduct an assessment with the aim of understanding the multiscale drivers of sugarcane production and expansion and the impacts of this activity on water resources in southern Africa (**Chapter Three, Paper Two**).
- Assess sugarcane yield declines as a result of recent climatic extremes across the region using a yield gap analysis. The results of the yield gap analysis were used to

assess and develop recommendations that can assist in combating yield declines by offering potential safeguards for the sugarcane industry against climatic extremes (**Chapter Four, Paper Three**).

- Assess the vulnerability and adaptation potential of sugarcane production to water stress in selected mill areas located across the region using a combination of the Crop Productivity Ratio (CPR) concept, and a well-established relationship between sugarcane yields and actual sugarcane water use (**Chapter Five, Paper Four**).

1.4 Thesis Outline

Apart from Chapters One and Six and Seven, this thesis consists of self-contained chapters written as manuscripts that can be (or in some cases already are) published in academic peer-reviewed journals. This approach notwithstanding, each preceding chapter formed the basis of subsequent chapters, and all chapters share a common theme: the assessment of the impacts of climate change on sugarcane production and the recommendation of adaptation strategies that can buffer the sugar industry against climatic extremes.

[Chapter Two](#) reviews the aspects of global change critical to southern Africa and assesses their interaction with drivers of local change and the vulnerability of society to these changes. The chapter concludes with a reflection on hard i.e., technology and infrastructure, and soft i.e., governance and management, adaptation activities considered critical to southern Africa, with lessons that are relevant beyond the region.

[Chapter Three](#) applies a frequency analysis approach to ascertain the multiscale proximate and ultimate drivers of sugarcane production. This chapter expounds on proximate drivers as the immediately observable drivers which cause specific environmental changes and ultimate drivers as the underlying, higher-level socio-economic demands placed upon the environment to deliver a certain product or raw material. The chapter develops water use estimates for rainfed and irrigated sugarcane for future low, medium and high production scenarios. The chapter concludes with the observation that ultimate drivers assume a more important role in sugarcane production and that water use may be anticipated to increase in response to increased production intensity, particularly in the medium and high growth scenarios.

[Chapter Four](#) develops a methodology for assessing yield declines based on a yield gap analysis approach. The yield gap analysis indicated that yield gaps, the differences between maximum potential yields and actual observed yields, remain high across all mill areas in the study. It was concluded that yield gaps are primarily attributed to existing crop management approaches as opposed to the climatic regimes in these mill areas. Climate change, thus far, assumes a less important role compared to agronomic management in the region.

[Chapter Five](#) assesses the vulnerability and adaptation potential of sugarcane production to water stress across southern Africa. The aim of this chapter was to assess the vulnerability and adaptation potential of sugarcane production in selected mill areas across southern Africa and recommend viable and realistic adaptation strategies. These strategies would necessarily need to be applicable across the majority of the southern African sugarcane production industry. The paper concluded that adapting to a changing climate necessitates recognition and rectification of the vulnerability and enhancing the adaptation potential of the various components of the sugarcane value chain.

[Chapter Six](#) provided a synthesis of the overall research study, *i.e.* Chapters One to Five. This chapter details the key messages from the research results and outlines the main contributions to new knowledge derived from this study.

Chapter Seven outlines the main conclusions to the study.

References

- Akpoti, K., Groen, T., Dossou-Yovo, E., Kabo-bah, A. T., & Zwart, S. J. (2022). Climate change-induced reduction in agricultural land suitability of West-Africa's inland valley landscapes. *Agricultural Systems*, 200, 103429. <https://doi.org/10.1016/j.agry.2022.103429>
- Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, 13(4), 043002. <https://doi.org/10.1088/1748-9326/aaa9c6>
- Alcamo, J., Schaldach, R., Koch, J., Kolking, C., Lapola, D and Priess, J. 2011. Evaluation of an Integrated Land Use Change Model Including a Scenario Analysis of Land Use Change for Continental Africa. *Environmental Modelling and Software* 26(8):1017-1027. <https://doi.org/10.1016/j.envsoft.2011.03.002>

- Aleman, J. C., Blarquez, O., & Staver, C. A. (2016). Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Global Change Biology*, 22(9), 3013–3025. <https://doi.org/10.1111/gcb.13299>
- Atedhor, G. O. (2023). Greenhouse gases emissions and their reduction strategies: Perspectives of Africa’s largest economy. *Scientific African*, 20, e01705. <https://doi.org/10.1016/j.sciaf.2023.e01705>
- Biggs, J. S., Thorburn, P. J., Crimp, S., Masters, B., & Attard, S. J. (2013). Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region, Australia. *Agriculture, Ecosystems & Environment*, 180, 79–89. <https://doi.org/10.1016/j.agee.2011.11.005>
- Booyesen, K. C., Foxon, K. M., & Davis, S. B. (2017). The development of a screening tool to identify new products for the South African sugarcane industry. *Proceedings of the Annual Congress - South African Sugar Technologists’ Association, No.90*, 431–454. <https://www.cabdirect.org/cabdirect/abstract/20183262257>
- Braidwood, R. J. (1960). The Agricultural Revolution. *Scientific American*, 203(3), 130–152. <https://www.jstor.org/stable/24940620>
- Chandiposha M. 2013. Potential impact of climate change in sugarcane and mitigation strategies in Zimbabwe. *African Journal of Agricultural Research* 2013, 8:2814-2818.
- Christina, M., Jones, M.-R., Versini, A., Mézino, M., Le Mézo, L., Auzoux, S., Soulié, J. C., Poser, C., & Gérardaux, E. (2021). Impact of climate variability and extreme rainfall events on sugarcane yield gap in a tropical Island. *Field Crops Research*, 274, 108326. <https://doi.org/10.1016/j.fcr.2021.108326>
- Cockburn, J., Coetzee, H., Van den Berg, J., & Conlong, D. (2014). Large-scale sugarcane farmers’ knowledge and perceptions of *Eldana saccharina* Walker (Lepidoptera: Pyralidae), push–pull and integrated pest management. *Crop Protection*, 56, 1–9. <https://doi.org/10.1016/j.cropro.2013.10.014>
- Coelho, S.T., Goldemberg, J. (2019). Sustainability and Environmental Impacts of Sugarcane Biofuels. In: Khan, M., Khan, I. (eds) *Sugarcane Biofuels*. Springer, Cham. https://doi.org/10.1007/978-3-030-18597-8_18
- Conradie, B., Piessse, J., & Stephens, J. (2019). The changing environment: Efficiency, vulnerability and changes in land use in the South African Karoo, 2012–2014. *Environmental Development*, 32, 100453. <https://doi.org/10.1016/j.envdev.2019.07.003>
- Crutzen, P. J. (2006). The “Anthropocene.” In E. Ehlers & T. Krafft (Eds.), *Earth System Science in the Anthropocene* (pp. 13–18). Springer. https://doi.org/10.1007/3-540-26590-2_3
- Dai, A., Zhao, T., & Chen, J. (2018). Climate Change and Drought: A Precipitation and Evaporation Perspective. *Current Climate Change Reports*, 4(3), 301–312. <https://doi.org/10.1007/s40641-018-0101-6>
- Dal Belo Leite, J. G., Langa, F. M., von Maltitz, G., Lima Verde Leal, M. R., & Barbosa Cortez, L. A. (2020). Sugarcane outgrower schemes model: Friend or foe? A question for smallholder farmers in Mozambique. *World Development Perspectives*, 19, 100232. <https://doi.org/10.1016/j.wdp.2020.100232>
- Deressa, T, Hassan, R and Poonyth, D. 2010. Measuring the Impact of Climate Change on South African Agriculture: The Case of Sugarcane Growing Regions. *Agrekon* 4(44):524-542. <https://doi.org/10.1080/03031853.2005.9523726>
- Desalegn, B., Kebede, E., Legesse, H., & Fite, T. (2023). Sugarcane productivity and sugar yield improvement: Selecting variety, nitrogen fertilizer rate, and bioregulator as a first-line treatment. *Heliyon*, 9(4), e15520. <https://doi.org/10.1016/j.heliyon.2023.e15520>

- Dias, H. B., & Sentelhas, P. C. (2021). Assessing the performance of two gridded weather data for sugarcane crop simulations with a process-based model in Center-South Brazil. *International Journal of Biometeorology*, 65(11), 1881–1893. <https://doi.org/10.1007/s00484-021-02145-6>
- du Preez, C. C., & van Huyssteen, C. W. (2020). Threats to soil and water resources in South Africa. *Environmental Research*, 183, 109015. <https://doi.org/10.1016/j.envres.2019.109015>
- Dubb, A. (2015). Dynamics of decline in small-scale sugarcane production in South Africa: Evidence from two ‘rural’ wards in the Umfolozi region. *Land Use Policy*, 48, 362–376. <https://doi.org/10.1016/j.landusepol.2015.06.029>
- Dubb, A., Scoones, I., & Woodhouse, P. (2017). The Political Economy of Sugar in Southern Africa – Introduction. *Journal of Southern African Studies*, 43(3), 447–470. <https://doi.org/10.1080/03057070.2016.1214020>
- Dube, K., Nhamo, G., Chikodzi, D., & Chapungu, L. (2023). Mapping and evaluating the impact of flood hazards on tourism in South African national parks. *Journal of Outdoor Recreation and Tourism*, 43, 100661. <https://doi.org/10.1016/j.jort.2023.100661>
- Ekolu, J., Dieppois, B., Sidibe, M., Eden, J. M., Trambly, Y., Villarini, G., Peña-Angulo, D., Mahé, G., Paturel, J.-E., Onyutha, C., & van de Wiel, M. (2022). Long-term variability in hydrological droughts and floods in sub-Saharan Africa: New perspectives from a 65-year daily streamflow dataset. *Journal of Hydrology*, 613, 128359. <https://doi.org/10.1016/j.jhydrol.2022.128359>
- Engelbrecht, C. J., Landman, W. A., Graham, R., & McLean, P. (2017). Seasonal predictive skill of intraseasonal synoptic type variability over the Cape south coast of South Africa by making use of the Met Office Global Seasonal Forecast System 5. *International Journal of Climatology*, 37(4), 1998–2012. <https://doi.org/10.1002/joc.4830>
- Fischer, K., & Hajdu, F. (2015). Does raising maize yields lead to poverty reduction? A case study of the Massive Food Production Programme in South Africa. *Land Use Policy*, 46, 304–313. <https://doi.org/10.1016/j.landusepol.2015.03.015>
- Forsell, N., Turkovska, O., Gusti, M., Obersteiner, M., Elzen, M. den, & Havlik, P. (2016). Assessing the INDCs’ land use, land use change, and forest emission projections. *Carbon Balance and Management*, 11(1), 26. <https://doi.org/10.1186/s13021-016-0068-3>
- Gannon, K. E., Conway, D., Pardoe, J., Ndiyoi, M., Batisani, N., Odada, E., Olago, D., Opere, A., Kgosietsile, S., Nyambe, M., Omukuti, J., & Siderius, C. (2018). Business experience of floods and drought-related water and electricity supply disruption in three cities in sub-Saharan Africa during the 2015/2016 El Niño. *Global Sustainability*, 1, e14. <https://doi.org/10.1017/sus.2018.14>
- Gasparatos, A., Maltitz, G. von, Roland, N., Ahmed, A., Mudombi, S., & Jarzebski, M. P. (2021). Institutional and socioeconomic transformation from sugarcane expansion in northern Eswatini. In *Political Ecology of Industrial Crops*. Routledge.
- German, L. A., Hepinstall-Cymerman, J., Biggs, T., Parker, L., & Salinas, M. (2020). The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. *Applied Geography*, 121, 102240. <https://doi.org/10.1016/j.apgeog.2020.102240>
- Gizaw, M. S., & Gan, T. Y. (2017). Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa. *Climate Dynamics*, 49(1), 665–682. <https://doi.org/10.1007/s00382-016-3366-2>
- Hennessy, K., Lawrence, J., & Mackey, B. (2022). *IPCC Sixth Assessment Report (AR6): Climate Change 2022 - Impacts, Adaptation and Vulnerability: Regional Factsheet*

- Australasia*. https://policycommons.net/artifacts/2264302/ipcc_ar6_wgii_factsheet_australasia/3023355/
- Herrmann, R., Jumbe, C., Bruentrup, M., & Osabuohien, E. (2018). Competition between biofuel feedstock and food production: Empirical evidence from sugarcane outgrower settings in Malawi. *Biomass and Bioenergy*, *114*, 100–111. <https://doi.org/10.1016/j.biombioe.2017.09.002>
- Hess, T. M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Montegudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A., Marin, F., & Knox, J. W. (2016). A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change*, *39*, 181–194. <https://doi.org/10.1016/j.gloenvcha.2016.05.003>
- Hewitson, B., Tadross, M. and Jack, C. 2005. Climate Change Scenarios: Conceptual Foundations, Large Scale Forcing, Uncertainty and the Climate Context. In: Schulze, R.E. (Ed) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 2, 21 - 38.
- Hof, C., Voskamp, A., Biber, M. F., Böhning-Gaese, K., Engelhardt, E. K., Niamir, A., Willis, S. G., & Hickler, T. (2018). Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *Proceedings of the National Academy of Sciences*, *115*(52), 13294–13299. <https://doi.org/10.1073/pnas.1807745115>
- Hoff, H. (2011). Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.
- Houghton, J. (2005). Global warming. *Reports on Progress in Physics*, *68*(6), 1343. <https://doi.org/10.1088/0034-4885/68/6/R02>
- Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). Climate change: The IPCC scientific assessment. *American Scientist; (United States)*, *80*:6. <https://www.osti.gov/biblio/6819363>
- IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 896 pp. <https://doi.org/10.1017/9781009157988>.
- Ishtiaque, A., Estoque, R. C., Eakin, H., Parajuli, J., & Rabby, Y. W. (2022). IPCC’s current conceptualization of ‘vulnerability’ needs more clarification for climate change vulnerability assessments. *Journal of Environmental Management*, *303*, 114246. <https://doi.org/10.1016/j.jenvman.2021.114246>
- James, P., & Woodhouse, P. (2017). Crisis and Differentiation among Small-Scale Sugar Cane Growers in Nkomazi, South Africa. *Journal of Southern African Studies*, *43*(3), 535–549. <https://doi.org/10.1080/03057070.2016.1197694>
- Johnson, K. A., Smithers, J. C., & Schulze, R. E. (2021). A review of methods to account for impacts of non-stationary climate data on extreme rainfalls for design rainfall estimation in South Africa. *Journal of the South African Institution of Civil Engineering*, *63*(3), 55–61. <https://doi.org/10.17159/2309-8775/2021/v63n3a5>
- Jones, M. R., Singels, A., Chinorumba, S., Patton, A., Poser, C., Singh, M., Martiné, J. F., Christina, M., Shine, J., Annandale, J., & Hammer, G. (2019). Exploring process-level genotypic and environmental effects on sugarcane yield using an international

- experimental dataset. *Field Crops Research*, 244, 107622. <https://doi.org/10.1016/j.fcr.2019.107622>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015a). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015b). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Kalantari, Z., Ferreira, C. S. S., Keesstra, S., & Destouni, G. (2018). Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. *Current Opinion in Environmental Science & Health*, 5, 73–78. <https://doi.org/10.1016/j.coesh.2018.06.003>
- Kasambala Donga, T., & Eklo, O. M. (2018). Environmental load of pesticides used in conventional sugarcane production in Malawi. *Crop Protection*, 108, 71–77. <https://doi.org/10.1016/j.cropro.2018.02.012>
- Kaufmann, R. K., Kauppi, H., Mann, M. L., & Stock, J. H. (2011). Reconciling anthropogenic climate change with observed temperature 1998–2008. *Proceedings of the National Academy of Sciences*, 108(29), 11790–11793. <https://doi.org/10.1073/pnas.1102467108>
- Kerridge, E. (2013). *The Agricultural Revolution*. Routledge.
- Knapp, A. K., Ciais, P., & Smith, M. D. (2017). Reconciling inconsistencies in precipitation–productivity relationships: Implications for climate change. *New Phytologist*, 214(1), 41–47. <https://doi.org/10.1111/nph.14381>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, 103(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Lewis, CA. 1990. The South African Sugar Industry. *The Geographical Journal*, Vol. 156, No. 1 (Mar., 1990), pp. 70–78 (9 pages). <https://doi.org/10.2307/635438>
- Lottering, S., Mafongoya, P., & Lottering, R. (2021). Drought and its impacts on small-scale farmers in sub-Saharan Africa: A review. *South African Geographical Journal*, 103(3), 319–341. <https://doi.org/10.1080/03736245.2020.1795914>
- Manda, S., Tallontire, A., & Dougill, A. J. (2020). Outgrower schemes and sugar value-chains in Zambia: Rethinking determinants of rural inclusion and exclusion. *World Development*, 129, 104877. <https://doi.org/10.1016/j.worlddev.2020.104877>
- Mararakanye, N., Le Roux, J. J., & Franke, A. C. (2022). Long-term water quality assessments under changing land use in a large semi-arid catchment in South Africa. *Science of The Total Environment*, 818, 151670. <https://doi.org/10.1016/j.scitotenv.2021.151670>
- Mbabazi, K. R., Oyet, S. M., Muggaga, C., & Okello-Uma, I. (2023). The influence of sugarcane growing by smallholder farmers on household livelihood, food security, and nutrition status of children below five years in mid-western Uganda. *Journal of Agriculture and Food Research*, 100895. <https://doi.org/10.1016/j.jafr.2023.100895>
- McKay, B., Sauer, S., Richardson, B., & Herre, R. (2016). The political economy of sugarcane flexing: Initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies*, 43(1), 195–223. <https://doi.org/10.1080/03066150.2014.992016>
- Meque, A., Pinto, I., Maúre, G., & Beleza, A. (2022). Understanding the variability of heatwave characteristics in southern Africa. *Weather and Climate Extremes*, 38, 100498. <https://doi.org/10.1016/j.wace.2022.100498>
- Meyer, J., & Antwerpen, R. (2021). Soil Degradation As A Factor In Yield Decline In The South African Sugar Industry.

- Meyfroidt, P., Lambin, E. F., Erb, K.-H., & Hertel, T. W. (2013). Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability*, 5(5), 438–444. <https://doi.org/10.1016/j.cosust.2013.04.003>
- Muller, S. J., Sithole, P., Singels, A., & Van Niekerk, A. (2020). Assessing the fidelity of Landsat-based fAPAR models in two diverse sugarcane growing regions. *Computers and Electronics in Agriculture*, 170, 105248. <https://doi.org/10.1016/j.compag.2020.105248>
- Musakwa, W., & Niekerk, A. V. (2013). Implications of land use change for the sustainability of urban areas: A case study of Stellenbosch, South Africa. *Cities*, 32, 143–156. <https://doi.org/10.1016/j.cities.2013.01.004>
- Narimoto, L. R., & Camarotto, J. A. (2018). Technology transfer and Anthropotechnology: An analysis of the sugarcane harvesting in Australia and Brazil. *African Journal of Agricultural Research*, 13(31), 1564–1576. <https://doi.org/10.5897/AJAR2017.12165>
- Nchanji, E. B., & Lutomia, C. K. (2021). COVID-19 challenges to sustainable food production and consumption: Future lessons for food systems in eastern and southern Africa from a gender lens. *Sustainable Production and Consumption*, 27, 2208–2220. <https://doi.org/10.1016/j.spc.2021.05.016>
- Ncoyini, Z., Savage, M. J., & Strydom, S. (2022). Limited access and use of climate information by small-scale sugarcane farmers in South Africa: A case study. *Climate Services*, 26, 100285. <https://doi.org/10.1016/j.cliser.2022.100285>
- Ndlela, S., & Worth, S. (2021). Creating self-reliance and sustainable livelihoods amongst small-scale sugarcane farmers. *The Journal of Agricultural Education and Extension*, 27(3), 325–339. <https://doi.org/10.1080/1389224X.2020.1851268>
- Ngcobo, S., Jewitt, G., Stuart-Hill, S., & Warburton, M. (2013). Impacts of global change on southern African water resources systems. *Current Opinion in Environmental Sustainability*, 5(6), 655–666. <https://doi.org/10.1016/j.cosust.2013.10.002>
- Odebiri, O., Mutanga, O., Odindi, J., Naicker, R., Slotow, R., & Mngadi, M. (2023). Evaluation of projected soil organic carbon stocks under future climate and land cover changes in South Africa using a deep learning approach. *Journal of Environmental Management*, 330, 117127. <https://doi.org/10.1016/j.jenvman.2022.117127>
- O’Gorman, P. A. (2015). Precipitation Extremes Under Climate Change. *Current Climate Change Reports*, 1(2), 49–59. <https://doi.org/10.1007/s40641-015-0009-3>
- Omotoso, A. B., Letsoalo, S., Olagunju, K. O., Tshwene, C. S., & Omotayo, A. O. (2023). Climate change and variability in sub-Saharan Africa: A systematic review of trends and impacts on agriculture. *Journal of Cleaner Production*, 414, 137487. <https://doi.org/10.1016/j.jclepro.2023.137487>
- Parnell, S and Walawege, R. 2011. Sub-Saharan African Urbanisation and Global Environmental Change. *Global Environmental Change 21S: S12-S20*.
- Ramlall, R., & Smithers, J. C. (2023). Assessing the performance of techniques for disaggregating daily rainfall in South Africa. *Water SA*, 49(3), Article 3. <https://www.ajol.info/index.php/wsa/article/view/252765>
- Ruddiman, W. F. (2013). The Anthropocene. *Annual Review of Earth and Planetary Sciences*, 41(1), 45–68. <https://doi.org/10.1146/annurev-earth-050212-123944>
- Schulze, R. E. (2000). Modelling Hydrological Responses to Land Use and Climate Change: A Southern African Perspective. *Ambio*, 29(1), 12–22. <https://www.jstor.org/stable/4314988>

- Silalertruksa, T., & Gheewala, S. (2020). Competitive use of sugarcane for food, fuel, and biochemical through the environmental and economic factors. *The International Journal of Life Cycle Assessment*, 25. <https://doi.org/10.1007/s11367-019-01664-0>
- Singels, A., Jones, M., Marin, F., Ruane, A., & Thorburn, P. (2014). Predicting Climate Change Impacts on Sugarcane Production at Sites in Australia, Brazil and South Africa Using the Canegro Model. *Sugar Tech*, 16(4), 347–355. <https://doi.org/10.1007/s12355-013-0274-1>
- Singels, A., Paraskevopoulos, A. L., & Mashabela, M. L. (2019). Farm level decision support for sugarcane irrigation management during drought. *Agricultural Water Management*, 222, 274–285. <https://doi.org/10.1016/j.agwat.2019.05.048>
- Smithers, J. C., Rowe, T. J., Horan, M. J. C., & Schulze, R. E. (2018). Development and assessment of rules to parameterise the ACRU model for design flood estimation. *Water SA*, 44(1), Article 1. <https://doi.org/10.4314/wsa.v44i1.11>
- Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. (2011). The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1938), 842–867. <https://doi.org/10.1098/rsta.2010.0327>
- Sulle, E. (2017). Social Differentiation and the Politics of Land: Sugar Cane Outgrowing in Kilombero, Tanzania. *Journal of Southern African Studies*, 43(3), 517–533. <https://doi.org/10.1080/03057070.2016.1215171>
- Theron, S. N., Archer, E. R. M., Midgley, S. J. E., & Walker, S. (2022). Exploring farmers' perceptions and lessons learned from the 2015–2018 drought in the Western Cape, South Africa. *Journal of Rural Studies*, 95, 208–222. <https://doi.org/10.1016/j.jrurstud.2022.09.002>
- Tongwane, M. I., & Moeletsi, M. E. (2018). A review of greenhouse gas emissions from the agriculture sector in Africa. *Agricultural Systems*, 166, 124–134. <https://doi.org/10.1016/j.agsy.2018.08.011>
- Tongwane, M., Mdlambuzi, T., Moeletsi, M., Tsubo, M., Mliswa, V., & Grootboom, L. (2016). Greenhouse gas emissions from different crop production and management practices in South Africa. *Environmental Development*, 19, 23–35. <https://doi.org/10.1016/j.envdev.2016.06.004>
- Turton, A. 2008. The State of Water Resources in Southern Africa: What the Beverage Industry Needs to Know. CSIR Version 2 for General Circulation: 1-8.
- Vincent, K. 2011. Coastal Risk in Dar es Salaam. In: Davis, CL (Ed.). 2011. *Climate Risk and Vulnerability: A Handbook for Southern Africa*. Council for Scientific and Industrial Research, Pretoria, South Africa.
- Veldkamp, A., & Lambin, E. F. (2001). Predicting land-use change. *Agriculture, Ecosystems & Environment*, 85(1), 1–6. [https://doi.org/10.1016/S0167-8809\(01\)00199-2](https://doi.org/10.1016/S0167-8809(01)00199-2)
- Verma, A. K., Garg, P. K., Prasad, K. S. H., & Dadhwal, V. K. (2023). Variety-specific sugarcane yield simulations and climate change impacts on sugarcane yield using DSSAT-CSM-CANEGRO model. *Agricultural Water Management*, 275, 108034. <https://doi.org/10.1016/j.agwat.2022.108034>
- von Maltitz, G. P., Henley, G., Ogg, M., Samboko, P. C., Gasparatos, A., Read, M., Engelbrecht, F., & Ahmed, A. (2019). Institutional arrangements of outgrower sugarcane production in Southern Africa. *Development Southern Africa*, 36(2), 175–197. <https://doi.org/10.1080/0376835X.2018.1527215>
- Warburton Toucher, M., Schulze, R., & Jewitt, G. (2010). Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences*, 7. <https://doi.org/10.5194/hess-14-2399-2010>
- Ward, P. J., de Ruiter, M. C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., von Uexkull, N., Wanders, N., AghaKouchak, A., Arnbjerg-Nielsen, K., Capewell, L.,

- Carmen Llasat, M., Day, R., Dewals, B., Di Baldassarre, G., Huning, L. S., Kreibich, H., Mazzoleni, M., Savelli, E., ... Wens, M. (2020). The need to integrate flood and drought disaster risk reduction strategies. *Water Security*, 11, 100070. <https://doi.org/10.1016/j.wasec.2020.100070>
- Wendimu, M. A., Henningsen, A., & Gibbon, P. (2016). Sugarcane Outgrowers in Ethiopia: “Forced” to Remain Poor? *World Development*, 83, 84–97. <https://doi.org/10.1016/j.worlddev.2016.03.002>
- Xiong, M., Zhao, R., Li, X., Wang, Y., Xu, Z., & Li, F. (2023). Climate resilience assessment of sustainability at national level: A case study of sub-Saharan Africa. *Journal of Cleaner Production*, 430, 139717. <https://doi.org/10.1016/j.jclepro.2023.139717>
- Yang, L., Zhou, Y., Meng, B., Li, H., Zhan, J., Xiong, H., Zhao, H., Cong, W., Wang, X., Zhang, W., Lakshmanan, P., Deng, Y., Shi, X., Chen, X., & Zhang, F. (2022). Reconciling productivity, profitability and sustainability of small-holder sugarcane farms: A combined life cycle and data envelopment analysis. *Agricultural Systems*, 199, 103392. <https://doi.org/10.1016/j.agsy.2022.103392>
- Zhou, M. (2013). Conventional Sugarcane Breeding in South Africa: Progress and Future Prospects. 2013. <https://doi.org/10.4236/ajps.2013.42025>
- Zinyengere, N., Crespo, O., & Hachigonta, S. (2013). Crop response to climate change in southern Africa: A comprehensive review. *Global and Planetary Change*, 111, 118–126. <https://doi.org/10.1016/j.gloplacha.2013.08.010>
- Zulu, N. S., Sibanda, M., & Tlali, B. S. (2019). Factors Affecting Sugarcane Production by Small-Scale Growers in Ndwedwe Local Municipality, South Africa. *Agriculture*, 9(8), 170. <https://doi.org/10.3390/agriculture9080170>

CHAPTER TWO
IMPACTS OF GLOBAL CHANGE ON SOUTHERN AFRICAN WATER
RESOURCE SYSTEMS*

Ngcobo, S.¹, Jewitt, G.P.W.¹, Stuart-Hill, S.¹ and Warburton, M¹.

¹*Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa*

Abstract

Southern Africa is considered to be highly vulnerable to the effects of global change. There is increasing evidence of negative demographic and environmental changes influenced by anthropogenically driven local changes in this region and these changes result in vulnerability exacerbated by the overarching effects of climate change. These are exemplified by the potential impacts on water resources and the opportunities, approaches and technologies developed in the region to consider these impacts. Thus, the aim of this paper is to review aspects of global change most critical to southern Africa and assess their interaction with drivers of local change and the vulnerability of society to these changes. Although local changes are influenced by global drivers such as climate change, land-use change and socio-economic development; these changes are not always direct consequences of global drivers, and they are rarely instigated by a single global change driver. This review shows that although global drivers are intricately related, their water resources impacts are highly complex, indirectly coupled and are spatially and temporally sensitive. It is concluded that the development of technologies, management approaches and policies, which can be applied in an integrated and adaptive management framework, are an imperative to the development of the region.

Keywords: Global Change, Southern Africa, Water Resources, Climate Change, Population Growth, Economic Development, Impacts, Responses, Vulnerability.

* Referencing adheres to the format of *Current Opinions in Environmental Sustainability*.

2.1 Introduction

Changes to myriad demographic, economic and environmental systems inspired by human activities over the past century have been rapid and pervasive enough that it has been suggested that a new geologic era termed the *Anthropocene* has already begun [1, 2, 3, 4]. These changes are expressed through the unifying phenomenon of global change. Global change can be considered as the complete suite of anthropic-related changes to the biosphere directly or indirectly initiated, promoted and sustained for the benefit of humanity by humanity. Included under the banner of global change are well-recognized subject matters such as climate change [5, 6], population growth [7, 8**], economic development [9, 10], urban sprawl and land use change [11,12,13,14], all of which are relevant in the rapidly developing southern Africa region.

The world's population has more than tripled since the 1930s to over 6 000 million [15, 16], urbanization has also grown nearly tenfold since the 1950s. To accommodate urban-specific population growth [3], pastures and croplands now account for almost 40% of the planet's total land cover [12], and the projected impacts of climate change on natural and anthropogenic systems are beginning to manifest in palpable and sobering ways [5]. As the term implies, issues of global change are considered on a global scale. However, there is a complex relationship between change which results from global drivers and the way in which these drivers manifest at continental, regional, country and local scale, the way in which change which may result from local drivers has specific local impacts [17*,18], but feeds back to these broader scales when their extent grows (**Figure 2.1**). The complexity of these relationships is a function of the inherent socio-economic and environmental dynamics unique to a particular location or, in this instance, region. The challenge of sustainable water supply provides clear examples of this.

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) and the river basins they share (**Figure 2.2**) form the basis of this paper. The effects of global change in this region are often expressed through highly localised impacts [17, 18, 19**]. For instance, rates of urbanization coupled with normal urban-specific population growth are high owing to mass migration from rural to urban regions,

economic development often takes precedence over environmental protection [20], and the impacts of climate change on water resources and other economically strategic natural and agricultural resources are becoming pervasive [21••, 22]. These changes, in conjunction with weak governance structures [23••], political instability and low institutional capacities characteristic of many countries in this region, highlight the risk of widespread environmental degradation and the destruction of many resources which sustain human well-being [23••]. The high vulnerability of this region to some of the factors of global change, such as climate change [5], land use change often termed ‘land grabbing’ and population growth [8••] coupled with shifts in economic practice driven by unexpected drivers such as the high proportion of the population with HIV/AIDS [23, 24], serve to accelerate environmental degradation and risks to water supply. To counter this, the direct implementation of innovative technologies, policies and management strategies designed to mitigate the harmful effects of anthropogenically induced global and local change is imperative. Thus, the aim of this paper is to review the aspects of global change most critical to this region and assess how they relate to local change. The review and examples presented herein reflect a diverse set of vulnerabilities at different levels, viz. national, regional and local and is approached by considering global change as a catalyst and a trigger of local environmental and socio-economic pressures. Further, the way in which these have been studied, the responses developed, and approaches followed, provide lessons that are relevant for all water resources practitioners. Hence, the paper concludes with a reflection on hard, i.e., technology and infrastructure, and soft, i.e., governance and management, adaptation activities considered critical to southern Africa, but with lessons that are relevant beyond the region.

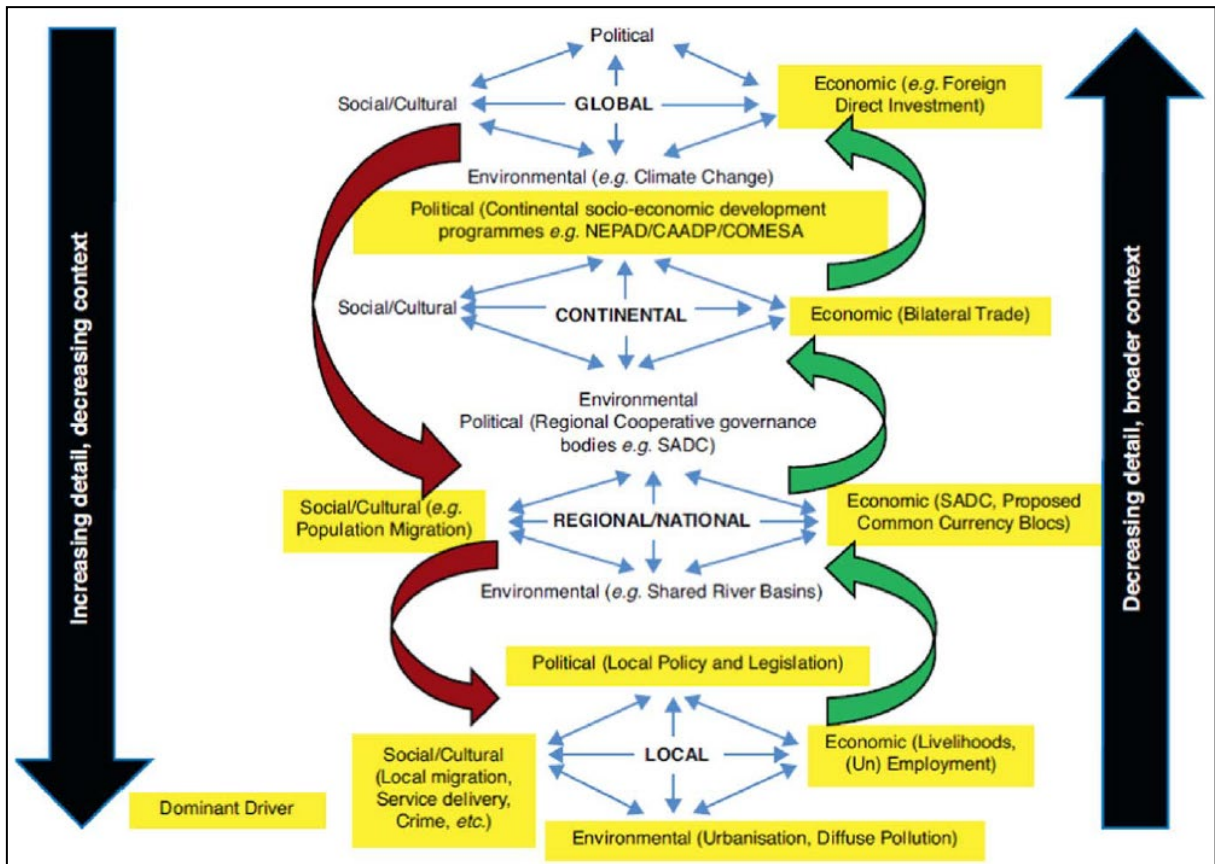


Figure 2.1 Diagram building from the ‘kite’ concept [88] indicating the various drivers of change unique to southern Africa across different spatial scales, but also illustrating the panarchy of changes ranging from rapid, small changes (‘revolt’) at local scales to large and slow changes (‘remember’) at larger scales. Rapid, small changes (revolt) can overwhelm larger and slower changes in the region (e.g. socio-political unrest related to poor public service delivery). The ‘remember’ progression of change represents the dissemination of wisdom accumulated from episodes of revolt to prevent further collapse of systems and, ideally, this wisdom cascades progressively from large to small scales.

2.2 Vulnerability to Global Change

Global change is a complex phenomenon with profound implications resulting in equally complex local effects and for a variety of reasons, southern Africa is considered to be particularly vulnerable. Across the region, rainfall is highly variable with high daily, monthly

and annual coefficients of variation with intra-annual anomalies common [25]. As a consequence, the flow in the rivers is highly variable. Together with Australia, Sub-Saharan Africa has the world's lowest rainfall: runoff ratio and an extremely low reliability of yield. Changes in the nature of rainfall and changes which affect the partitioning of runoff are likely to have exaggerated effects on human wellbeing. This has led some to suggest that the countries in this region are "hostage to their hydrology" [26], a perspective which highlights the strong link between economic performance and development and rainfall and runoff regimes. In this region, the concept of the average condition, often presented as mean annual information estimated at a broad spatial scale, is not useful. Instead, this information should be presented on a daily, or at the very least, seasonal scale to highlight the high hydroclimatic variability characteristic of this region. As expanded on below, a more local context is required. In the regions, water resource planning is often focussed on floods and droughts. Storage of water is major part of (**Figure 2.2**) and increasingly seen as an important component of the suite of measures being developed to counter the effects of climate change [27].

The rapid population increases observed over the past century coupled with increasing economic development and the successful exploitation of natural resources have resulted in unpredictable changes in the state of the biosphere [15, 28]. Land, soil and water resources and the production of goods and services such as of food, fibre, fodder and more recently fuel (i.e. bioenergy) are closely linked. In this developing region, society is largely dependent upon the land for its survival, but that land is also subject to pressure due to a growing demand, from local populations moving and expanding, through trade of agricultural produce within a country and across the region and globally from foreign investors. A significant proportion of the world's food insecure and impoverished people live in Africa. Southern Africa is subject to the socio-economic effects of global change. In fact, the most rapid responses of economic development and population growth occur primarily in low-income countries, of which there are many in this region [10, 29, 30, 31, 32]. These changes usually proceed with little resistance and this elevates the susceptibility of natural resources to depletion and degradation [19, 33].

The value of land to food security and economic development in the region is recognised through the Comprehensive Africa Agriculture Development Programme (CAADP)

(<http://www.nepad-caadp.net>) which aims to coordinate agricultural growth, food security, and rural development in Africa with the goal of attaining an average annual growth rate of 6 percent per annum in agriculture. Currently, the region can be described as being in rapid transition from subsistence livelihoods with a corresponding transition to intensive agriculture and associated land use change including urbanisation. It is estimated that some 1 125 000Ha of this land is now owned by foreign investors [‘The New Scramble for Africa’] and within the region, agricultural development is often in response to global, not local markets. A well-known example of this is the large-scale development of irrigation areas used to grow flowers for export in the Lake Navaisha region of Kenya [33]. Indeed, the rate and extent of change is unprecedented and is likely to be exacerbated by the effects of climate change. The rapid growth of urban centres in southern Africa results in the deterioration of water quality in numerous catchments owing to the increased generation of pollution [33, 34]. This introduces additional strain on already pressured supply and reticulation systems [6, 35], and downstream water quality, and can potentially affect economic production in the region, and ultimately economic growth, food security and socio-political stability [36, 37].

These examples illustrate that although the effects of global change on local systems are fairly well recognised [3, 37, 38, 39], these effects are by no means linearly correlated [40••], that they are not limited to a single global change driver, and that uncertainty and lack of understanding of the complexity of these interactions increases the vulnerability of society [41]. Consequently, the most adverse climate change related impacts are anticipated to occur in the developing regions of the world, of which Southern Africa is a part [5]. Although sufficient evidence exists for generally increasing trends with respect to drivers of change at the global level [3, 8], it remains imperative to identify and understand sources of local pressures derived from the suite of these change drivers. In other words, the quantification and understanding of impacts and reasonable responses at local scales needs to be based on a sound investigation of local pressures elicited by these drivers.

Depending on the policies and management strategies in place, different countries in the region may be expected to manage the impacts of global change on local systems differently. Given the natural environment, the foci of these is generally on flood and drought and the consequences thereof. South Africa, for instance, has in place intensive monitoring

programmes applying principles from the National Water Resource Quality Monitoring Programme, Integrated Water Resources Management (IWRM) principles, the internationally acclaimed National Water Act (Act. No. 36) of 1998 and advanced water resources modelling tools [43, 44]. Similarly, Namibia employs the Water Policy of 2000 and the National Drought Policy to manage and protect the water resources of the country [45]. Other nations in the SADC region have in place similar laws and policies, all of which are designed to explicitly uphold the integrity and highlight the paramount importance of water in this semi-arid region. These integrated management approaches are underpinned by a participatory philosophy, building on a wide recognition that this is a prerequisite to ensure sustainable development [23].

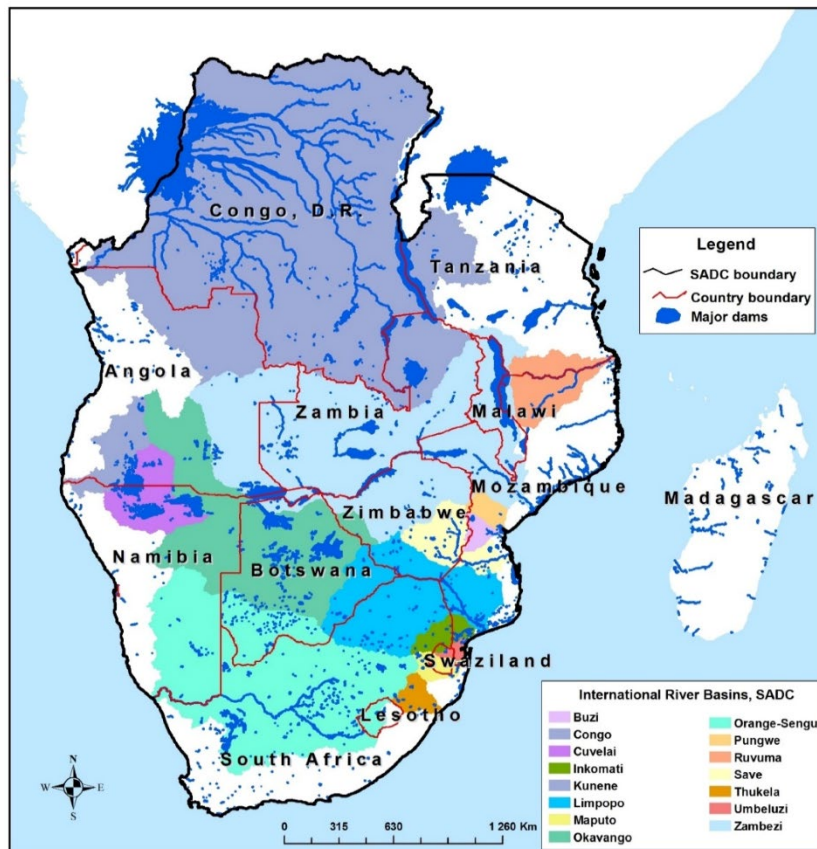


Figure 2.2 Map indicating the contiguous nations of southern Africa, shared river basins and major reservoirs [42].

2.3 Aspects of Global Change

2.3.1 Climate Change

Climate change projections, generated from various General Circulation Models (GCMs) present persuasive evidence that climatic regimes and hydrological systems of southern Africa are going to change despite mitigation actions [5, 21, 39, 46, 47[•]] (**Figure 2.3**). Coupled with human-induced changes to the biosphere, climate change is anticipated to induce additional and overarching pressures on the local environmental and socio-economic aspects such as ecological health and integrity, food and water security, human well-being, economic and political stability, and socio-economic development [30, 39, 48]. It is acknowledged that the impacts of climate change will result in changes in the state of local water resource systems [5, 21, 30, 39, 49], which will have far-reaching impacts on water-centric production systems such as agriculture, forestry and mining.

Precipitation trends under climate change scenarios indicate that increases in mean annual precipitation, increases in raindays and increases in rainfall event intensities may be expected for eastern and central parts of the region while the opposite is anticipated for south-western parts [50]. In South Africa, extensive climate change studies have been conducted in which the projected impacts of climate change on the water resources of the country were assessed through climate scenario development and impact modelling [21]. Runoff and, consequently, streamflow responses to the projected changes in precipitation instigated by climate change were projected to increase between two to three times relative to current trends [21] and this ‘amplification’ was attributed primarily to climate change [21, 40, 50]. A high dependence on climate-sensitive economic sectors, geographic exposure and low-income status characteristic of this region [48], mean that the region is particularly vulnerable to such projected changes, particularly through its water resources [21, 46, 51, 52, 53, 54[•]]. The design and implementation of locally specific adaptation strategies is, therefore, important in order to protect the viability of local production systems which sustain human well-being in this region.

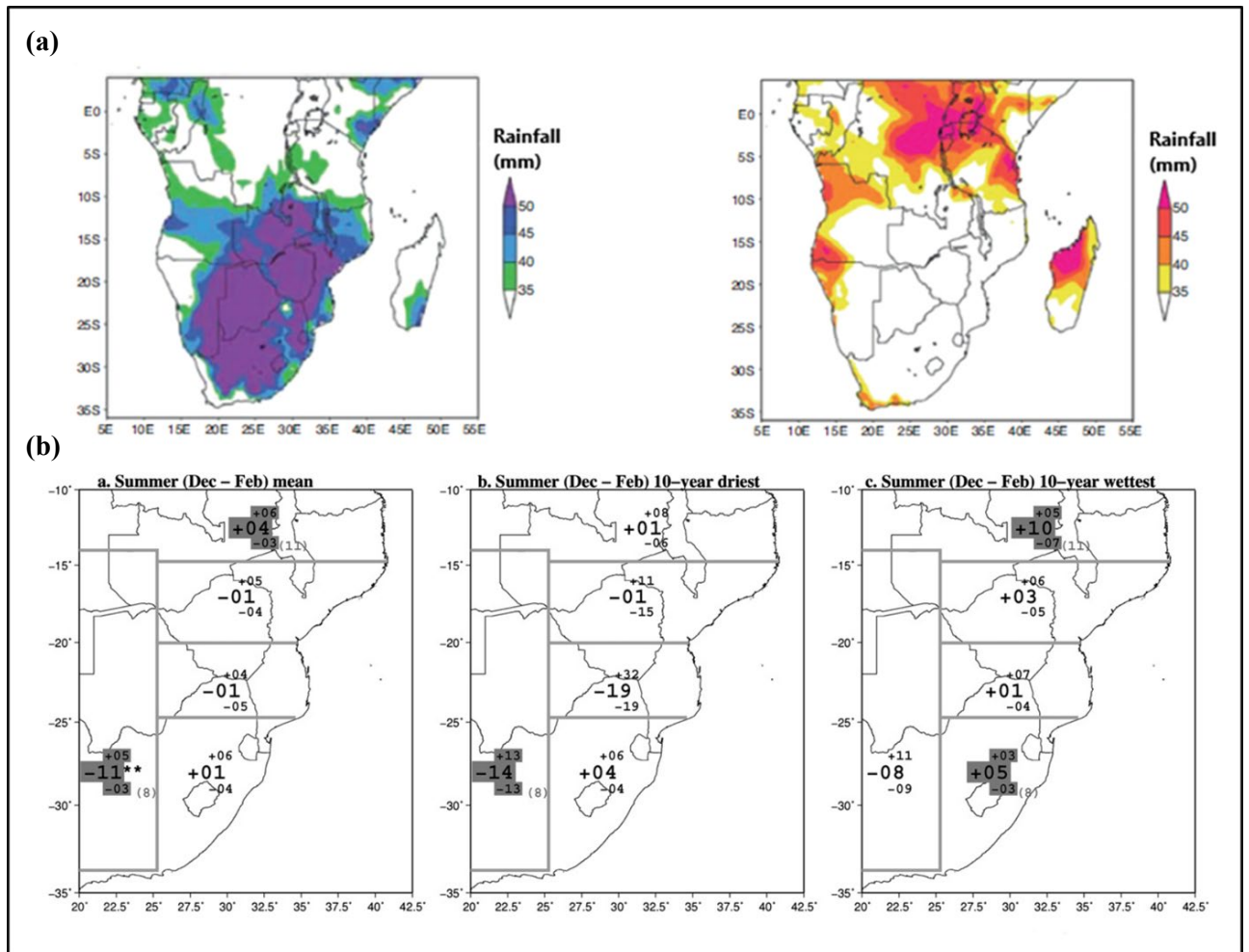


Figure 2.3 (a) Multi-model probabilistic forecasting for the likelihood of February-March-April 2011 rainfall totals exceeding the 85th percentile (extremely wet, left panel) and 15th percentile (extremely dry, right panel) percentiles of the climatological record [55, used with permission] and (b) projected changes (%) in austral summer (Dec-Feb) mean daily precipitation rates in each of the 5 climatic zones of Southern Africa generated from multi-model ensembles [47^o, used with permission].

2.3.2 Land Use Change

Land-use change is one of the key drivers of change in southern Africa. The rapid economic expansion and population growth seen over the past few years in this region [16] has resulted in the extensive alteration of land to supply economic trade-commodities (e.g. primary minerals, industrial machinery and equipment, iron ore and steel and high value agricultural

crops) and accommodate this socio-economic expansion. Development and a change of land-use in the region are inevitable and will probably carry on in the near to far future [3, 56]. However, this usually leads to the degradation of natural ecosystems which are necessary in providing important ecosystem goods and services [12, 20]. Water resources related impacts, including the role of soil and the associated benefits and losses associated with the carbon, nitrogen and phosphate cycles are foci of ongoing research, both in terms of the monitoring of its extent and quantification of its impacts, for example using remote sensing estimates of total evaporation from natural and altered land uses [40^{••}, 57^{••}] and an understanding of the *in situ* impacts thereof [58^{••}, 59^{••}, 60^{••}].

Sustaining these goods and services requires the implementation of policies and management tools that draw on appropriate levels of understanding to guide such development [61^{••}]. It has already been mentioned that the vast majority of nations in this region are heavily dependent on their natural resources as a source of economic growth and human well-being. It follows, therefore, that the rate of growth of these resource-based economies may be considered to be inversely correlated to the sustainability and long-term integrity of natural ecosystems in this region. In effect, short-term economic growth and production associated with land-use change are traded for long-term environmental degradation and loss of ecosystem goods and services [12, 62^{••}], particularly where governance systems are weak as evidenced by the endemic inadequate implementation of environmental protection laws [63^{••}, 64].

The current and projected rate of urbanization and population growth for this region implies that increased land-use change may be anticipated and, thus, increased potential for the degradation of natural ecosystems may be expected [65]. Increasing food production using both dryland and irrigated systems, securing water resources by constructing impoundments, infrastructural developments for shelter, transport and industry, establishing biodiversity conservancies and afforestation all require considerable land-use change and since southern Africa is projected to experience rapid economic and population growth, substantial land-use change may be anticipated for this region. Indeed, Grafton et al., [66], in a study of four river basins throughout the world, including the Orange River shared basin between South Africa, Zimbabwe, Botswana and Namibia, concluded that the hydrological effects of water resources developments far exceed the projected impacts of climate change.

Responses to such pressures include careful monitoring and allocation of water use licenses, the National Water Resource Quality Monitoring Programme, the Ecological Reserve and the Streamflow Reduction Activity decision-support framework and the innovative ‘Working for Water’ programme where the clearing of water-use intensive invasive alien plants is undertaken as a job creation programme [67•].

The Environmental Kuznets Curve theory [68•] (**Figure 2.4**) offers a more positive outlook on the long-term effects of land-use change for developing countries and emerging economies. According to this theory, the initial stages of economic growth are usually associated with increased environmental degradation and pollution; however, beyond a certain level of income per capita this trend starts to reverse and at high income levels, environmental protection increases and the state of natural resources improves [9, 12, 68•], provided system thresholds are not exceeded [69]. Based on this theory, the currently observed and projected trends in economic expansion in southern Africa will lead to land-use change and environmental degradation. This condition may reverse with an increase in education, per capita economic growth and individual and institutional environmental awareness. It has been argued (Ausebel et al., [70•]) that ongoing improvement in the production of crops will allow future populations to be sustained by less as opposed to more agricultural land, allowing for increasing areas to be restored or set aside for conservation purposes. Whilst there is clear evidence of opportunities for improved yields from the bulk of southern Africa’s cropping systems [71••], the limitations faced in this region, arguably not adequately considered in the treatise of Ausebel et al., [70•] are water availability coupled with soil nutrient and fertiliser availability, which raises some risks with respect to the expected trajectories of the Environmental Kuznets Curve (**Figure 2.4**). Ongoing efforts to improve agricultural production are aligned with this and include detailed spatial and temporal monitoring of crop water use and biomass production using remote sensing technologies ([72••] www.fruitlook.co.za), improved crop breeding [73, 74••] and improved agricultural water management practices [59••, 71••]. Regardless of whether or not a healthy level of environmental awareness is attained in southern Africa, it is critical that land-use change be detailed, and its effects managed judiciously.

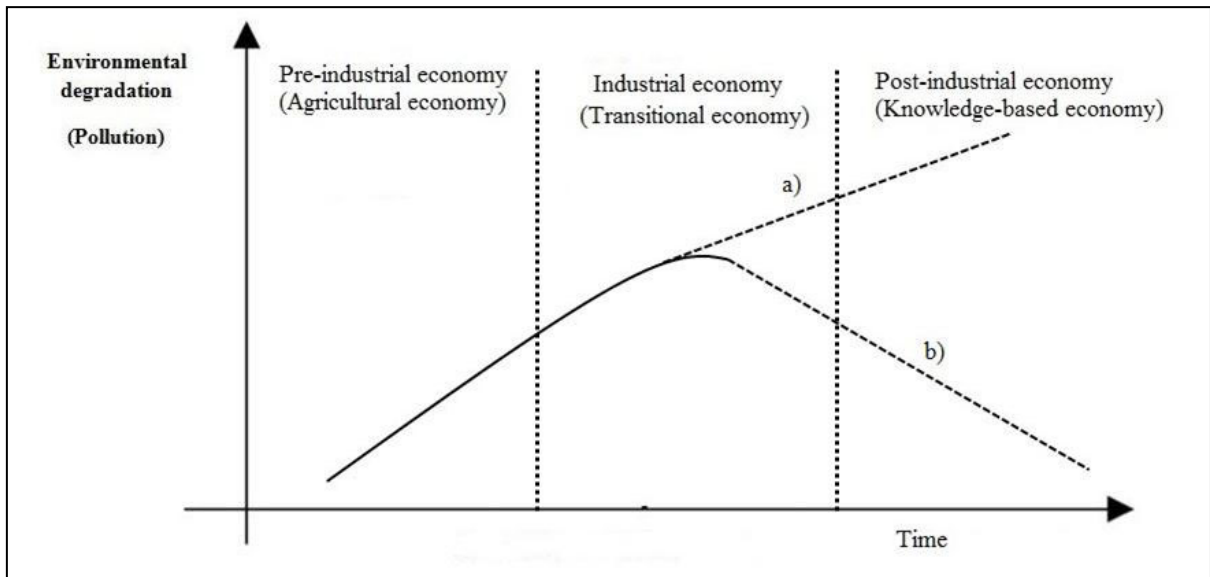


Figure 2.4 Modified Environmental Kuznets Curve showing two possible environmental degradation trajectories (a, b) across various stages of economic development for South Africa: **a)** under the current limited implementation of environmental protection policies designed to limit environmental degradation; **b)** effective implementation of environmental protection policies (e.g. NWA and NWRS) and availability of capacity to facilitate implementation [67, reproduced with permission].

2.3.3 Population Growth and Economic Development

One of the fundamental and perhaps defining aspects of development in southern Africa is the current and projected rapid rate of population growth, improving lifestyles and economic growth in this region. Although population growth is projected to slow by 2030 [8^{••}], it remains a key factor in the rapid utilisation of natural resources [75, 76] which are important in sustaining human well-being [77[•]]. This presents significant implications for the integrity of these economy-sustaining resources as highlighted through the current focus on a nexus of food-water-energy [75, 86]. Arguably, the dominant issue in southern Africa is not necessarily one of population growth but associated population movement, or migration. There is a noticeable transition in southern Africa from being a predominantly rural region to one with burgeoning urban centres which attract a significant portion of rural citizens [8^{••}, 78]. This is not surprising considering the current economic growth of numerous countries in this region. This growth acts as a precursor and continues in parallel to the expansion of

urban centres which are generally associated with economic prosperity. One consequence of this is the change in the landscape of the region owing to the physical expansion of cities and the migration of people to them [8••]. The rate of urbanization, assumed to be coupled with economic growth, is projected to increase [32]. A key aspect highlighted by rapid urban growth is that of the provision of water and sanitation to rapidly urbanising areas and the associated individual and environmental health risks. This phenomenon is expected to increase the exposure of people to the potential proliferation of water-borne and water-based diseases worsened by poor urban management and substandard sanitation and reticulation.

Thus, population and economic growth in this region are not necessarily coupled. Rather, urban specific population growth driven by the increasingly attractive economic opportunities drives the exploitation of natural resources in this region. For example, growth of cities such as Maputo and Dar-Es-Salaam leads to increasing demands for fuel wood and charcoal and results in the deforestation of the surrounding areas. Similar to land-use change, this is a condition which cannot be avoided. With such rapid growth, uneven and inequitable access to resources, including finances is inevitable. Poverty is thus a major concern in much of the population and its concomitant effects of increasing water and food insecurity, particularly when associated migration leads to break-down of social relationships and so decreasing capacity to adapt to change. Governments, some of them relatively newly formed, are struggling with these aspects whilst simultaneously developing capacity across various governance levels to address them.

2.4 Discussion and Conclusions

Southern Africa is considered to have commenced progressive development relatively late compared to other global regions such as the Caribbean, Latin America, Eastern Europe and Oceania [10, 32]. The intricate and close relationships between global drivers as indicated by Vincent [71] show that this region with its highly variable climate and uneven distribution of resources, and perhaps as a consequence of this development lag [8••], is hypersensitive to the effects of global change. This hypersensitivity, or vulnerability, is projected to increase as the impacts of global change drivers, particularly climate and land-use change, begin to directly impact natural ecosystems [79]. These effects are anticipated to be manifested on a localised scale with direct impacts on the functioning and behaviour of socio-economics and

demographics (**Figure 2.1**). For instance, it was highlighted in this review that climate change is anticipated to not only have an impact on the behaviour of natural resources, most notably water [79, 81[•]], but also on the long-term demographics of this region. These lessons can serve as guides to allow the suggestion and development of resource management strategies to cope with or even avert local change-driven pressures and consequential impacts.

It has been argued [8^{••}, 81[•]] that as southern Africa develops, the rates of natural resource cultivation, processing and consumption will increase (**Figure 2.4**) leading to the irreversible erosion of economy-sustaining resources. As this is an unsustainable approach, it would be more prudent to adopt more balanced and forward-thinking strategies such as knowledge-based and indexed economies wherein the focus is on investing in natural resource and environmental protection and frugal resource extraction coupled with innovation in both technology and policy development and implementation. This is critical considering the increasingly unpredictable changes to the biosphere which would necessarily threaten the integrity of natural resources and the provisioning of ecosystem goods and services upon which human well-being relies [61^{••}]. The unpredictability of change is further complicated by the overarching effects of climate change. This particular global change driver has been shown [*e.g.* 5, 46, 39, 32] to proceed at an unprecedented rate and so introduce added complexity to the already complex global and local change discussion. Although the Environmental Kuznets Curve theory suggests that, in the long-term, southern Africa has the potential to withstand the effects of global change as the region continues to develop economically, the actual transformation process driven by global change is harmful to socio-economic and demographic systems and the unique nature of the region means impacts will be translated and expressed differently.

The vulnerability of this region to the effects of global and local change makes it an absolute necessity to base the development of policies and management strategies related to resources and systems on highly incisive and progressive water resources research. Research in this region needs to recognize and maintain pace with change, and go a step further and offer tangible and actionable solutions which recognize the transdisciplinary nature of global and local change. A number of studies specific to this region have, in fact, provided useful outcomes. The following are examples of lessons sourced from the work of various

researchers based in southern Africa across different research fields. The relevance of these lessons is not limited to southern Africa. These lessons, drawn from a region undergoing rapid change, can be applied in an international context and represent a meaningful knowledge contribution to water resources management.

2.4.1 Science and Technology Lessons

- Remote sensing can be applied as a useful tool in monitoring total evaporation from natural and altered land uses and improving water use efficiencies in agricultural production [57^{••}, 72^{••}].
- Erosion mitigation requires proactive management of soil cover through appropriate livestock management and conservation agriculture particularly in locations most vulnerable to natural erosion [57^{••}, 58^{••}, 59^{••}].
- A number of modelling systems have been developed with the dual purposes of serving as decision-support tools and for furthering the understanding of the unique biophysical environment of the region [80, 81^{••}, 82^{••}].

2.4.2 Governance, Policy and Management Lessons

- Enhancing resilience and reducing vulnerabilities requires the development of initiatives which recognise the links between biophysical and socio-economic changes [83[•]].
- A number of innovative, research-based products have been formulated, including the Streamflow Reduction Activities decision-support framework, the human and environmental flows Reserve, the National Water Act and the National Water Resource Strategy [63^{••}].

2.4.3 Socio-economic Lessons

- The effects of global change on local systems are not linearly correlated, they are not limited to a single driver of change and the vulnerability of society to these effects is a factor of the limited understanding and the uncertainty related to these effects [40^{••}, 41].

- The CADDP initiative seeks to highlight the value of land in food security and economic development by coordinating and increasing agricultural growth, food security and rural development.
- Societal vulnerability to sudden external disturbances can be enhanced by various factors including political inaction, lack of access to resources and information, and failure to enhance active community resilience [84].

The issue of global change is complex and requires treatment above the limited scope presented in this paper. This review serves to provide an overview of the effects of global change in southern Africa and the importance of considering global change as a catalyst of local change and a trigger of local environmental and socio-economic pressures. As indicated in this review, global change drivers which include climate change, land-use change, population growth and economic development are all coupled and interrelated anthropic-forms of change and they need to be treated as such. The management of the impacts of global and local change, therefore, requires a holistic approach which recognizes the interrelationships and adopts an integrated and adaptive management framework.

Acknowledgements

The authors wish to acknowledge the National Research Foundation and the Water Research Commission for funding this research and the Centre for Water Resources Research at the University of KwaZulu-Natal for providing the research facilities.

References

1. Crutzen, PJ and Stoermer, EF. 2000. The “Anthropocene”. *Global Change Newsletter* No. 41: 17-18.
2. Crutzen, PJ and Steffen, W. 2003. How Long Have We Been in the Anthropocene Era? *Climatic Change* 61: 251-257.
3. Steffen, W, Sanderson, A, Tyson, PD, Jager, J, Matson, PA, Moore III, B, Oldfield, F, Richardson, K, Schellnhuber, HJ, Turner II, BL and Wasson RJ. 2005. *Global Change and the Earth System: A Planet Under Pressure*. Springer, Berlin, Germany.

4. Syvitski, J. 2012. Anthropocene: An Epoch of Our Making. *Global Change International Geosphere-Biosphere Programme* 78:12-15.
5. Bates, BC, Kundzewicz, ZW, Wu, S and Palutikof, JP. (Editors). 2008. *Climate Change and Water: IPCC Technical Paper IV*. Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva.
6. Pittock, AB. 2009. *Climate Change: The Science, Impacts and Solutions*. CSIRO Publishing, Collingwood, Australia.
7. Döös, BR. 2002. Population Growth and Loss of Arable Land. *Global Environmental Change* 12: 303-311.
8. Parnell, S and Walawege, R. 2011. Sub-Saharan African Urbanisation and Global Environmental Change. *Global Environmental Change* 21S: S12-S20.
9. Ewers, RM. 2006. Interaction Effects Between Economic Development and Forest Cover Determine Deforestation Rates. *Global Environmental Change* 16: 161-169.
10. World Bank. 2010. *World Development Report: Development and Climate Change*. The World Bank, Washington DC, United States of America.
11. Veldkamp, A and Verburg, PH. 2004. Modelling Land Use Change and Environmental Impact. *Journal of Environmental Management* 72:1-3.
12. Foley, JA, Defries, R, Asner, GP, Barford, C, Bonan, G, Carpenter, SR, Chapin, FS, Coe, MT, Daily, GC, Gibbs, HK, Helkowski, JH, Holloway, T, Howard, EA, Kucharik, CJ, Monfreda, C, Patz, JA, Prentice, IC, Ramankutty, N and Snyder, PK. 2005. Global Consequences of Land Use. *Science* 309:570-574.
13. Dams, J, Woldeamlak, ST, Batelaan, O. 2008. Predicting Land-Use Change and its Impact on the Groundwater System of the Kleine Nete Catchment, Belgium. *Hydrology and Earth Systems Science* 12:1369-1385.
14. Tu, J. 2008. Combined Impact of Climate and Land Use Changes on Streamflow and Water Quality in Eastern Massachusetts, USA. *Journal of Hydrology* 379:268-283.
15. United Nations Environment Programme (UNEP). 2010. ADAPTCost Project: Analysis of the Economic Costs of Climate Change Adaptation in Africa. UNEP, Nairobi, Kenya.
16. UNFPA. 2011. *The State of World Population 2011*. United Nations Population Fund, United Nations, New York, United States.

17. Vincent, K. 2011. Coastal Risk in Dar es Salaam. In: Davis, CL (Ed.). 2011. Climate Risk and Vulnerability: A Handbook for Southern Africa. Council for Scientific and Industrial Research, Pretoria, South Africa.
18. Paavola, J. 2008. Livelihood, Vulnerability and Adaptation to Climate Change in Morogoro, Tanzania. *Environmental Science and Policy* 2:642-654.
19. Reid, P and Vogel, C. 2006. Living and Responding to Multiple Stressors in South Africa: Glimpses from KwaZulu Natal. *Global Environmental Change* 16:195-206.
20. Biggs, R, Simons, H, Bakkenes, M, Scholes, RJ, Eickhout, B, Van Vuuren, D and Alkemade, R. 2008. Scenarios of Biodiversity Loss in Southern Africa in the 21st Century. *Global Environmental Change* 18: 296-309.
21. Schulze, RE. (Ed). 2005. *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA.
22. Descheemaeker, K, Amede, T and Haileslassie, A. 2010. Improving Water Productivity in Mixed Crop-Livestock Farming Systems of Sub-Saharan Africa. *Agricultural Water Management* 97:579-586.
23. Pollard, S, and Du Toit, D. 2011. Towards Adaptive Integrated Water Resources Management in Southern Africa: The Role of Self-organisation and Multi-scale Feedbacks for Learning and Responsiveness in the Letaba and Crocodile Catchments. *Water Resources Management* 25:4019-4035.
24. Hunter, M. 2007. The Changing Political Economy of Sex in South Africa: The Significance of Unemployment and Inequalities to the Scale of the AIDS Pandemic. *Social Science and Medicine* 64(3):689-700.
25. Nicholson, SE. 2000. The Nature of Rainfall Variability Over Africa on Time Scales of Decades to Millenia. *Global Planetary Change* 26:137-158.
26. Grey, D and Sadoff, CW. 2007. Sink or Swim? Water Security for Growth and Development. *Water Policy* 9:545-571.
27. McCartney, MP, and King, J (Editors). 2011. Use of Decision Support Systems to Improve Large Dam Operation and Planning in Africa. Research for Development(R4D) Paper. CGIAR Challenge Program on Water and Food. Colombo, Sri Lanka.
28. Bärlund, I and Carter,TR. 2002. Integrated Global Change Scenarios: Surveying Use Needs in Finland. *Global Environmental Change* 12: 219-229.

29. Huang, GH and Xia J. 2001. Barriers to Sustainable Water Quality Management. *Journal of Environmental Management* 91:1-23.
30. Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
31. Statistics South Africa. 2009. *National Accounts: Water Accounts for South Africa*. Discussion Document No. D0405.1. Statistics South Africa, Pretoria, South Africa.
32. National Planning Commission. 2011. *Development Plan of South Africa: Vision for 2030*. The Presidency, Pretoria, Republic of South Africa.
33. Bere, T. 2007. The Assessment of Nutrient Loading and Retention in the Upper Segment of the Chinyika River, Harare: Implications for Eutrophication Control. *WaterSA* 33:279-284.
34. Edwards, AC and Withers, PJA. 2008. Transport and Delivery of Suspended Solids, Nitrogen and Phosphorus from Various Sources to Freshwaters in the UK. *Journal of Hydrology* 350:144-153.
35. Lange, G-M, Mungatana, E and Hassan, R. 2006. Water Accounting for the Orange River Basin: An economic Perspective on Managing a Transboundary Resource. *Ecological Economics* 61: 660-670.
36. Palmer, B. 2009. Water Accounting. *The Institute of Chartered Accountants in Australia*. Publication No. 0909-02. Sydney, Australia.
37. Kundzewicz, ZW, Mata, LJ, Arnell, NW, Döll, P, Kabat, P, Jiménez, B, Miller, KT, Oki, T, Sen, Z and Shiklomanov, IA. 2007. Freshwater resources and their management. In Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
38. Falkenmark, M and Rockström, J. 2006. The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management* (3): 129:132.
39. Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis. Summary for Policymakers*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

40. Warburton, ML, Schulze, RE and Jewitt, GPW. 2011. Hydrological Impacts of Land Use Change in Three Diverse South African Catchments. *Journal of Hydrology* 414-415:118-135.
41. Cilliers, P, Biggs, HH, Blignaut, S, Scholes, A, Hofmeyr, JH, Jewitt, GPW and Roux, DJ. 2013. Complexity, Modelling and Natural Resource Management. *Ecology and Society* 18(2).
42. Food and Agriculture Organization of the United Nations (FAO). 2005. Irrigation in Africa in Figures: AQUASTAT Survey 2005. United Nations, Rome, Italy.
43. Republic of South Africa Department of Water Affairs and Forestry (DWAF). 2003. A Conceptual Introduction to the Nature and Content of the Water Quality Management and Assessment Components of a Catchment Management Strategy. Sub-Series No. MS 8.1, Department of Water Affairs and Forestry, Pretoria, South Africa.
44. Republic of South Africa Department of Water Affairs and Forestry (DWAF). 2004. *Strategic Framework for National Water Resource Quality Monitoring Programmes*. Report No N/0000/REQ004, Department of Water Affairs and Forestry, Pretoria, South Africa.
45. Namibian Ministry of Agriculture, Water and Rural Affairs (MAWF). 2000. *National Water Policy White Paper*. Windhoek, Republic of Namibia.
46. Desanker, P and Magadza, C. 2001. *Africa*. In: Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
47. Shongwe, ME, van Oldenborgh, GJ, van den Hurk, BJJM, de Boer, B, Coelho, CAS and van Aalst, MK. 2009. Projected Changes in Mean and Extreme Precipitation in Africa under Global Warming. Part I: Southern Africa. *Journal of Climate* 22:3819–3837.
48. Heltberg, R, Siegel, PB and Jorgensen, ST. 2009. Addressing Human Vulnerability to Climate Change: Towards a “No-Regrets” Approach. *Global Environmental Change* 19:88-99.
49. Sadoff, CW and Muller, M. 2007. Perspectives on Water and Climate Change Adaptation: Better Water Resources Management-Greater Resilience Today, More Effective Adaptation Tomorrow. Global Water Partnership, Stockholm, Sweden.

50. Hewitson, B., Tadross, M. and Jack, C. 2005. Climate Change Scenarios: Conceptual Foundations, Large Scale Forcing, Uncertainty and the Climate Context. *In: Schulze, R.E. (Ed) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 2, 21 - 38.
51. Paavola, J and Adger, NW. 2005. Fair Adaptation to Climate Change. *Ecological Economics* 56:594-609.
52. Boardley, S. and Schulze, RE. 2005. Policy in Regard to Potential Impacts of Climate Change on Water Resources in South Africa: An Overview. *In: Schulze, R.E. (Ed) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* *Water Research Commission.* WRC Report 1430/1/05. Pretoria, RSA.
53. United Nations Environment Programme. 2010. ADAPTCost Project: Analysis of the Economic Costs of Climate Change Adaptation in Africa. UNEP, Nairobi, Kenya.
54. Stuart-Hill, SI and Schulze, RE. 2010. Does South Africa's Water Law and Policy Allow for Climate Change Adaptation. *Climate and Development* 2(2010):128-144.
55. Landman, WA, Tadross, M, Engelbrecht, F, Van Garderen, EA, and Joubert, A. 2008. Chapter 2: Seasonal Forecasts: Communicating current climate variability in southern Africa. *In: Davis, C (Ed). 2008. Climate Risk and Vulnerability: A Handbook for Southern Africa.* Council for Scientific and Industrial Research, Pretoria, South Africa.
56. Kongo, MV, Jewitt, GPW and Lorentz, SA. 2011. Evaporative Water Use of Different Land Uses in the Upper-Thukela River Basin Assessed from Satellite Imagery. *Agricultural Water Management* 98:1727-1739.
57. Dlamini, P, Orchard, C, Jewitt, G, Lorentz, S, Titshall, L and Chaplot, V. 2011. Controlling Factors of Sheet Erosion Under Degraded Grasslands in the Sloping Lands of KwaZulu-Natal, South Africa. *Agricultural Water Management* 98:1711-1781.
58. Mchunu, C, Manson, A, Jewitt, G, Lorentz, S and Chaplot, V. 2011. No-Till Impact On Soil And Soil Organic Carbon Erosion Under Crop Residues Scarcity In South Africa. *Soil Science Society of America Journal* 75(4):1503-1512.

59. Chaplot, V, Mchunu, CN, Manson, A, Lorentz, S and Jewitt, G. 2012. Water Erosion Induced CO₂ Emissions from Tilled and Non-Tilled Soils and Sediments. *Agriculture, Ecosystems and Environment* 159:62-69
60. Jewitt, G, and Kunz, R. 2011. The Impact of Biofuel Feedstock Production on Water Resources: A Developing Country Perspective. *Biofuels, Bioproducts and Biorefining* 5:387-398.
61. Jewitt, G. 2002. Can Integrated Water Resources Management Sustain the Provision of Ecosystem Goods and Services? *Physics and Chemistry of the Earth* 21:887-895.
62. Quinn, N. 2012. Water Governance, Ecosystems and Sustainability: A Review of Progress in South Africa. *Water International* 37:760-772.
63. Schreiner, B. 2013. Why Has the South African National Water Act Been so Difficult to Implement? *Water Alternatives* 6(2):239-245.
64. United Nations Human Settlements Programme (UN-HABITAT). 2010. State of the World's Cities 201/2011. UN-HABITAT, Nairobi, Kenya.
65. Grafton, RQ, Pittock, J, Davis, R, Williams, J, Fu, G, Warburton, M, Udall, B, McKenzie, R, Yu, X, Che, N, Connell, D, Jiang, Q, Kompas, T, Lynch, A, Norris, R, Possingham, H, and Quiggin, J. 2012. Global Insights into Water Resources, Climate Change and Governance. *Nature Climate Change* 3:315-321.
66. Van Wilgen, BW, Dyer, C, Hoffmann, JH, Ivey, P, Le Maitre, DC, Moore, JL, Richardson, DM, Rouget, M, Wannenburgh, A, and Wilson, JRU. 2011. National-Scale Strategic Approaches for Managing Introduced Plants: Insights from Australian Acacias in South Africa. *Diversity and Distributions* 17:1060-1075.
67. Panayotou, T. 1993. Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development. Working Paper WP238. Technology and Employment Programme, International Labour Office, Geneva, Switzerland.
68. Rockström, J, Steffen, W, Noone, K, Persson, A, Chapin, FS, Lambin, T, Lenton, TM, Scheffer, M, Folke, C, Schellnhuber, H, Nykvist, B, De Wit, CA, Hughes, T, van der Leeuw, S, Rodhe, H, Sörlin, S, Snyder, PK, Costanza, R, Svedin, U, Falkenmark, M, Karlberg, L, Corell, RW, Fabry, VJ, Hansen, J, Walker, B, Liverman, D, Richardson, K, Crutzen, P and Foley, J. 2009. Planetary Boundaries: A Safe Operating Space For Humanity. *Nature* 461: 472-475.

69. Ausubel, JH, Wernick, IK and Waggoner, PE. 2013. Peak Farmland and the Prospect for Land Sparing. *Population and Development Review* 38:221-242.
70. Bossio, D, Jewitt, G, and Van De Zaag, P. 2011. Smallholder System Innovation for Integrated Watershed Management in Sub-Saharan Africa. *Agricultural Water Management* 98(11):1683-86.
71. Jovanovic, NZ, Jarman, C, de Clercq, WP, Vermeulen, T, and Fey, MV. 2011. Total Evaporation Estimates from a Renosterveld and Dryland Wheat/Fallow Surface at the Voelvlei Nature Reserve (South Africa). *WaterSA* 37 (4):471-82.
72. Mabhaudhi, T, and Modi, AT. 2010. Early Establishment Performance of Local and Hybrid Maize under Two Water Stress Regimes. *South African Journal of Plant and Soil* 27(4):299-304.
73. Wenge, A, Shimelis, H, Derera, J, Mosisa, W, Danson, J and Laing, MD. 2013. Genetic Interrelationships Among Medium to Late Maturing Tropical Maize Inbred Lines Using Selected SSR Markers. *Euphytica* 191(2):269-77.
74. Hoff, H. 2011. Understanding the Nexus: Background Paper for the Bonn 2011 Conference: The Water, Energy, and Food Security Nexus. Stockholm Environment Institute, Stockholm, Sweden.
75. Water Research Commission. 2002. *State of Rivers Report: Mngeni River and Neighbouring Rivers and Streams*. WRC report No. TT200/02, Water Research Commission, Pretoria, South Africa.
76. Van Wilgen, BWV and Biggs, HC. 2010. A Critical Assessment of Adaptive Ecosystem Management in a Large Savanna Protected Area in South Africa. *Biological Conservation* 144:1179-1187.
77. Turpie, JK, Marais, C and Blignaut, JN. 2008. The Working For Water Programme : Evolution Of A Payments For Ecosystem Services Mechanism That Addresses Both Poverty And Ecosystem Service Delivery In South Africa. *Ecological Economics* 65:788-798.
78. Pegram, GC and Bath, AJ. 1995. Role of Non-Point Sources in the Development of a Water Quality Management Plan for the Mgeni River Catchment. *Water, Science and Technology* (6):175:182.
79. Rivers-Moore, NA, Goodman, PS and Nkosi, MR. 2007. An Assessment of the Freshwater Natural Capital In Kwazulu-Natal For Conservation Planning. *WaterSA* 33(5): 665-67.

80. Smithers, J and Schulze, RE. 2004. *ACRU Agrohydrological System User Manual Version 4.00*. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
81. Rivers-Moore, N, and Jewitt, GPW. 2007. Adaptive Management and Water Temperature Variability Within a South African River System: What are the Management Options? *Journal of Environmental Management* 82: 39-50.
82. Giannecchini, M., Twine, W, and Vogel, C. 2007. Land-cover Change and Human-Environment Interactions in a Rural Cultural Landscape in South Africa. *The Geographical Journal* 173:26-42.
83. Mgquba, SK. And Vogel, C. 2004. Living with Environmental Risks and Change in Alexandra Township. *South African Geographical Journal* 86:30-38.
84. Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
85. Molden, D (Ed). 2007. *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute and Earthscan, London, United Kingdom.
86. Novotny, V. 2003. *Water Quality: Diffuse Pollution and Watershed Management*. 2nd Edition. John Wiley and Sons Inc, New York, United States of America.
87. Turton, A. 2008. The State of Water Resources in Southern Africa: What the Beverage Industry Needs to Know. *CSIR Version 2 for General Circulation*: 1-8.
88. Campbell, DJ an Olsen, JM. 1991. Environment and Development in Kenya: Flying the Kite in Kajiado District. *The Centennial Review XXXV* (2):295-314.

CHAPTER THREE
MULTISCALE DRIVERS OF SUGARCANE EXPANSION AND IMPACTS ON
WATER RESOURCES IN SOUTHERN AFRICA*

Ngcobo, S.I.¹; Jewitt, G.P.W²

¹*Centre for Water Resources Research, University of KwaZulu-Natal, Private Bag X01, Scottsville, 3209, South Africa.*

²*IHE Delft Institute for Water Education, Delft, Westvest 7, 2611 AX Delft, The Netherlands.*

¹*Corresponding Author: (+27) 33 260 5174, E-mail Address: NgcoboS21@ukzn.ac.za*

Abstract

The reality of sugarcane expansion and intensification across southern Africa requires greater scrutiny than is currently the case, particularly considering the impacts of this activity on water resources in this region. This study uses of a frequency analysis approach to determine the multiscale proximate and ultimate drivers of sugarcane production as reported in case studies across the uMngeni, (South Africa), Ubombo (eSwatini) and Kilombero (Tanzania) Catchments. Applying a relationship between observed sugarcane yields and future low, medium and high production scenarios, this study determines water use estimates for rainfed and irrigated sugarcane over six production cycles, *viz.* 2013/14 - 2019/20. Results indicate that ultimate drivers such as foreign direct investment and increased local and international demand for sugar play a dominant role in expanding sugarcane production at both a regional and catchment scale. Water use is anticipated to increase in response to increased production intensity, particularly in the medium and high growth scenarios. However, this may be mitigated by increased water use efficiency and the development and adoption of improved cane crop varieties. More detailed water use modelling studies are required to account for critical aspects related to crop water use such as changes to temperature, total evaporation and CO₂ concentration as a consequence of climate variability and change. This will provide useful policy advice for regional agricultural development initiatives.

Key words: *Proximate drivers, ultimate drivers, land use change, sugarcane water use, frequency analysis, spatiotemporal scales.*

* Referencing adheres to the format of *Environmental Development*.

3.1 Introduction

Considered to be one of the ‘last frontiers’ of socio-economic development (Pretty *et al.*, 2011; Hoff *et al.*, 2012), southern Africa is a region undergoing major land use change (LUC) owing to economic transformation and expansion (Alcamo *et al.*, 2011). Consequently, water resources are subject to increasing pressure from a number of competing activities such as agriculture, mining and energy generation (Conway *et al.*, 2015). Despite low abstraction rates penned at 170 m³/capita/year or 44 km³/year from a total of 2 300 km³/year of potentially available renewable water resources (SADC, 2012; FAO Aquastat, 2015), a number of catchments are either closed or rapidly approaching closure owing to the combined effects of resource over-allocation (Turton, 2010), high natural variability and poor rainfall to runoff conversion ratios (Schulze *et al.*, 2005) underscored by high evaporation rates (Gleick, 2000; Hewitson *et al.*, 2005; Hennessy *et al.*, 2022).

The continuing LUC trends throughout the region in response to rapidly escalating domestic and international demands for natural resources (Brauman *et al.*, 2007; Daccache *et al.*, 2015), superimposed with an intensive socio-economic development agenda currently being adopted throughout this region (SADC, 2012; Mulenge, 2013) pose numerous threats to the sustainability of regional water resources. For instance, the fifteen member states of the Southern African Development Community (SADC) recently adopted a multi-billion dollar SADC Regional Infrastructure Development Master Plan (RIDMP). This plan has multiple complementary objectives which include enhancing market integration, stimulating economic and social development and growth and fostering environmental protection (SADC, 2012; UNDP, 2014; SADC Sugar Digest, 2014). The scope and intensity of the RIDMP implies that, in all likelihood, its success will hinge on the development and mobilisation of a substantial portion of water resources to support the proposed infrastructural and socio-economic developments.

A fundamental vehicle for socio-economic development with arguably the greatest potential for success in the SADC region is agriculture (Mathews, 2008a; Watson, 2011; Verburg *et al.*, 2013; Hess *et al.*, 2016). The production of high-value commodity crops such as sugarcane (Zuurbier and Van de Vooren, 2008; Knox *et al.*, 2010; Hess *et al.*, 2016), which, *inter alia*, require substantial water resources to establish and sustain them (**Table 3.1**)

(Inman-Bamber and Smith, 2005; Bezuidenhout *et al.*, 2006; Jewitt and Kunz, 2011; FAO Aquastat, 2015) is an interesting case. This is particularly true when the expansionist policies related to the production of this crop (SADC Sugar Digest, 2014; Hess *et al.*, 2016) and high risk hydroclimatic environment of this region are considered simultaneously (**Figure 3.1 and Figure 3.2**). This is underscored by the observation that sugar consumption in southern Africa will grow faster than anywhere else in the world over the next 10-20 years (International Sugar Association, 2010).

Sugarcane (complex hybrid of *Saccharum officinarum*), as the major focal crop of interest in this discourse, occupies a unique agronomic space in this region owing to the manner of its cultivation and management (**Table 3.1**). For example, sugarcane in southern Africa is grown under both rain-fed and irrigated conditions and has a reported mean annual crop water use of ~1 400 mm/annum for a full canopy crop (Bezuidenhout *et al.*, 2006). Other estimates place the average regional water use of sugarcane between 1 100 and 1 800 mm/annum depending on location and management (Carr and Knox, 2010). Further, sugarcane occupies approximately 785 000 Ha, of which more than 40% is irrigated (FAO Aquastat, 2015) (**Figure 3.3**). These water and land use estimates notwithstanding, sugarcane production is demonstrably a resource intensive activity, particularly in light of the hydroclimatic characteristics of the region (**Figure 3.1 and Figure 3.2**). Consequently, as will be demonstrated in this paper, sugarcane has the unique potential to be a high-impact and high-benefit crop with regard to the dynamics of regional and local water resources and socio-economic systems (Hess *et al.*, 2016).

Despite the apparent availability of adequate reserves of water resources and low withdrawal rates in southern Africa (Watson, 2011; SADC, 2012; Conway *et al.*, 2015; FAO Aquastat, 2015), the current lack of adequate infrastructure necessary to render these resources available for development means that water remains a major limiting resource in this region (Turton, 2008) (**Figure 3.2**). Further, owing to the high spatial and temporal hydroclimatic variability of the region (Hewitson *et al.*, 2005) (**Figure 3.1**), water resources management policy and practices tend to evolve and change, not only at the national scale, but also at the local catchment scale. The consequence of these differences in water resources management policy and practices is that the impacts of LUC as a consequence of sugarcane production on water resources are expressed over a wide range of spatial and temporal scales (Wagener

et al., 2010; IPCC, 2014a). This makes quantitative prediction and robust management difficult (Meiyappan *et al.*, 2015).

Table 3.1 Hydrological indicators, estimated sugarcane water use and approximate harvested sugarcane area by country in the SADC region.

Country	Mean Annual Precipitation (mm)	Mean Annual Potential Evaporation (mm)	Sugarcane Water Use (mm/annum)	Sugarcane Area Harvested (Ha)	Average Sugarcane Production (tonnes/Ha)	Reference Data Sources
Angola	1 050	1 400	285**	13 000	38	
Botswana	400	2 000	Nil	Nil	Nil	Schulze <i>et al.</i> ,
DRC	1 534	1 300	315**	16 500	42	1997; Shahin,
Lesotho	760	1 634	Nil	Nil	Nil	2002;
Madagascar	1 513	1 800	Not Established	103 000	Not Established	Hewitson <i>et al.</i> , 2005;
Malawi	1 104	1 610	788**	27 000	105	Bezuidenhout
Mauritius	2 041	1 600	548**	53 871	73	<i>et al.</i> , 2006;
Mozambique	969	1 900	773**	48 000	103	Carr and
Namibia	254	2 600	Nil	Nil	Nil	Knox, 2010;
Seychelles	2 330	1 688	Nil	Nil	Nil	FAO Aquastat,
South Africa	497	1 943	598	325 000	63	2015;
Swaziland	788	1 904	1799	56 000	93	FAOSTAT,
Tanzania	937	2 800	795	58 500	106	2015; World
Zambia	1 011	1 818	795	39 000	106	Bank, 2015.
Zimbabwe	652	1 750	1825**	44 800	105	

**.: Water use estimates based on calculations proposed by Cheesman (2004), Watson (2011) and FAO Aquastat (2015).

The current and projected land use changes across southern Africa, in response to the regional developmental agenda, will undoubtedly amplify the pressure on hydrological systems, particularly water resources. Sugarcane production, whether irrigated or rain-fed, may be conceptualized with the intent of fostering economic growth and mitigating poverty. However, the drivers and impacts of this activity on water resources and, by extension, society, at appropriate spatio-temporal scales need to be adequately quantified to enhance the potential of designing appropriate social and technical solutions. This remains a surmountable, yet major challenge in this region.

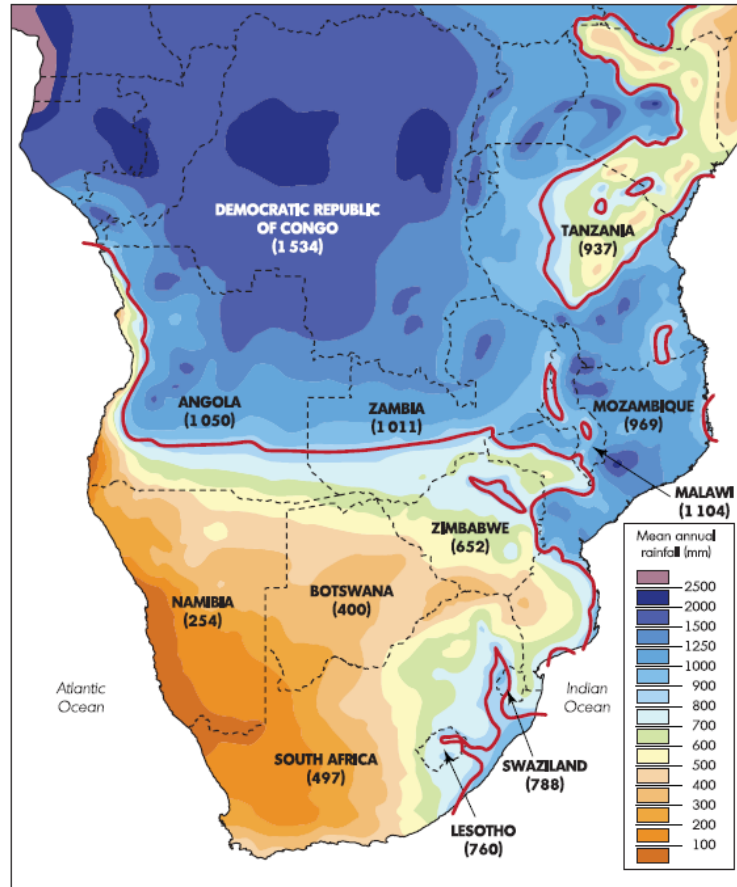


Figure 3.1 Mean annual precipitation (MAP) across southern Africa highlighting the high spatial variability of rainfall across the region. The global average of 860mm/yr is represented by the thick red line (Data Sources: Hewitson *et al.*, 2005; Turton, 2008).

Like any other comparable LUC activity, sugarcane production is often a consequence of both proximate and ultimate drivers (Geist and Lambin; 2001; Steffen *et al.*, 2005; Azevedo *et al.*, 2014). Proximate drivers are the immediately observable drivers which trigger specific environmental changes while ultimate drivers are the underlying, higher-level socio-economic demands placed upon the environment to deliver a certain product or raw material (Steffen *et al.*, 2005). The concept of proximate and ultimate drivers and their relevance to sugarcane production is expanded on in **Section 3.2**.

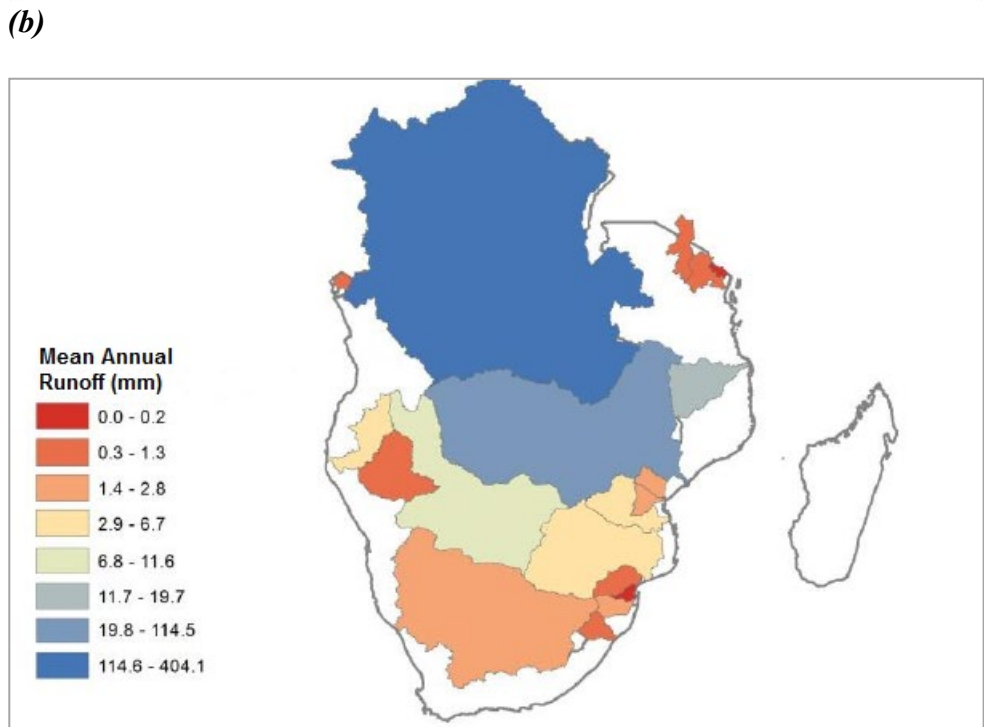
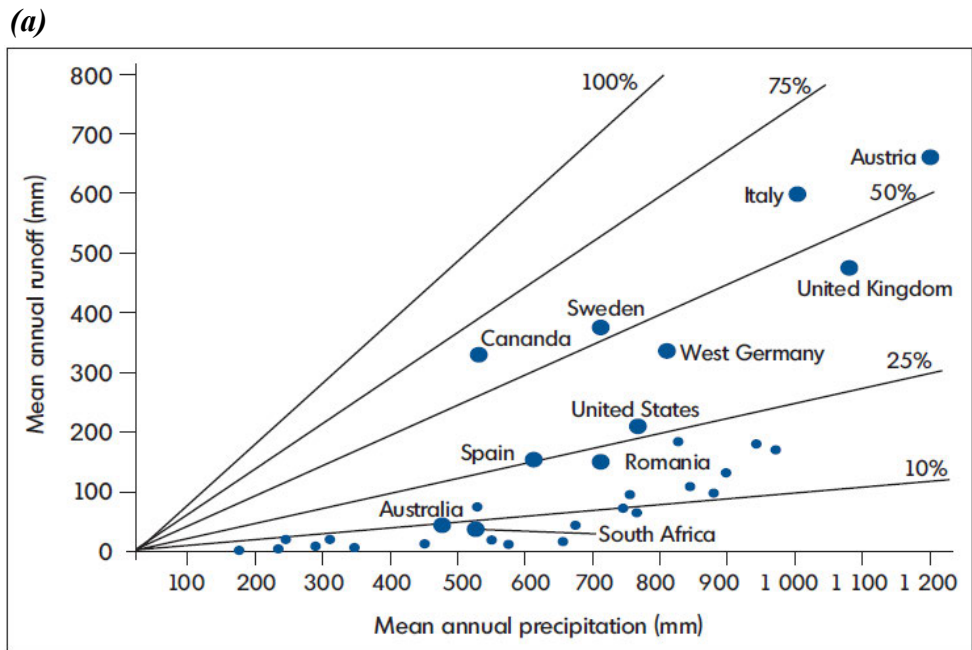


Figure 3.2 Mean annual precipitation (MAP) and mean annual runoff (MAR) conversion ratios relative to various countries (a) (Turton, 2008) and (b) MAR ranges across major shared basins in Southern Africa (Modified After: Schulze *et al.*, 2001). The MAR: MAP conversion ratio across southern Africa is only 20%, at best (Gleick, 2000).

The proximate and ultimate drivers of LUC which simultaneously induce and amplify impacts on water resources are becoming increasingly well-recognised as vital ecosystems rapidly approach total collapse and large-scale regime shifts occur, often with unpredictable and costly ecological, social and economic consequences (Walker and Salt, 2006; Van der Walt *et al.*, 2015). However, an increase in the recognition of the interface between anthropogenic LUC and water resource systems does not necessarily translate to an increase in the understanding of the consequences of this interface. This is particularly true in the SADC region (Hassan *et al.*, 2005; Warburton *et al.*, 2012).

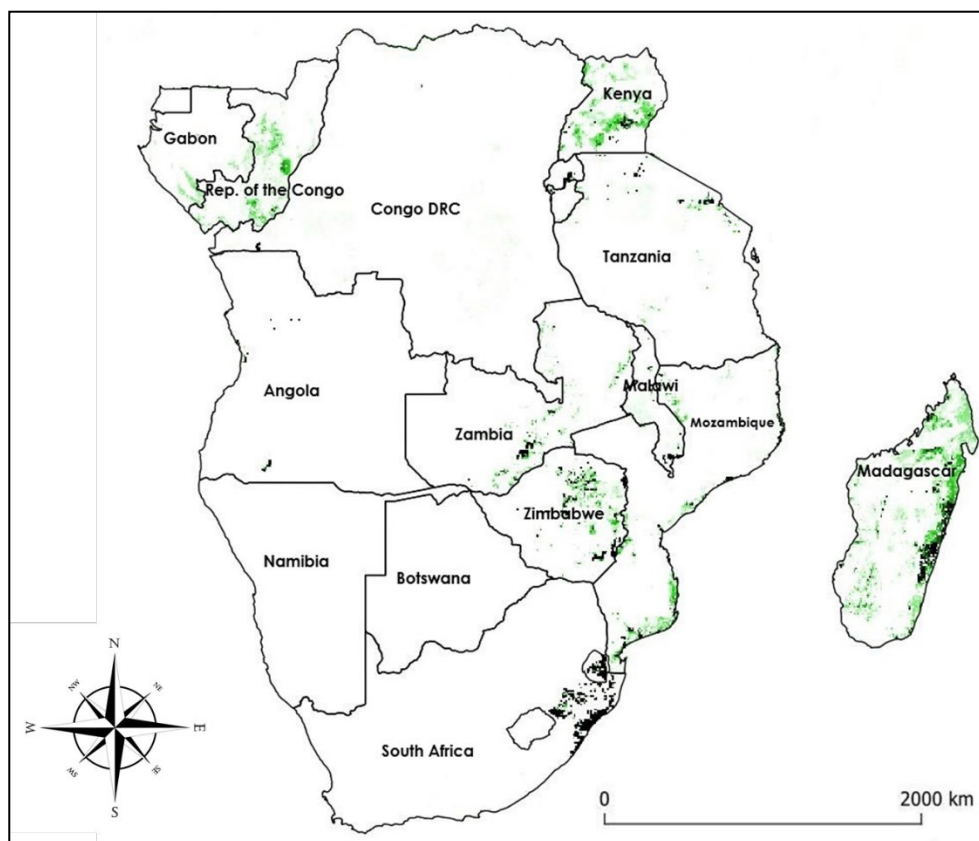


Figure 3.3 Sugarcane harvested areas across southern Africa occupying an area of approximately 785 000 Ha (Modified From: Harvest-Choice, 2015).

The added pressure engendered by the current and projected expansion and intensification of sugarcane production in the region will elicit multiscale impacts and responses on regional water resources and introduce added complexity to prediction and management. This complexity will be further compounded by the vulnerability of the region to the impacts of climate change and climate variability (IPCC, 2014a) underscored by relatively low socio-economic and biophysical adaptive capacity and resilience (Desanker and Magadza, 2001;

Stuart-Hill and Schulze, 2010; Hoff *et al.*, 2012). Despite some recognition of these issues (e.g., Alcamo *et al.*, 2011; Jewitt and Kunz, 2011; Ngcobo *et al.*, 2013; IPCC, 2014a; Naidoo, 2014; Msimanga and Sebitosi, 2014; Gasparatos *et al.*, 2015) there remains a dearth of place-based studies detailing the impacts of sugarcane production on water resources at appropriate spatial and temporal scales across southern Africa. The interface between sugarcane production and water resources in this region thus requires greater scrutiny than is currently the case. This is evidenced by the significant water use requirements of this crop as indicated in **Table 3.1**, and the high spatial and temporal variability of water resources. This paper, therefore, seeks to describe proximate and ultimate drivers and provide quantitative descriptions of the potential water resource impacts and responses engendered by LUC in the context of sugarcane production across southern Africa. In support of these aims, the following section describes the dynamics of sugarcane production in this region.

3.2 Proximate and Ultimate Drivers of Sugarcane Expansion in southern Africa

3.2.1 Sugarcane expansion in southern Africa

The reality of sugarcane expansion in southern Africa is demonstrated by national policies enacted to support the accelerated production of sugarcane-derived biofuels and stimulate employment creation and serve as a tool of industrial development (De la Torre Urgate and He, 2007; RSA Biofuels Strategy, 2007; SADC Sugar Digest, 2014). The expansion and intensification of sugarcane production across southern Africa (**Figure 3.3**) presents significant challenges for water resources management in this region. This is owing to the complex interface between the water use characteristics of sugarcane (**Table 3.1**) and the high inter- and intra-annual variability of rainfall and runoff across the region (**Figure 3.2b**) (Grey and Sadoff, 2007). Water use estimates developed by various researchers for the SADC region (e.g. Inman-Bamber and McGlinchey, 2003; Inman-Bamber and Smith, 2005; Bezuidenhout *et al.*, 2006; Mark and Luckson, 2010; Dunkelberg *et al.*, 2014; Eksteen *et al.*, 2014; FAOAquastat, 2015; Jones *et al.*, 2015; Olivier and Singels, 2015; Van Eekelen *et al.*, 2015) have demonstrated that sugarcane, owing to its high potential and actual total evaporation rates (PET and AET), requires significant volumes of water to achieve economically viable yields.

Against this background, it is important to note that the local knowledge and understanding of the sugar production process, value chain and water use signature is substantial (e.g. Bezuidenhout *et al.*, 2006; Bezuidenhout and Singels, 2007; Singels *et al.*, 2011; South African Sugarcane Research Institute, 2013; Mashoko *et al.*, 2013; Smithers, 2014). A concerning aspect, however, is that despite the vast knowledge base regarding the sugarcane production value chain and considering the potential of sugarcane as a viable tool of socio-economic development in Southern Africa (Hess *et al.*, 2016), the main impetuses of sugarcane expansion remain largely obscure or ignored. To elucidate the drivers and the associated impacts of sugarcane production on water resources, this study will attempt to establish and describe the causative patterns of sugarcane production expansion and intensification at different spatial and temporal scales based on the concept of proximate and ultimate drivers as postulated by Geist and Lambin (2001) and Steffen *et al.*, (2005) and will outline water resource impacts by developing estimates of water use through the introduction of various sugarcane production growth scenarios.

3.3 Proximate and Ultimate Drivers

Proximate drivers are the observable anthropogenic activities which trigger specific environmental responses (Geist and Lambin, 2001; Steffen *et al.*, 2005). An example of a proximate driver, in the context of sugarcane production, is the burning and clearing of forests by smallholder growers to create space for cane cultivation (e.g. Dlamini *et al.*, 2014; Dunkelberg *et al.*, 2014). The immediate impact of this land use conversion would be an immediate change in, *inter alia*, local albedo (Loarie *et al.*, 2011), actual and potential total evaporation (Inman-Bamber and Smith, 2005), direct and indirect water withdrawals through irrigation and soil water abstraction, respectively (Van Eekelen *et al.*, 2015), and a potential depletion of soil nutrient reserves (Cherubin *et al.*, 2015).

Sugarcane is a highly valuable commodity crop with a global export trade worth US\$47 billion (in 2011) and the sugar industry supports the livelihoods of millions of people and forms an important part of national economic wellbeing for several countries (Fairtrade Foundation, 2013). The demands for raw sugar and sugar-based derivatives such as bioethanol, widely considered to be a viable energy alternative to conventional fossil fuels, have been steadily increasing over the past few years (OECD-FAO, 2011).

In light of these statements, ultimate drivers, as Steffen *et al.*, (2005) note, are the human demands that shape consumption expectations and patterns. This human dimension introduces depth and complexity to these drivers and has the potential to introduce confirmation bias with regard to actual and perceived drivers, particularly as scales change. For instance, the dominant ultimate driver of sugarcane production at local catchment scales in South Africa may not necessarily be the same as that of Tanzania or Swaziland owing to, *exempli gratia*, differences in demographics, politics, management and global influences. A common theme, however, which characterises ultimate drivers is the pursuit of social and economic (*i.e.* financial) prosperity. Further, while the causal relationship between proximate and ultimate drivers may apparently be linear, the multiscale impacts of sugarcane production on water resources are often non-linear.

3.4 The Significance of Scale in Understanding Drivers and Impacts

The dominance of drivers and the severity and extent of impacts changes with spatial scale. Local drivers can instigate regional and global impacts (*e.g.* climate change driven by local enhanced greenhouse gas emissions) (**Figure 3.4, Green Arrows**) and global drivers can result in regional and local impacts (*e.g.*, foreign direct investment resulting in local LUC) (**Figure 3.4, Red Arrows**). Similarly, impacts can vary significantly across different temporal scales. This has been demonstrated by the Intergovernmental Panel on Climate Change (*e.g.* IPCC, 2001a; IPCC, 2007; Bates *et al.*, 2008; Cubasch *et al.*, 2013; IPCC, 2014a) and other collaborative research bodies such as the International Food Policy Research Institute (IFPRI, 2014) and the Future Earth Initiative (ICSU, 2013). As spatial and temporal scales change, however, connectivity patterns evolve and cross-scale interactions change (Kumar, 2011; IPCC, 2014a), and such multiscale nonlinearity engendered by new levels of complexity introduced at different scales cannot be described by simply upscaling or downscaling data (Blöschl and Sivapalan, 1995; Blöschl *et al.*, 2015). Most hydrological studies circumvent the difficulty of multiscale nonlinearity by conducting investigations and analyses at either fixed spatial or temporal scales. The validity of this approach notwithstanding, the argument proposed in this study is that this complexity can be overcome, or at least managed, and will suggest ways of accomplishing this.

The relationships depicted in **Figure 3.4** form the conceptual basis of this study. The feedbacks, feedforwards and cross-sectoral links (Blue Arrows) highlight the tightly-coupled connectivity of drivers across spatial scales and this presents important implications for the sustainability of water resource systems and socio-economic development in this region. Further, though not highlighted in **Figure 3.4**, drivers and impacts change as temporal scales change. For instance, Adger and Pulhin (2014) in an extensive study of climate change impacts on various dimensions of human security note that risks and potential for adaptation are time-sensitive factors. As climate-related drivers of impacts such as extreme temperature and rainfall increase in frequency and severity, delaying mitigation and adaptation only serves to amplify vulnerability and lends increased potency to the eventual impacts.

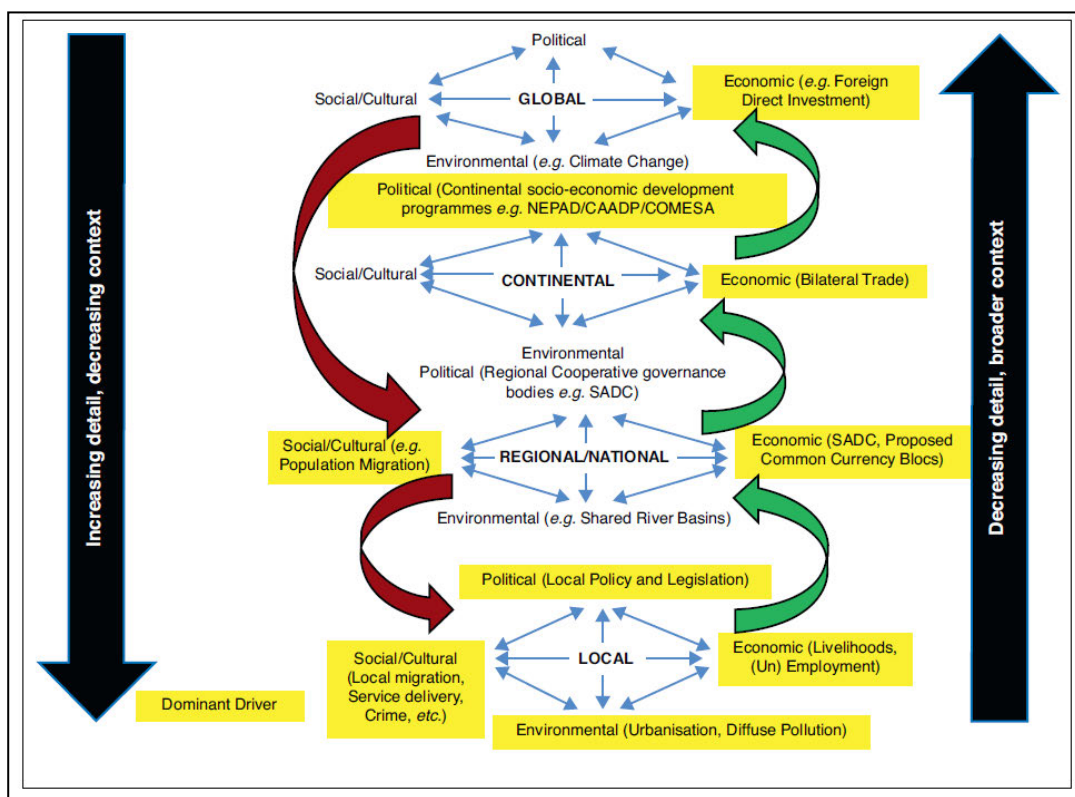


Figure 3.4 Diagram building from the 'kite' concept indicating the dominance of various drivers of change applicable to Southern Africa across different spatial scales. The green arrows indicate changes in dominant drivers as scale is progressively increased and red arrows reflect changes as scales are reduced (After: Ngcobo *et al.*, 2013). This indicates that at large scales, ultimate drivers become increasingly dominant, whereas at smaller scales proximate drivers assume the dominant role.

3.5 Methods

3.5.1 Data Acquisition and Processing

To capture the dynamics of sugarcane production in southern Africa, 161 case studies spanning local (*i.e.* sub-national or catchment) and regional scales were considered. These case studies included peer-reviewed scientific articles, national statistical reports and specialist reports and these were supplemented with information from various data repositories such as the UN-Food and Agriculture Organization and the Fairtrade Foundation (Fairtrade Foundation, 2013; FAO Aquastat, 2015). From these, a total of 87 cases considered directly relevant for purposes of this paper were selected for analysis. The complement of cases had to necessarily correspond with the conceptual framework depicted in **Figure 3.4** and describe catchment and regional dynamics of sugarcane production, specifically with respect to proximate and ultimate drivers and observed and probable impacts to water resources. In that regard, the total number of case studies ($n = 87$) incorporates studies conducted at both catchment ($n = 34$) and regional scales ($n = 53$). Finally, the case studies had to provide some indication of the temporal variations or trends of local and regional sugarcane production.

For local scale analyses, and as a means of comparison, three catchments from the region, each with highly active commercial and smallholder sugarcane production enterprises, were selected. These are the Mngeni Catchment in the KwaZulu-Natal Province of South Africa, the Kilombero Catchment in the Morogoro Region of Tanzania and the Ubombo Catchment in the Lubombo Region of Swaziland (**Figure 3.5**). These three catchments were selected on the basis of their varied hydroclimatic conditions, high sugarcane production levels, geographic placement and sugarcane agronomic management (**Table 3.2**). By extension, regional scale analyses were conducted only on cases carried out with the sole purpose of capturing the regional dynamics of sugarcane expansion. This approach allowed the description of local drivers and impacts and provides a representative regional ‘snapshot’ of the sugarcane production environment.

Temporal scale analyses were conducted on cases that directly addressed the prospects of the sugar industry across different time periods following the IPCC approach (*e.g.* IPCC, 2014a). These included the present (2015-2020), near-future (2020-2050) and distant future

(2050 and beyond). Data extracted from reports and articles considered current and projected water use estimates, areas under cultivation, costs of production, average yields per hectare and demographic data (*e.g.* number of employees per processing plant). These data were used to discern the actual, underlying drivers (as opposed to perceived drivers) of sugarcane production throughout the region.

Since proximate and ultimate drivers can simultaneously be biophysical and anthropogenic (**cf. Section 3.3**), data collected included both qualitative interpretations of secondary information and data developed through quantitative analyses. To allow for a standardised analysis, interpretation and presentation of results and remove confirmation bias, both forms of data (*i.e.* qualitative and quantitative) were treated as non-exclusive. This implies that all case studies - since they were conducted in the same region and share a similar narrative describing change and associative impacts - are comparable.

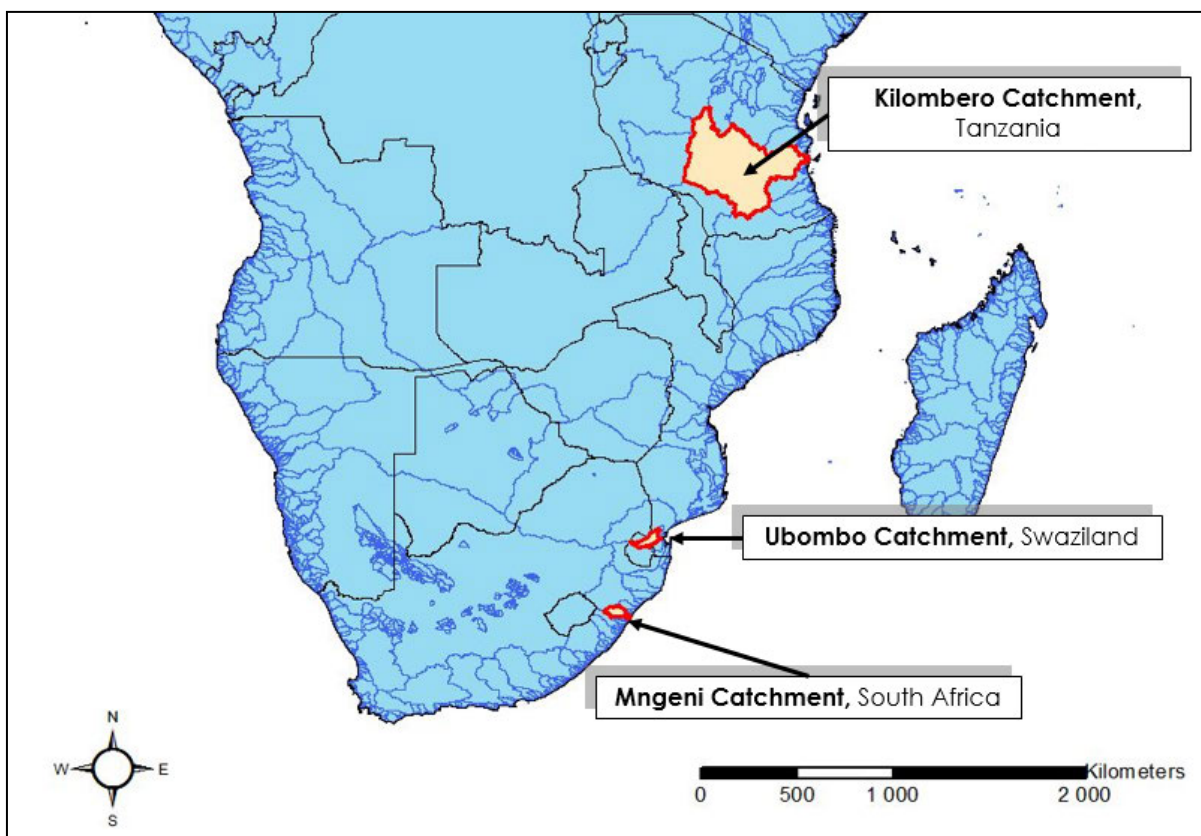


Figure 3.5 Location of case study catchments in southern Africa.

Table 3.2 Background information on case study catchments (Sources: SA Canegrowers Association, 2018; Swaziland Sugar Association, 2018; Kasinthula Canegrowers Association, 2015; Illovo Sugar Africa, 2018; Illovo Malawi, 2018; The Sugar Engineers, 2018).

Catchment	Location	Area (km ²)	MAP Range (mm)	MAE Range (mm)	Production System	Area Under Sugarcane (Ha)	Annual Output* (tonnes/annum)
Mngeni	KwaZulu-Natal, South Africa	4 474	700 - 1 550	1 570 - 1 740	Irrigated and Rainfed	25 300	3 392 653
Ubombo	Lubombo, Swaziland	5 502	500 - 710	2 000 - 2 200	Irrigated	10 981	1 303 750
Kilombero	Morogoro, Tanzania	17 736	1 000 - 1 800	1 600 - 1 800	Irrigated and Rainfed	21 800	1 200 000

*Total sugarcane crushed by mills in the 2013/2014 production cycle.

3.5.2 Frequency Analysis of Proximate and Ultimate Drivers

A frequency analysis is a systematic measure of the number of times a particular condition is met or exceeded and is generally used to construct a categorical frequency distribution (Bluman, 2009). To facilitate the frequency analysis, a set of broad themes which encompass proximate and ultimate drivers of sugarcane production were identified from the 87 cases. These broad themes were adapted from LUC indicators proposed by Geist and Lambin (2001) and tailored for sugarcane expansion. The frequency of drivers was determined by observing the number of times a particular broad theme was addressed across the cases. Owing to the wide scope of proximate and ultimate drivers, the frequency of each driver could not be counted individually. To prevent double accounting, only broad thematic drivers were counted and *not* the individual drivers associated with a specific broad theme. For instance, ‘agricultural expansion’- as a broad thematic driver- is often associated with both land clearing and increased demand for raw and refined sugar as proximate and ultimate drivers, respectively. A case study describing both the former and latter drivers would thus be counted as a *single* case describing ‘agricultural expansion’. The inherent subjectivity of this methodological approach is acknowledged. It was nonetheless adopted since it offers a means of comparing and describing otherwise divergent themes of LUC through a single approach.

Sugarcane production in this region is primarily driven -or limited- by four broad themes, viz. agricultural expansion, economics and demographics, technological advances and policy. These four themes are in turn characterized by unique, often overlapping, proximate and ultimate drivers. To highlight the distinct nature of each theme, however, it is important to define each one in turn, thus:

Agricultural Expansion (AGEX): Refers to the spatial expansion of cropped land in absolute and relative terms as a consequence of, *inter alia*, land conversion, agricultural infrastructural developments, growth in subsistence and commercial farming and shifting cultivation.

Economics and Demographics (ECD): Describes economic factors such as commercialisation, foreign direct investment, economic growth and development and factors related to human population dynamics such as population growth and movement.

Technological Advances (TECH): Refers to changes and advances in technology which directly or indirectly influences (agricultural) productivity. Examples include the development of new drought and pest-resistant sugarcane cultivars and improved in-field mechanisation.

Policy and Institutional Factors (POL): This refers to the evolution and change of political and related institutions via changes in legislation, leadership philosophies and public opinion.

These broad themes, their associated proximate and ultimate drivers and probable impacts on water resources are summarised in **Table 3.3** and the results of this exercise are summarised in **Section 3.7**. **Figure 3.6** summarizes the methodological approach adopted in this study.

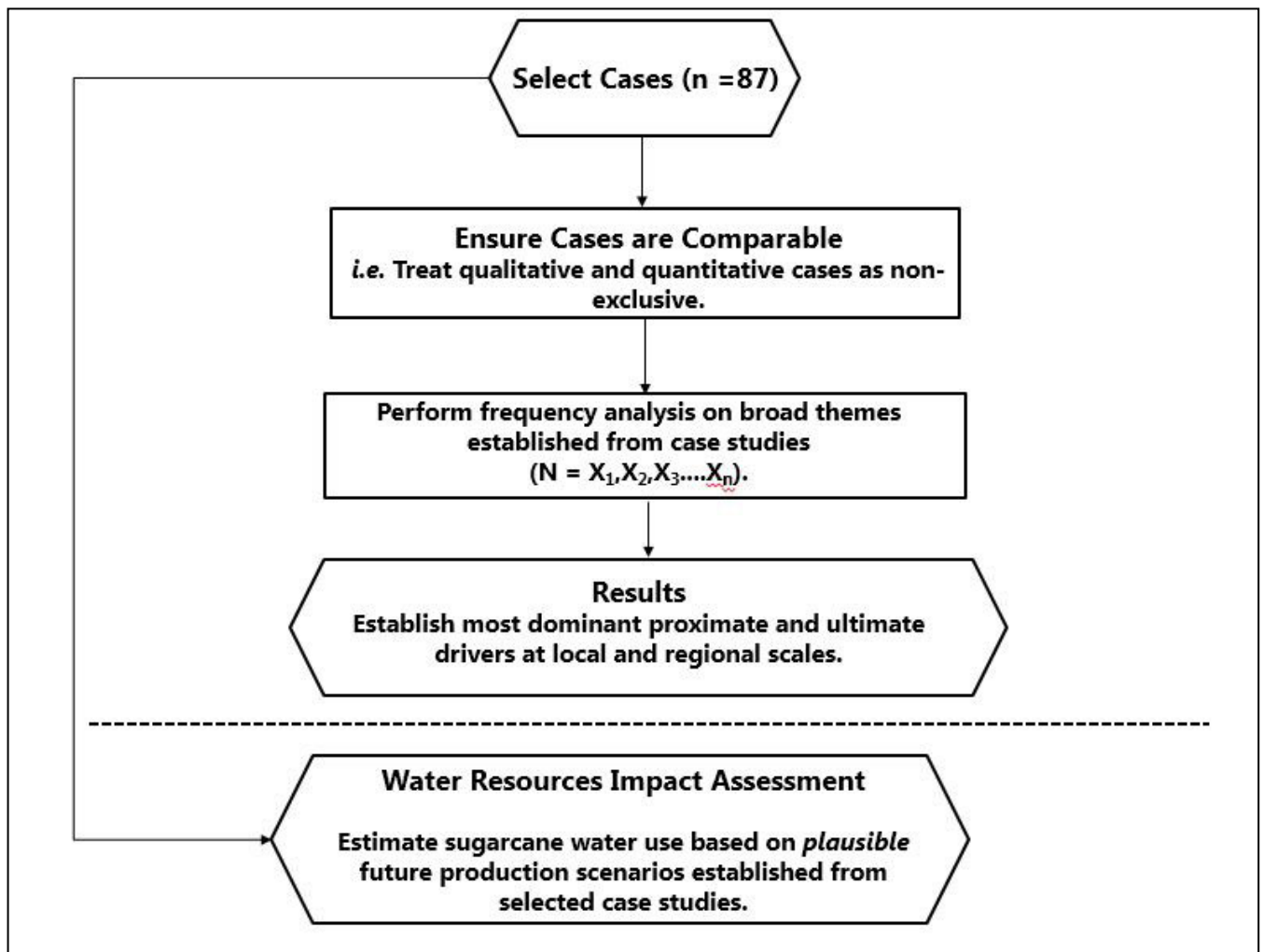


Figure 3.6 Schematic representation of the methodological approach.

Table 3.3 Broad themes and variables which culminate in proximate and ultimate drivers for sugarcane production and the associated impacts on water resources (After: Geist and Lambin, 2001; Steffen *et al.*, 2005).

Theme	Proximate Drivers	Ultimate Drivers	Water Resource Response/Impact
Agricultural Expansion (AGEX)	Land clearing (<i>e.g.</i> forest clearing and cutting; “slash and burn” practices).	Increased demand for raw and processed sugar.	Accelerated sedimentation and water quality decline.
	Irrigation Management (<i>i.e.</i> Scheduling and Expansion).	Increased requirement for access to water for sugar production.	Decline in renewable water resources.
	Soil and water conservation structures (<i>e.g.</i> contour ploughing).	Imperatives to minimise the environmental impact signature of sugarcane.	Potential improvement of water resource quality.
	Construction of farm dams and waste disposal sites.	Increased demand for water in processing plants.	Redirection of water resources from essential services.
	Permanent cultivation (<i>i.e.</i> monoculture farming systems).	Demand for energy co-generation (<i>i.e.</i> burning of residual biomass).	Intensive water use.
	Urbanisation and Land Abandonment.	Irreversible land degradation (loss of soil nutrients). Altered business practice.	Loss of soil structure and increased infiltration. Increased surface runoff from impervious surfaces.
Economic and Demographic Indicators (ECD)	Construction of new mills/processing plants. -----	Global demand for sugar and sugar-based derivatives. Demand for sugarcane ethanol (<i>i.e.</i> biofuel feedstock).	Reallocation and diversion of water for industry -----

	Increase in influx of people seeking employment in the sugar industry.	Demand for food, employment and financial security.	Increase in domestic water demand and potential water quality decline in instances of poor sanitation.
Technological Advancements (TECH)	Crop variety development and changes.	Demand for improved yields and reduced crop susceptibility to disease and drought.	Potential increases in water use efficiency.
	Optimisation of In-Field Mechanisation.	Demand to reduce in-field traffic and reduce compaction.	Increases in production efficiency and possible water conservation.
	Access to Real-Time Weather Data (e.g. Automatic Weather Station Installation).	Demand for optimal irrigation management.	Improved irrigation scheduling and, thus, water use efficiency.
	Land Re-Distribution (i.e. Resulting in agronomic practice changes).	Declaration of Sugarcane as a Streamflow Reduction Activity (i.e. in South Africa).	Mitigation of long-term losses in renewable water resources (streamflow and groundwater).
Policy and Institutional Factors (POL)	Establishment and expansion of cane growers' associations (e.g. Fairtrade Foundation and the SUSFARMS Initiative).	Demand for food and financial security, poverty alleviation and improved lifestyles. Ethical considerations (Environmental Responsibility).	Risks of water resource over-allocation. Potential for improved water resources management practices.
	"Land Grab" Phenomenon.	Policies which support sugarcane cultivation.	No direct water resources impact.

3.6 Water Resources Impact Assessment

3.6.1 Sugarcane Production Growth Scenarios

A series of sugarcane production growth scenarios were introduced based on plausible output prospects across the study catchments (**Figure 3.5**). These scenarios were intended to provide a description of the water resource impacts manifested by expanding sugar production. Using guidelines and projections from the International Sugar Association (ISO), the South African Cane Growers Association (SACGA), the Bureau for Food and

Agricultural Policy (BFAP), the OECD-FAO Agricultural Outlook Yearbook and the South African Sugar Association (SASA), three scenarios are considered, *viz.* the low, medium and high production scenarios (**Table 3.4**).

The southern African sugar industry collectively produces approximately 5 million tonnes of refined sugar annually. This is anticipated to increase by 57 thousand tonnes under the low production scenario, 1.9 million tonnes in the medium production scenario and upwards of 3.2 million tonnes in the high production scenario by 2020 (SADC Sugar Digest, 2014; ISO, 2014). (It is important to note that these scenarios only consider refined sugar output and not raw sugarcane crushed at individual mills). These scenarios are based on critical assumptions including:

- The successful completion and initiation of all major sugar production projects in Tanzania and Mozambique and the ability of South Africa to maintain an annual production rate of 2.5 million tonnes,
- The continued economic, social and political reforms in the region creating a favourable environment for foreign investors, and
- The stabilisation of international sugar prices and the positive outcome of the EU sugar policy reform.

It is acknowledged that these regional projections of sugarcane production rates do not reflect the production potential within the individual catchments in this study. However, since local cane growers and millers ultimately contribute to regional sugar production, these projections can be used as an indicator of the potential and idealised rate of sugarcane production growth in these catchments. That is to say, if the regional production rate is anticipated to grow by 1.14% (a year-on-year factor of 0.19%) in the ‘low’ production scenario and 64% between 2014 and 2020 (a year-on-year factor of 10.67%) in the ‘high’ production scenario, it is not unreasonable to assume comparable growth rates within the individual catchments assuming ideal production conditions. The limitations of this assumption are recognised; particularly the fact that these are geographically distinct catchments, both in terms of production potential and hydroclimatic conditions. However, to the authors’ knowledge, no catchment-scale objective projections of sugarcane production growth rates have been developed. Therefore, the projections developed herein are assumed

to be applicable and appropriate. **Table 3.4** summarises the key aspects related to these projections and production scenarios respectively.

Table 3.4 Current sugarcane production rates and prospective production scenarios.

Production Scenarios (2014-2020)*					
Catchment	Area	Annual	Low	Medium	High
	Under Sugarcane (Ha)	Output (tonnes/annum)	(1.14%) (tonnes/annum)	(32%) (tonnes/annum)	(64%) (tonnes/annum)
Mngeni	25 300	3 392 653	3 431 513	4 632 890	6 233 313
Ubombo	10 981	1 303 750	1 318 684	1 780 356	2 395 376
Kilombero	21 800	1 200 000	1 213 745	1 638 678	2 204 757

* These are rates of production (t/annum) at the end of 2020 assuming year-on-year production rates of 0.19%, 5.33% and 10.67% under the low, medium and high scenarios respectively.

3.6.2 Estimating Sugarcane Water Use

Sugarcane water use reflects the actual total evaporation or evapotranspiration (ET_C in $\text{mm}\cdot\text{day}^{-1}$) of the cane crop, as limited by available soil moisture. Using **Equation 3.1**, ET_C is calculated from a reference crop evapotranspiration (ET_O in $\text{mm}\cdot\text{day}^{-1}$) which assumes ideal growth conditions, *i.e.* no limitations related to water, soil, nutrition, CO_2 and minimal disease or pest interference:

$$ET_C = K_C ET_O \quad (3.1)$$

Where K_C is an empirical crop coefficient which, in this study, was assumed to be 1.25 for a full canopy, mid-season cane crop (Inman-Bamber and McGlinchey, 2003) and, using **Equation 3.2**, ET_O is calculated from a standard parameterisation of the Penman-Monteith equation for a short-grassed surface (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta (R_n - G) + \gamma \frac{900}{T_2 + 273} uD}{\Delta + \gamma (1 + 0.34\mu)} \quad (3.2)$$

Where R_n represents the net radiation ($\text{W}\cdot\text{m}^{-2}$), T is the air temperature ($^{\circ}\text{C}$), u is the wind speed ($\text{m}\cdot\text{s}^{-1}$), D is the vapour pressure deficit (kPa), all measured at 2m above the soil

surface, G is the soil heat flux density ($W \cdot m^{-2}$), γ is the psychrometric constant ($kPa \cdot ^\circ C^{-1}$) and Δ is the slope of the saturation vapour pressure curve ($kPa \cdot ^\circ C^{-1}$) at temperature T . Bakker (1999), after an extensive field-based investigation of sugarcane water use, made use of **Equation 3.2** to derive a relationship between sugarcane yield and ET_C as summarised in **Equation 3.3**:

$$Yield = 9.53 \frac{\Sigma ET_C}{100} - 2.36 \quad (3.3)$$

Where ΣET_C (mm) is the total actual crop evapotranspiration since crop initiation and *Yield* is sugarcane yield ($t \cdot ha^{-1}$). Following on the work by Thompson (1976) and Bakker (1999), Bezuidenhout *et al.*, (2006) derived a relationship to determine sugarcane mean annual water use as a function of mean production per hectare per annum. This relationship is summarized in **Equation 3.4**:

$$wu = \frac{100 (P+2.36)}{9.53} \quad (3.4)$$

where wu is the mean annual water use within the mill area in $mm \cdot a^{-1}$ and P is the mean production per hectare per annum in $t \cdot ha^{-1} \cdot a^{-1}$. Using **Equation 3.4**, this study determined sugarcane water use using observed P in the Mngeni, Ubombo and Kilombero catchments for the 2013/2014 production cycle. Further, the probable water use estimates related to the projected sugarcane production estimates as detailed in **Table 3.4**, were also calculated using **Equation 3.4**. The results of this exercise are summarised in **Section 3.7**.

3.7 Results and Discussion

3.7.1 Drivers of Sugarcane Production across Spatial Scales

A frequency analysis was performed according to the four established broad themes in Section 3.5.2 (see Table 3.3) to discern the most pertinent proximate and ultimate drivers of sugarcane production in the three catchments. The results of this analysis are presented in Table 3.5 and Figure 3.7. As expected, ultimate drivers assume a more important role in determining the expansion and intensification of sugarcane production at both catchment and regional scales. This is owing to the strong inherent human dimension intrinsic to ultimate drivers; a dimension which exerts enormous pressure on the environment to deliver goods and raw materials to meet demands and secure social and economic prosperity.

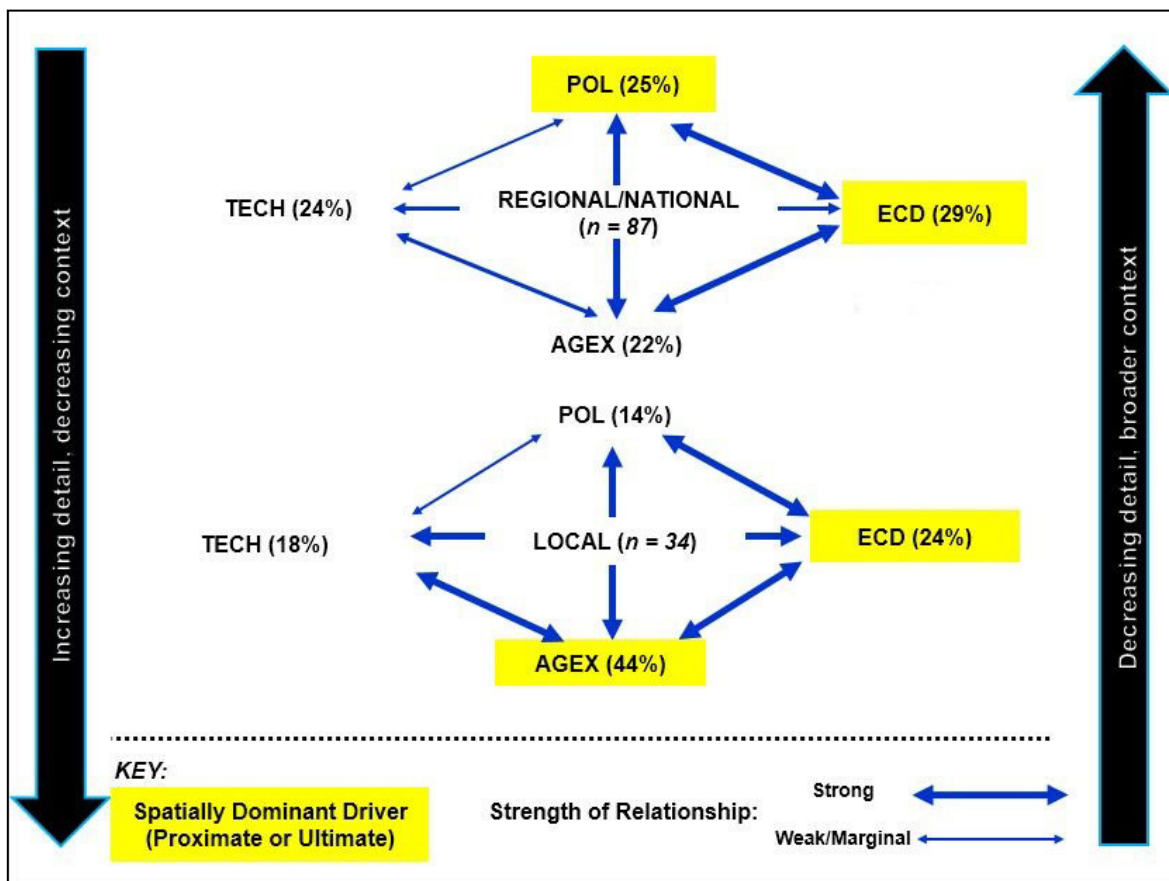


Figure 3.7 Spatial relative dominance of drivers at local catchment and regional scales also indicating the strength of the causal relationships between themes of drivers.

Table 3.5 Spatial frequency of cases describing broad proximate and ultimate drivers across local catchment and regional scales.

Theme	Local Scale (n = 34)						Regional Scale (n = 87)		
	Mngeni		Ubombo		Kilombero		Proximate Drivers	Ultimate Drivers	
	Proximate Drivers	Ultimate Drivers	Proximate Drivers	Ultimate Drivers	Proximate Drivers	Ultimate Drivers			
Agricultural Expansion	5	2	2	0	0	1	Agricultural Expansion	11	8
Economics and Demographics	2	3	0	3	0	0	Economics and Demographics	6	19
Technological Advances	2	7	1	1	0	0	Technological Advances	9	12
Policy and Institutional Factors	1	4	0	0	0	0	Policy and Institutional Factors	6	16
Total	9	17	3	4	0	1		32	55

At the local catchment scale, agricultural expansion (AGEX) and economic and demographic factors (ECD) are the most dominant themes accounting for over 44% and 24% of drivers respectively (**Figure 3.7**). Cases describing ultimate drivers were proportionally greater ($\Sigma = 22$) than those describing proximate drivers ($\Sigma = 12$) (**Table 3.5**). This is indicative of the rapid growth of the sugar industry across all three catchments in a bid by parent countries to raise the gross domestic product, create employment, enhance foreign trade and promote rural development (*i.e.* ECD). Substantial investments in new processing plants, distribution infrastructure and improved sugarcane varieties have been made within these catchments. The consequence of these investments has been the physical expansion of sugarcane cropland (AGEX), particularly in the Kilombero and Ubombo Catchments, and the intensification of this activity in the Mngeni catchment. These trends provide some explanation of the dominance of ultimate drivers related to AGEX and ECD at the local catchment scale.

This, however, does not diminish the importance of proximate drivers. At this scale, physical changes to the landscape, typified by proximate drivers are more likely to result in direct impacts to water resources in the form of altered hydrological responses and fluxes. For instance, in the Mngeni Catchment, proximate drivers ($n = 9$) are outweighed by ultimate drivers ($n = 17$) (**Table 3.5**). However, on close inspection it is apparent that the bulk of ultimate drivers in this catchment are influenced by Technological Advancements (TECH). In the Mngeni Catchment, sugarcane production is intensifying rather than expanding spatially. This intensification is preceded by limitations to AGEX which necessitate improved production techniques in the form of new crop varieties, more efficient irrigation schemes and advanced in-field mechanisation. This is to ensure greater sugar production with the same or less crop land. Regardless, such intensification of production may be expected to impact water resources directly, most likely in a positive manner insofar as improved water resources management is concerned, at least within the Mngeni catchment.

It is important to note that there exists a complementarity between the various themes of drivers. One theme tends to be influenced by another by varying degrees. At local scales, AGEX, ECD and POL strongly influence one another, whereas POL and TECH share a markedly weak relationship.

The strong relationship between these LUC themes at local scales (**Figure 3.7**) reflects the highly sensitive nature of the sugar industry to both proximate and ultimate LUC drivers. Technological advancements (TECH) such as irrigation optimisation, mechanisation, storage and processing and the construction of dams can immediately prompt significant changes in sugar production rates (AGEX), thus changing the economics of production (ECD) which can lead to changes in policies (POL) which support (or oppose) the production of sugarcane. At the regional scale, however, the strength of these relationships changes markedly (**Figure 3.7**). Drivers related to policy and legislation (POL) not only dominate at this scale but have a direct influence on the expansion of sugar production (AGEX). This is owing to factors such as land redistribution and the establishment of new smallholder and commercial cane growers (**Table 3.3**). The prospective rapid growth of the sugar industry in the region may result in economic gains (ECD) which might render the goal of human well-being and livelihood security more attainable.

LUC drivers change as spatial scales change (**Figure 3.4**). At local scales, LUC drivers are often specific and readily observable whereas the main mechanisms behind these drivers are often obscure. At larger scales (*i.e.* as we ‘zoom out’ spatially), the regional scale in this instance, the underlying mechanisms influencing LUC become more obvious. This is the ‘increasing detail, decreasing context’ (local ‘zoomed in’ scale) vs. ‘decreasing detail, broader context’ (regional scale and above) narrative (**Figure 3.4** and **Figure 3.7**). The increase in detail and loss of context allows a perspective showing that proximate drivers dominate at local scales and the decrease in detail and broader context makes it clear that ultimate drivers dominate at regional and larger scales. This was not the case in this study. At both local and regional scales, ultimate drivers across all four (4) themes and across all three catchments dominated. This is evidence of the strong political and economic impetus to propel sugarcane production as a key industry to ameliorate the social and economic complexities in the region.

3.7.2 Drivers of Sugarcane Production across Temporal Scales

The number of cases describing the drivers of sugarcane production at different temporal scales in this region was negligible ($n = 8$). Nonetheless, these cases provided some indication of the temporally sensitive drivers of sugarcane production (**Table 3.6**).

Table 3.6 Frequency of cases describing drivers of sugarcane production across various temporal scales.

Theme	Mngeni (n = 4)			Ubombo (n = 3)			Kilombero (n = 1)		
	Time Frame			Time Frame			Time Frame		
	2015-2020	2020-2050	2050 and Beyond	2015-2020	2020-2050	2050 and Beyond	2015-2020	2020-2050	2050 and Beyond
Production and Consumption Patterns	4	0	0	0	0	0	1	0	0
Biophysical Stressors (LUC; Climate Change)	0	4	0	0	3	0	0	0	0

The International Sugar Association (ISA), in conjunction with the SADC Technical Committee on Sugar (TCS), in a review of the prospects of southern Africa as a major sugar production region published in the annual SADC Sugar Digest (2014), made the observation that in this region, sugar consumption will grow faster than anywhere else in the world over the next 10-20 years. Further, southern Africa is poised to be a surplus sugar producer as a consequence of domestic and foreign direct investment in the industry (Bureau for Food and Agricultural Policy, 2014; OECD-FAO Agricultural Outlook, 2015; Hess *et al.*, 2016). These trends are most likely going to be driven by increases in local and global sugar demands, access to international markets by local cane growers and millers and by the increasing competitiveness of the southern African sugar industry. The cases assessed in this study appear to agree with these observations. Production and consumption patterns will, for the most part, drive sugarcane production in the present (2015-2020), at least in the Mngeni and Kilombero Catchments. However, it is unclear if this trend will persist in the near-future (2020-2050) and distant future (2050 and beyond).

Climate change and climate variability will undoubtedly affect the production of sugarcane by instigating changes to hydrological processes and fluxes such as rainfall, runoff, temperature, total evaporation and infiltration. Changes to these processes and fluxes in any direction can severely affect the growth of sugarcane and consequently the production of economically viable yields. For instance, sugarcane is particularly vulnerable to the African sugarcane stalk borer (*Eldana saccharina*) during periods of water stress (SASRI, 2013). The projected increases in hydroclimatic variability as a direct consequence of climate change in the region, imply that the frequency of droughts will likely increase in the near-future (Schulze *et al.*, 2005; IPCC, 2014a). This implies that sugarcane will become increasingly susceptible to the *Eldana* stalk borer owing to an increase in the frequency of dry conditions. This will necessitate increased irrigation of an already water use intensive crop. These observations were recognised in a few cases conducted in the Mngeni (n = 3) and the Ubombo (n = 2) Catchments. Despite the large investments in programmes designed to promote sugarcane production across all three catchments and across the region, climate change, as a direct biophysical stressor, will assume a much greater role in limiting the successful cultivation of this crop in the near-future.

Major collaborative research efforts have been initiated in southern Africa to manage, and adapt to, the inevitable impacts of climate change on key LUC activities, including sugarcane production. The most notable of these efforts include the Future Climate for Africa (FCFA) (<http://futureclimateafrica.org/what-fcfa-does/> Accessed June 2016, Future Climate for Africa, 2015) and the Drought Early Warning and Forecasting to Strengthen Preparedness and Adaptation in Africa (DEWFORA) project (<http://www.ecmwf.int/en/research/projects/dewfora>, Accessed July 2016).

3.8 Water Resources Impacts

The results of sugarcane water use (wu) as a function of mean annual production (P) in the 2013/2014 cycle across the study catchments are presented in **Table 3.7**. **Figure 3.8** indicates actual and projected yield trends based on the low, medium and high growth scenarios for the period 2013/14-2019/20 and the current and projected sugarcane water use trends correlated to annual production rates.

Under current conditions, representing the 2013/14 production cycle, observed raw sugarcane yields for the Mngeni Catchment were reported as 3 392 653 tonnes or 134 t.ha⁻¹.a⁻¹, with an associated water use (wu) estimate of 1 432 mm.a⁻¹. This estimate compares favourably with the findings of Bezuidenhout *et al.*, (2006) which placed the wu of sugarcane in this catchment at 1 468 mm.a⁻¹. This estimate compares favourably with the estimated mid-season, full canopy sugarcane peak wu of 1 723 mm as calculated using **Equation 3.1** and a Kc factor of 1.25.

In the Ubombo Catchment, where the current yield, for the same aforementioned production cycle, was reported as 1 303 750 tonnes or 119 t.ha⁻¹.a⁻¹, the estimated sugarcane wu was 1 271 mm.a⁻¹. This estimate was considered to be significantly different from the reference crop evaporation (ET_0) of 1 904 mm.a⁻¹ as reported by Schulze *et al.*, (1997). Further, using **Equation 3.1**, the estimated peak wu was calculated as 2 380 mm from a Kc factor of 1.25, a significant deviation from the wu reported in the current study. It is, however, crucial to note that these differences in wu estimates for the Ubombo Catchment reflect two critical aspects: 1) the ET_0 estimate presented by Schulze *et al.*, (1997) was an average for the entire country of Swaziland and does not reflect the actual hydroclimatic conditions of the Ubombo

Catchment, 2) by extension, since **Equation 3.1** relies on ET_0 estimates to derive ET_C or actual wu , it stands to reason that wu estimates calculated from *actual* observed sugarcane production will be different from estimates based on *average* ET_0 estimates.

The Kilombero Catchment managed an output of 1 200 000 tonnes in the 2013/2014 cycle translating to a production rate of $55.10 \text{ t.ha}^{-1}.\text{a}^{-1}$ and an estimated wu of 602 mm.a^{-1} . Similar to the Ubombo Catchment, this estimate was significantly different from the estimated peak wu of $1\ 875 \text{ mm}$ calculated using **Equation 3.1**. These differences between the wu estimates derived from **Equation 3.1** and **Equation 3.4** stem directly from the explicit assumption of ideal conditions as presupposed in ET_0 estimates. Such conditions are seldom observed in reality. It is therefore the opinion of the authors that the wu estimates reported in this study be considered to be closer to the actual sugarcane wu in the various catchments since these were based on actual sugarcane production yields.

Table 3.7 Average sugarcane water use (wu) and ET_C estimates as functions of mean annual production rates (P) and crop coefficients (K_C) respectively, for the 2013/14 production cycle, for the various catchments under study.

Catchment	MAP (mm)	ET_0 (mm.a^{-1})	ET_C (mm.a^{-1})	Crop Coefficient (K_C)	Mean Production ($P \text{ t.ha}^{-1}.\text{a}^{-1}$)	wu (mm.a^{-1})
Mngeni	918.18	1378.00	1722.50	1.25	134.10	1431.90
Ubombo	710.00	1904.00	2380.00	1.25	118.73	1270.60
Kilombero	1310.10	1500.00	1875.00	1.25	55.05	602.37

In **Figure 3.8(a)**, no appreciable increases in sugarcane yields were observed between the 2013/14 and the 2019/20 cycles owing to the negligible annual growth rate of 0.19% in the low production scenario. This scenario suggests a possible structural failure to effectively achieve the conditions detailed in the assumptions outlined in **Section 3.6.1**. Conversely, both the medium and high growth scenarios presuppose the marginal and absolute realization of these assumptions, respectively. Should the conditions of these assumptions come to

fruition, therefore, it is reasonable to expect the yield trends detailed in **Figure 3.8(b, c)** become a reality. This does not, however, necessarily imply a corresponding increase in *wu* as alluded to earlier.

The Mngeni and Ubombo Catchments consistently outperform the Kilombero Catchment in terms of total yield. This is despite the Ubombo Catchment using less land (10 981Ha) and the Mngeni using a similar proportion of land (25 300Ha) in comparison to the Kilombero (21 800Ha) to grow sugarcane. This is most likely due to the following factors:

- The majority of growers in the Mngeni and Ubombo are commercial farmers often with access to advanced irrigation and in-field mechanisation technologies,
- The Kilombero growers and millers (*i.e.* the KSCL Mill) produce sugarcane from smaller areas than those in the Ubombo and Mngeni Catchments,
- Access to irrigation is a challenge in the Kilombero Catchment,
- The Kilombero growers are limited by the physical geography of their catchment which limits their horizontal expansion (*i.e.* the Udzungwa Mountain Range), and
- Fewer sunshine hours (*i.e.* greater cloud cover) contribute to a lower sucrose content of sugarcane from the Kilombero Catchment and this negatively impacts the competitiveness of growers in the marketplace.

Despite these trends (**Figure 3.8**), it should be noted that increases in yield do not necessarily translate to increases in crop water use. As mentioned in **Section 3.5.2**, improvements in irrigation technology (TECH), development and adoption of improved varieties and better agronomic management (*e.g.* the Sustainable Sugarcane Farm Management System [SUSFARMS] in the Mngeni Catchment), can contribute to significant improvements in sugarcane water use efficiency. In this study, *wu* estimates were not adjusted to account for these possibilities. Sugarcane is well-recognised across all three catchments as a water resource intensive crop (*e.g.* sugarcane cultivation in the Ubombo Catchment is almost entirely irrigated) and various Best Management Practices (BMPs) are in place to minimize the environmental impact signature of this crop. It is therefore more likely that sugarcane water use will reflect an average of the projections indicated in the low and medium scenarios (**Figure 3.8a, b**) rather than the projections of the high scenario. An annual increase in water use in excess of 60%, as suggested by the high production scenario, cannot

be considered reasonable or sustainable in an already water-stressed environment. For instance, both the Mngeni and Ubombo Catchments are fast approaching their limits with regard to available renewable resources. The currently observed expansion and intensification of sugarcane production in these catchments implies that this activity will come under increased scrutiny, and this may lead to significant changes in the approaches to cultivating and managing this crop.

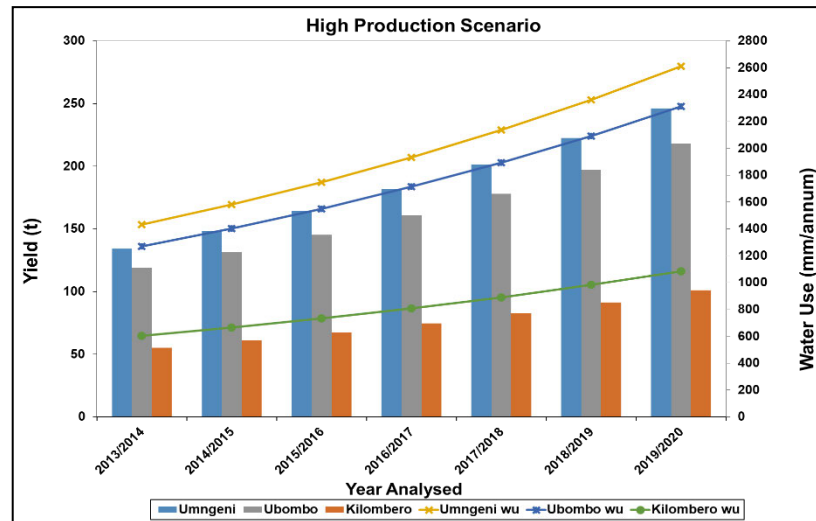
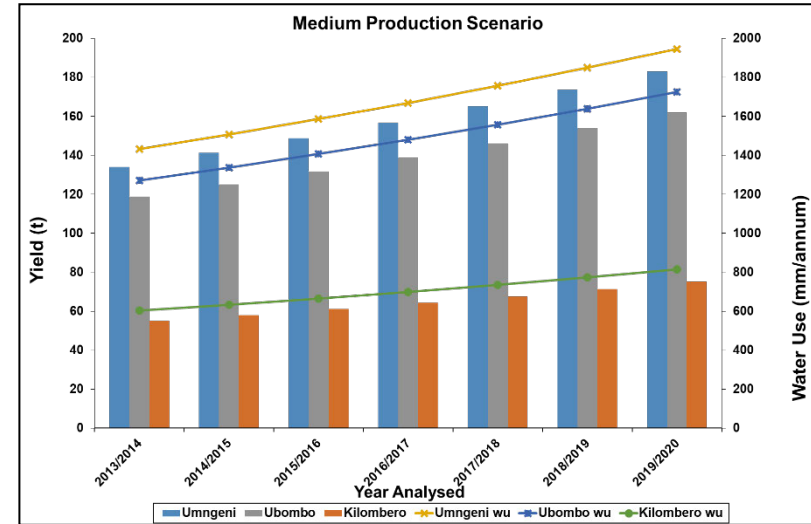
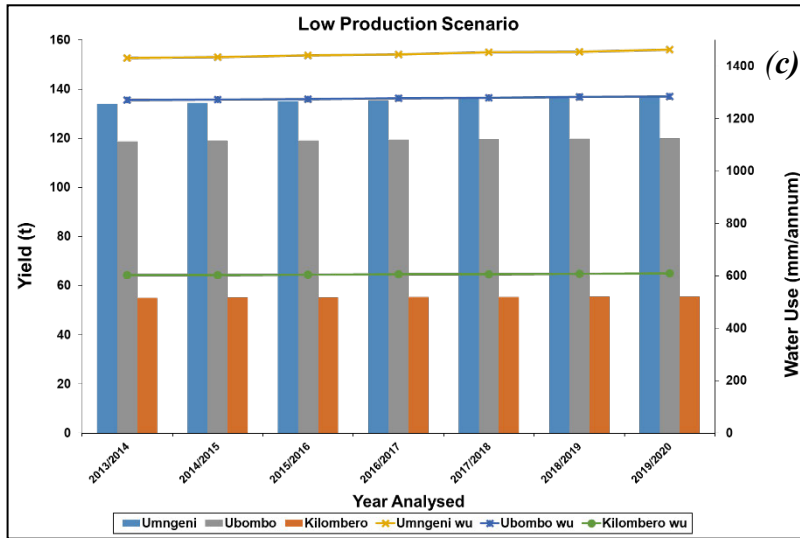


Figure 3.8 Actual and projected sugarcane yields (t) for the 2013/14-2019/20 cycles based on (a) low, (b) medium and (c) high production scenarios. Water use estimates (mm.a⁻¹) are reported in direct relation to the projected sugarcane production rates (based on Eq. 4 as postulated by Bezuidenhout *et al.*, 2006).

3.9 Conclusions

By most accounts, the intensification of sugarcane production across southern Africa is a certainty. This is owing to the region's strong socio-economic development agenda; an agenda is anticipated to witness investments being made in high-value commodity crops such as sugarcane. It is, however, apparent that the expansion of sugarcane production will incur significant costs, not only in terms of economic resources but also environmental resources, most notably water. This is a well-recognised observation and one which is critical to the successful implementation of major sugarcane production ventures in the region. Recognizing that water is a major limiting resource in sugarcane production can, and already is, driving the adoption of efficient irrigation technologies and progressive land and water resource management policies. This, *inter alia*, may assist in positioning southern Africa as a globally competitive sugar-producing region.

The primary aim of this paper was to provide qualified descriptions of proximate and ultimate drivers and outline the potential water resource impacts resulting from sugarcane cultivation in three specific catchments across southern Africa. The results of the frequency analysis of the current literature to assess trends in proximate and ultimate drivers, provided a strong indication of the actual drivers of sugarcane production in this region. From a complement of 87 case studies, it became apparent that for all three catchments, ultimate drivers such as foreign direct investment and increased sugar demand, owing to their intrinsic human dimension, assume a far greater role in influencing the expansion and intensification of sugarcane production in this region. This fact notwithstanding, proximate drivers such as land use change, which are often closely related to ultimate drivers, are more relevant with regard to impacts to water resources. This is because proximate drivers involve the direct alteration of the landscape which, by extension, changes hydrological processes and fluxes thus changing water resource responses.

The interactions between the various themes of drivers (AGEX, TECH, POL and ECD) was shown to display different strengths of the causal relationships at local and regional scales (**Figure 3.7**). As spatial scales change, the degree to which various drivers interact changes. This is a consequence of the evolution of connectivity patterns and cross-scale interactions, demonstrating the importance of ultimate drivers in determining LUC patterns. The decisions made at the local catchment scale can ultimately affect the regional dynamics of

sugarcane production. An example of this is the SUSFARMS initiative in the Mngeni Catchment. This initiative is designed to encourage sustainable sugarcane production by implementing industry-wide Best Management Practices. Owing to the success of this initiative, the Mngeni Catchment is arguably the most competitive and dominant sugar producing catchment when compared to both the Kilombero and the Ubombo Catchments. This is despite the enormous difficulties related to labour, policy and water resources management prevalent in this catchment. The following key lessons were drawn from this exercise:

- Sugarcane production in southern Africa is primarily driven by economic, political and demographic factors that directly prompt land expansion under sugarcane.
- Proximate drivers are important to consider as they directly impact the region's water resources by driving land use changes.
- The relative influence of ultimate and proximate drivers, changes as spatial scales change and this is determined by the political and socio-economic dynamics within each catchment.
- The risks posed by climate variability and change are well-recognized in the region and are, fortunately, increasingly being incorporated into policy and decision-making.

The use of sugarcane production scenarios to estimate water use indicated the potential water resources impacts that could occur should the various scenarios become a reality. The low and medium production scenarios were considered to provide the most realistic and probable indication of the potential water use of sugarcane in the three catchments over the next six years. The water use estimates in the high production scenario (>50% *wu* increase) were considered to be unrealistic in light of the current water resources limitations already being observed across the three catchments. The apparently linear correlation between sugarcane yield and sugarcane water use (**Figure 3.8**) may be true only to a certain degree. It is perhaps more likely that sugarcane water use will increase marginally and not necessarily maintain pace with yield increases owing to improvements in crop breeding, agronomic management and technological advancements. Although this study developed estimates of water use based on actual and projected sugarcane yields, the use of the same methodology to estimate future water use is subject to some limitations. The most obvious of these is that modelling

future hydrological responses requires long term historical data which can be used to verify and validate the veracity of models and thus provide more realistic projections of water use.

References

- Adger, NW. and Pulhin, J. (Editors). 2014. Human Security. In: Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
- Alcamo, J, Schaldach, R, Koch, J, Kolking, C, Lapola, D and Priess, J. 2011. Evaluation of an Integrated Land Use Change Model Including a Scenario Analysis of Land Use Change for Continental Africa. *Environmental Modelling and Software* 26(8):1017-1027. <https://doi.org/10.1016/j.envsoft.2011.03.002>
- Allen, RG, Pereira, LS, Raes, D and Smith, M. 1998. *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage Paper 56 (FAO56)*. United Nations Food and Agricultural Organization, Rome, Italy.
- Azevedo, JC, Perera, AH, and Pinto, MA. 2014. *Forest Landscape and Global Change: Challenges for Research and Management*. Springer, New York, United States.
- Bakker, H. 1999. *Sugar Cane Cultivation and Management*. Kluwer Academic/Plenum Publishers, New York.
- Bates, BC, Kundzewicz, ZW, Wu, S and Palutikof, JP. (Editors). 2008. *Climate Change and Water: IPCC Technical Paper IV*. Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva.
- Bezuidenhout, CN and Singels, A. 2007. Operational Forecasting of South African Sugarcane Production: Part 1-System Description. *Agricultural Systems* 92(1-3):23-38. <https://doi.org/10.1016/j.agsy.2006.02.001>
- Bezuidenhout, CN, Lecler, NL, Gers, C and Lyne, PWL. 2006. Estimates of Regional Scale Water Use for Sugarcane in South Africa. *Proceedings of the South African Sugar Technologies Association* 32(2):169-173. doi: 10.4314/wsa.v32i2.5245
- Bluman, AG. 2009. *Elementary Statistics: A Step by Step Approach*. 8th Edition. McGraw-Hill, New York, United States.
- Blöschl, G and Sivapalan, M.1995. Scale Issues in Hydrological Modelling: A Review. *Hydrological Processes* 9:251-290. <https://doi.org/10.1002/hyp.3360090305>
- Blöschl, G, Thybo, H and Savenije, H. 2015. *A Voyage Through Scales: The Earth System in Space and Time*. European Geosciences Union, Edition Lammerhuber, Baden, Austria.
- Brauman, KA, Daily, GC, Duarte, TK and Mooney, HA. 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annual Review of Environment and Resources* 32(1):1-32. <https://doi.org/10.1146/annurev.energy.32.031306.102758>
- Bureau for Food and Agricultural Policy (BFAP). 2014. BFAP Baseline Agricultural Outlook 2014-2023. BFAP, Pretoria, South Africa.
- Campbell DJ, an Olsen JM. 1991. Environment and development in Kenya: flying the kite in Kajiado District. *Centennial Reviews* 1991 (35):295-314. <https://doi.org/10.1007/s10584-017-2087-9>
- Carr, MKV and Knox, JW. 2011. The Water Relations and Irrigation Requirements of Sugar Cane (*Saccharum Officinarum*): A Review. *Experimental Agriculture* 1(47):1-25. <https://doi.org/10.1017/S0014479710000645>.

- Cheesman, OD. 2004. *Environmental Impacts of Sugar Production: The Cultivation and Processing of Sugarcane and Sugar Beet*. CABI Publishing, Wallingford, United Kingdom.
- Cherubin, MR, Franca, MLC, Cerria, CEP, da Silva Oliveiraa, DM, Davies, A, Cerric, CC. 2015. Sugarcane Expansion in Brazilian Tropical Soils—Effects of Land Use Change on Soil Chemical Attributes. *Agriculture, Ecosystems and Environment* 211:173-184. doi:10.1016/j.agee.2015.06.006.
- Conway, D, Archer van Garderen, E, Deryng, D, Dorling, S, Krueger, T, Landman, W, Lankford, B, Lebek, K, Osborn, T, Ringler, C, Thurlow, J, Zhu, T and Dalin, C. 2015. Climate and Southern Africa's Water-Energy-Food Nexus. *Nature Climate Change* 5(9):873-846. doi:10.1038/nclimate2735.
- Cubasch, U, D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Culverwell, TL, Proksch, L and Swartz, C. 1999. An extension pilot project to promote sustained irrigation scheduling of sugarcane crops by Umfolozi growers. *Proceedings of the Annual Congress – South African Sugar Technologists' Association* 73: 3–8.
- Daccache, A, Sataya, W and Knox, JW. 2015. Climate Change Impacts on Rain-Fed and Irrigated Rice Yield in Malawi. *International Journal of Agricultural Sustainability* 13(2):87-103. <https://doi.org/10.1080/14735903.2014.945317>
- De La Torre Ugarte, D and He, L. 2007. Is the Expansion of Biofuels at Odds with the Food Security of Developing Countries? *Biofuels, Bioproducts and Biorefining* 1:92-102. doi: 10.1002/bbb.16
- Deenanath, ED, Iyuke, S and Rumbold, K. 2011. The Bioethanol Industry in SubSaharan Africa: History, Challenges and Prospects. *Journal of Biomedicine and Biotechnology* 10:1-11. doi:10.1155/2012/416491.
- Deressa, T, Hassan, R and Poonyth, D. 2010. Measuring the Impact of Climate Change on South African Agriculture: The Case of Sugarcane Growing Regions. *Agrekon* 4(44):524-542. <https://doi.org/10.1080/03031853.2005.9523726>
- Desanker, P and Magadza, C. 2001. *Africa*. In: Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
- Dlamini, NS, Rowshon, MK, Makhanya, M and Sithole, S. 2014. The CDAA Framework for Development of Sustainable Large-Scale Smallholder Irrigation Schemes in Swaziland. *Agriculture and Agricultural Science Procedia* 2:386-393. <https://doi.org/10.1016/j.aaspro.2014.11.054>
- Dunkelberg, E, Finkbeiner, M and Hirschl, B. 2014. Sugarcane Ethanol Production in Malawi: Measures to Optimize the Carbon Footprint and to Avoid Indirect Emissions. *Biomass and Bioenergy* 71:37-45. <https://doi.org/10.1016/j.biombioe.2013.10.006>
- Eksteen, A, Singels, A and Ngxaliwe, S. 2014. Water Relations of Two Contrasting Sugarcane Genotypes. *Field Crops Research* 168:86-100. <https://doi.org/10.1016/j.fcr.2014.08.008>
- Ellis, RD, Wilson, JH and Spies, PM. 1985. Development of an irrigation policy to optimize sugar production during seasons of water shortage. *Proceedings of the South African Sugar Technologists' Association* 59:142–147.

- Esterhuizen, D. 2013. Swaziland Sugar Annual: A Report on Supply and Demand Trends for Sugar in Swaziland. USDA Foreign Agricultural Service, Swaziland.
- Fairtrade Foundation. 2013. *Fairtrade and Sugar: Commodity Briefing*. Fairtrade Foundation, London, United Kingdom.
- Funke, T. 2013. Impact of Proposed Electricity Tariffs on Sugarcane Growers in KZN. South African Canegrowers Association, Wartburg, South Africa.
- Future Climate for Africa. 2015. *Future Climate for Africa: Programme Rationale, Structure and Scientific Focus*. Climate and Development Knowledge Network, Salt River, Cape Town, South Africa.
- Gasparatos, A, von Maltitz, GP, Johnson, EX, Lee, L, Mathai, M, Oliveira, JA and Willis, KJ. 2015. Biofuels in Sub-Saharan Africa: Drivers, Impacts and Priority Policy Areas. *Renewable and Sustainable Energy Reviews* 46:879-901. <https://doi.org/10.1016/j.rser.2015.02.006>
- Geist, HJ and Lambin, EF. 2001. *What Drives Tropical Deforestation?* LUCR Report Series No. 4, Louvain-la-Neuve, Belgium.
- George, E. 2013. The Sugar Trade in Africa. Ecobank Research. Ecobank, Lome, Togo.
- Gleick, PH. 2000. The Changing Water Paradigm: A Look at Twenty-First Century Water Resources Development. *Water International* 25(1):127-138. <https://doi.org/10.1080/02508060008686804>
- Grey, D and Sadoff, CW. 2007. Sink or Swim? Water Security for Growth and Development. *Water Policy* 9(2007):545-571. doi: 10.2166/wp.2007.021
- Gunderson LM, Holling CS. 2001. *Panarchy: Understanding Transformations in Systems of Humans and Nature*. Island Press, 2001: 21.
- Haley, S. 2015. Projecting World Raw Sugar Prices. United States Department of Agriculture. A report from the Economic Research Service. USDA.
- HarvestChoice. 2015. <http://www.harvestchoice.org/maps/sugar-cane-area-harvested-ha-2000.html>
- Hassan, R, Scholes, R, and Ash, N (Eds.) 2005. Ecosystems and Human Well-Being: Current State and Trends, Volume 1. *Millennium Ecosystem Assessment*. Island Press, Washington DC, United States.
- Hess, TM, Sumberg, J, Biggs, T, Georgescu, M, Haro-Montegudo, D, Jewitt, G, Odzogan, M, Marshall, M, Thenkabail, P, Daccache, A, Marin, F and Knox, JW. 2016. A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change*. 39:181-194. doi:10.1016/j.gloenvcha.2016.05.003
- Hewitson, B., Tadross, M. and Jack, C. 2005. Climate Change Scenarios: Conceptual Foundations, Large Scale Forcing, Uncertainty and the Climate Context. In: Schulze, R.E. (Ed) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 2, 21 - 38.
- Hoff, H, Gerten, D and Waha, K. 2012. Green and Blue Water in Africa: How Foreign Direct Investment Can Support Sustainable Intensification. In: Allan, T, Keulertz, Sojamo, S and Warner, J (Editors). *Handbook of Land and Water Grabs in Africa*. 2013. Routledge International Handbooks, Oxon, United Kingdom.
- Illovo Sugar. 2014. Swaziland Socio-Economic Impact Assessment: Internal Management Report. Corporate Citizenship, London, United Kingdom.
- Inman-Bamber, NG and McGlinchey, MG. 2003. Crop Coefficients and Water-Use Estimates for Sugarcane Based on Long-Term Bowen Ratio Energy Balance Measurements. *Field Crops Research* 83(2):125-138. [https://doi.org/10.1016/S0378-4290\(03\)00069-8](https://doi.org/10.1016/S0378-4290(03)00069-8)

- Inman-Bamber, NG and Smith, DM. 2005. Water Relations in Sugarcane and Response to Water Deficits. *Field Crops Research* 92(2-3):188-202. <https://doi.org/10.1016/j.fcr.2005.01.023>
- Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
- Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
- Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge, United Kingdom.
- International Council for Science (ICSU). 2011. *Future Earth Initial Design*. ICSU, Paris.
- International Food Policy Research Institute (IFPRI). 2014. *Global Nutrition Report: Actions and Accountability to Accelerate the World's Progress on Nutrition*. IFPRI, Washington, DC, United States.
- International Sugar Organization. 2010. World Sugar Demand: Outlook to 2020. ISO Study –MECAS (10)17. Milecourt Limited, London, United Kingdom.
- Jewitt, G and Kunz, R. 2011. The Impact of Biofuel Feedstock Production on Water Resources: A Developing Country Perspective. *Biofuels, Bioproducts and Biorefining* 5:387-398. <https://doi.org/10.1002/bbb.314>
- Jones, MR, Singels, A and Ruane, AC. 2015. Simulated Impacts of Climate Change on Water Use and Yield of Irrigated Sugarcane in South Africa. *Agricultural Systems* 139:260-270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Knox, JW, Diaz, JA, Nixon, DJ and Mkhwanazi, M. 2010. A Preliminary Assessment of Climate Change Impacts on Sugarcane in Swaziland. *Agricultural System* 103(2):63-72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Kumar, P. 2011. Typology of hydrologic predictability. *Water Resources Research* (47): 1-9. doi:10.1029/2010WR009769.
- Licht, FO. 2015. World Sugar Outlook. *International Sugar Journal* 2015.
- Loarie, SR, Lobell, DB, Asner, GP, Mu, Q and Field, CB. 2011. Direct Impacts on Local Climate of Sugar-Cane Expansion in Brazil. *Nature: Climate Change* 1(2011):105-109.
- Magwenzi, OE. 2000. Evaluation of irrigation efficiency in the Swaziland sugar industry. *Proceedings of the Annual Congress – South African Sugar Technologists' Association* 74:151–156.
- Magwenzi, OE. 2002. Development of a decision support tool for assessing economics of irrigation in sugarcane. *Proceedings of the Annual Congress – South African Sugar Technologists' Association* 76(2002):135–146.
- Mark, M and Luckson, M. 2010. The Relationship Between Satellite Derived and Ground Measured Sugar Cane Water Use: The Case of Hippo Valley Estimates in Zimbabwe. *Journal of Sustainable Development in Africa* 12(8):191-216.
- Mashoko, L, Mbohwa, C and Thomas, VM. 2013. Life Cycle Inventory of Electricity Cogeneration from Bagasse in the South African Sugar Industry. *Journal of Cleaner Production* 39:42-49. <https://doi.org/10.1016/j.jclepro.2012.08.034>
- Mathews, JA. 2008. Opinion: Is Growing Biofuels Crops a Crime Against Humanity? *Biofuels, Bioproducts and Biorefining* 2(97):97-99. <https://doi.org/10.1002/bbb.59>
- Meiyappan, P, Dalton, M, O'Neill, BC, Jain, AK. 2014. Spatial Modelling of Agricultural Land Use Change at Global Scale. *Ecological Modelling* 291:152-174. <https://doi.org/10.1016/j.ecolmodel.2014.07.027>

- Msimanga, B and Sebitosi, AB. 2014. South Africa's Non-Policy Driven Options for Renewable Energy Development. *Renewable Energy* 69:420-427. <https://doi.org/10.1016/j.renene.2014.03.041>
- Mulenge, G. 2013. *Developing Economic Corridors in Africa: Rationale for the Participation of the African Development Bank*. African Development Bank Group, Tunis, Tunisia.
- Naidoo, D. 2014. The Global Hunger Crisis-Water as a Route to Nutritional Security. Editorial. *The Water Wheel March/April 2014*. Volume 13 No. 2.
- New Partnership for Africa's Development (NEPAD). 2013. *Comprehensive Africa Agriculture Development Programme (CAADP)*. NEPAD, Midrand, South Africa.
- Ngcobo, S, Jewitt, GPW, Stuart-Hill, SI and Warburton, ML. 2013. Impacts of Global Change on Southern African Water Resources Systems. *Current Opinion in Environmental Sustainability* 5(6):655-666. <https://doi.org/10.1016/j.cosust.2013.10.002>
- Nyberg, J. 2010. Sugar: International Market Profile. Background Paper for the Competitive Commercial Agriculture in Sub-Saharan Africa. United Nations Food and Agricultural Organization, New York, United States.
- Olivier, FC and Singels, A. 2015. Increasing Water Use Efficiency of Irrigated Sugarcane Production in South African through Better Agronomic Practices. *Field Crops Research* 176:87-98. <https://doi.org/10.1016/j.fcr.2015.02.010>
- Organization for Economic Cooperation and Development-Food Agricultural Organization. 2011. *Chapter 6: Sugar*. In: OECD-FAO Agricultural Outlook 2011-2020. United Nations FAO, New York, United States of America.
- Pretty, J, Toulmin, C and Williams, S. 2011. Sustainable Intensification in African Agriculture. *International Journal of Agricultural Sustainability* 9(1):5-24. <https://doi.org/10.3763/ijas.2010.0583>
- Republic of South Africa Department of Agriculture, Forestry and Fisheries (DAFF). 2011. *A Profile of the South African Sugar Market Value Chain*. DAFF, Directorate Marketing, Arcadia, South Africa.
- Republic of South Africa Department of Minerals and Energy (DME). 2007. *Biofuels Industrial Strategy*. Department of Minerals and Energy, Government Printer, Pretoria, South Africa.
- Republic of South Africa Department of Trade and Industry (DTI). 2011. *Good Management Practices Manual for the Cane Sugar Industry*. PGBI Sugar and Bioenergy, Johannesburg, South Africa.
- Republic of South Africa Department of Water Affairs. 2013. *National Water Resources Strategy: Water for an Equitable and Sustainable Future*. Department of Water Affairs, Pretoria, South Africa.
- Schulze, RE. 199. *South African Atlas of Agrohydrology and Climatology*. Water Research Commission. Report TT82/9. Pretoria, South Africa.
- Schulze, RE and Schutte, S. 2015. Local and Accumulated Downstream Impacts of Dryland Sugarcane on Streamflows In Three South African Catchments: Can A Case Be Made for Sugarcane to Become A 'Stream Flow Reduction Activity'? *Proceedings of the South African Sugar Technologists' Association* 88:70-89.
- Schulze, RE, Lumsden, T, Horan, M, Warburton, M and Maharaj, M. 2005. An Assessment of Impacts of Climate Change on Agrohydrological Responses over South Africa. In: Schulze, RE (Ed). 2005. *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission. WRC Report 1430/1/05. Pretoria, RSA.

- Singels, A, Ferrer, S, Leslie, GW, McFarlane, SA, Sithole, P and Van Der Laam, M. 2011. Review of South African Sugarcane Production in the 2010/2011 Season From An Agricultural Perspective. *Proceedings of the South African Sugar Technologists' Association* 84:66-83.
- Siyao, PO. 2012. Barriers in Accessing Agricultural Information in Tanzania with a Gender Perspective: The Case Study of Small-Scale Sugar Cane Growers in Kilombero District. *EJISDC* (51):1-19.
- Smalley, R, Sulle, E and Malale, L. 2014. Opportunities and Challenges in Tanzania's Sugar Industry: Lessons for SACGOT and the New Alliance. *PLAAS Policy Brief* 76:1-12.
- Smithers, J. 2014. Review of Sugarcane Trash Recovery Systems for Energy Cogeneration in South Africa. *Renewable and Sustainable Energy Reviews* 32: 915-925. <https://doi.org/10.1016/j.rser.2014.01.042>
- South African Development Community (SADC). 2012. Regional Infrastructure Development Master Plan. SADC House, Gaborone, Botswana.
- South African Sugar Association. 2010. 10 Things You Never Knew About the South African Sugarcane Association. SASA, Mount Edgecombe, South Africa.
- South African Sugar Millers Association Limited. 2006. *Sugar*. South African Sugar Association, Mount Edgecombe, South Africa.
- South African Sugarcane Research Institute (SASRI). 2013. *Progress Report: 2013*. SASRI, Mount Edgecombe, Durban, South Africa.
- Southern African Development Community (SADC). 2014. *Sugar Digest: Your Guide to the Sugar Industry*. Media Matters Publishing, Prestondale, South Africa.
- Steffen W, Sanderson A, Tyson PD, Jager J, Matson PA, Moore B III, Oldfield F, Richardson K, Schellnhuber HJ, Turner BL II, Wasson RJ (Eds). 2005. *Global Change and the Earth System: A Planet Under Pressure*. Springer, Berlin, Germany.
- Stuart-Hill, SI and Schulze, RE. 2010. Does South Africa's Water Law and Policy Allow for Climate Change Adaptation. *Climate and Development* 2:128-144. <https://doi.org/10.3763/cdev.2010.0035>
- Swart, B. 2014. Water Use Efficiency of Commercial Sugarcane Production in Mpumalanga. Unpublished Study.
- Tanzania Sugar. 2013. *Tanzanian Sugarcane Yields Lower Than Elsewhere in East Africa*. Rabobank Industry Note #386, Rabobank International, Utrecht, the Netherlands.
- Tarimo, AJP and Takamura, YT. 1998. Sugarcane Production, Processing and Marketing in Tanzania. *African Study Monographs* 19(1):1-11
- Thompson, GD. 1976. Water Use by Sugar-Cane. *South African Sugar Journal* 60(11):627-635.
- Turton, A. 2008. Three Strategic Water Quality Challenges that Decision Makers Need to Know About and How the CSIR Should Respond. CSIR Report No. CSIR/NRE/WR/EXP/2008/0160/A. Council for Scientific and Industrial Research, Pretoria, South Africa.
- Turton, A. 2010. *New Thinking on the Governance of Water and River Basins in Africa: Lessons from the SADC Region*. South African Institute of International Affairs, Johannesburg, South Africa.
- Tyler, G. 2010. The African Sugar Industry - A Frustrated Success Story. Background Paper for the Competitive Commercial Agriculture in Sub-Saharan Africa. United Nations Food and Agricultural Organization, New York, United States.
- United Nations Food and Agricultural Organisation. 2015. AQUASTAT Main Database. <http://fao.org/nr/water/aquastat/data/query/index.html>. Accessed: March 2015.
- United Nations Population Division. 2014. *The Millennium Development Goals Report*. United Nations, New York, United States.

- Van der Walt, L, Cilliers, SS, Kellner, K, du Toit, MJ and Tongway, D. 2015. To What Extent Does Urbanisation Affect Fragmented Grassland Functioning? *Journal of Environmental Management* 151(2015):517-530. <https://doi.org/10.1016/j.jenvman.2014.11.034>
- Van Eekelen, MW, Bastianssen, WGM, Jarman, C, Jackson, B, Ferreira, F, Van Der Zaag, P, Okello-Saraiva, A, Bosch, J, Dye, P, Bastidas-Obando, E, Dost, RJJ and Luxemburg, WMJ. 2015. A novel approach to estimate direct and indirect water withdrawals from satellite measurements: a case study from the Incomati basin. *Agriculture, Ecosystems and Environment* 200:126-142. <https://doi.org/10.1016/j.agee.2014.10.023>
- Verburg, PH, Mertz, O, Erb, K, Haberl, H and Wu, W. 2013. Land System Change and Food Security: Towards Multi-Scale Land System Solutions. *Current Opinion in Environmental Sustainability* 5(5):494-502. <https://doi.org/10.1016/j.cosust.2013.07.003>
- Wagener, T, Sivapalan, M, Troch, PA, McGlynn, BL, Harman, CJ, Gupta, HV, Kumar, P, Rao, SC, Basu, NB and Wilson, JS. 2010. The Future of Hydrology: An Evolving Science for a Changing World. *Water Resources Research* 46:1-10. <https://doi.org/10.1029/2009WR008906>
- Walker, B and Salt, D. 2006. *Resilience Thinking*. Island Press, Washington, DC, United States of America.
- Warburton, ML, Schulze, RE and Jewitt, GPW. 2012. Hydrological Impacts of Land Use Change in Three Diverse South African Catchments. *Journal of Hydrology* 415:118-135. <https://doi.org/10.1016/j.jhydrol.2011.10.028>
- Watson, HK. 2011. Potential to Expand Sustainable Bioenergy from Sugarcane in Southern Africa. *Energy Policy* 39(10):5746-5750. <https://doi.org/10.1016/j.enpol.2010.07.035>
- Wood, C. 2013. The Southern African Sugar Sector. PERISA Case Study. SAIIA, South Africa.
- You, L, Ringler, C, Wood-Sichra, U, Robertson, R, Wood, S, Zhu, T, Nelson, G, Guo, Z and Sun. 2011. What is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach. *Food Policy* 36(6):770-782. <https://doi.org/10.1016/j.foodpol.2011.09.001>
- Zinyengere, N, Crespo, O and Hachigonta, S. 2013. Crop Response to Climate Change in Southern Africa: A Comprehensive Review. *Global and Planetary Change* 111:118-126. <https://doi.org/10.1016/j.gloplacha.2013.08.010>
- Zuurbier P and Van de Vooren J (2008). Introduction to Sugarcane Ethanol Contributions to Climate Change Mitigation and the Environment. In Zuurbier P and Van deVooren (Eds): *Sugarcane ethanol – Contributions to climate change mitigation and the environment*. Wageningen Academic Publishers, Wageningen, the Netherlands.

CHAPTER FOUR
A YIELD GAP ANALYSIS TO ASSESS VULNERABILITY OF
COMMERCIAL SUGARCANE TO CLIMATIC EXTREMES IN SOUTHERN
AFRICA*

Ngcobo, S.I.^{1*}, Jewitt, G^{2,3}, Hill, T.R⁴, Archer, E⁵.

¹ 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.

² Department Water Resources and Ecosystems, IHE Delft Institute for Water Education, PO Box 3015, 2601DA Delft, The Netherlands.

³ Water Management, Civil Engineering & Geosciences, TU Delft, PO Box 5048, 2600 GA Delft, The Netherlands.

⁴ Discipline of Geography, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg Campus, King Edward Avenue, Scottsville, Pietermaritzburg, 3209, South Africa.

⁵ Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Hatfield 0028, South Africa.

* *Corresponding author.*

E-mail address: ngcobos21@ukzn.ac.za (S. Ngcobo)

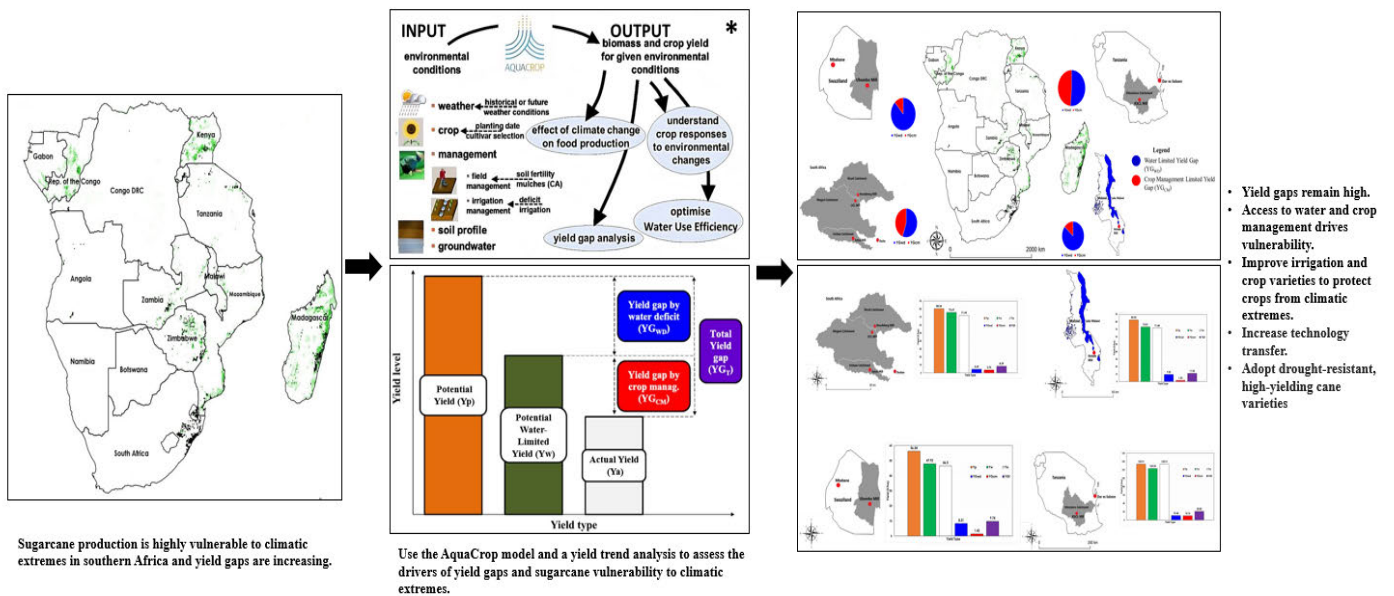
* Referencing adheres to the format of *Journal of Agriculture and Food Research*.

Highlights

- The research assesses the vulnerability of sugarcane production to climatic extremes through analysis of yield declines, and by performing a yield gap analysis.
- Using a combination of the AquaCrop crop model and observed growing cycle yields, maximum potential yields and yield gaps were simulated based on observed climate and yield data spanning 25 years.
- Yield gaps remain high across all mill areas, and sugarcane production remains vulnerable to climatic extremes.
- Access to water resources will be increasingly stressed under climate change, and sugarcane production will be under increased pressure to maintain and/or increase yields.
- It is critical that outgrowers and commercial growers increase technology transfer amongst themselves, adopt innovative and proactive agronomic management approaches and adopt drought-resistant, high-yielding cane varieties.

Graphical Abstract

The following graphical abstract summarises the research content of this article.



**Image of examples of practical AquaCrop applications sourced from Vanuytrecht et al., (2014). All other images were produced by the authors.

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 minimising 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.

Keywords: Yield Decline, Yield Gaps, Sugarcane Production, AquaCrop, Southern Africa, Water Deficit, Crop Management.

4.1 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 (Deressa et al., 2005; Hess et al., 2016; German et al., 2020), but also constitutes a significant proportion of the biofuels industry (Jewitt & Kunz, 2011; Hiloidhari et al., 2021) which, if widely adopted, could contribute to the reduction of greenhouse gas emissions across the region (Oosterveer & Mol, 2010; de Fátima Rodrigues de Souza et al., 2018). 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 (World Bank, 2019; Mudombi et al., 2021). 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 (Dlamini, 2021).

In addition to its contribution to the economies of the region, the sugarcane industry assumes a vital role in education and training (Ngcobo & Jewitt, 2017), agronomic research (Richardson, 2009; Zulu et al., 2019), science and technology and in ensuring environmental sustainability (Sulle & Dancer, 2020). 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, export markets and consumers (**Figure 4.1**) (Koo et al., 2020). 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 (Knox et al., 2010a; Jones et al., 2015b). This exposure is already undermining yields by increasing water deficits (Jones et al., 2019; Dias & Sentelhas, 2021), and by forcing changes in crop management which can threaten the long-term sustainability of the sugar industry in the region (Biggs et al., 2013).

Sugarcane is a perennial C₄ carbon-fixing perennial plant that is grown across a variety of hydroclimatic zones in southern Africa (Carr & Knox, 2011). It is usually cultivated over a period of 18 to 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 (Bezuidenhout & Singels, 2007; Stokes et al., 2016). Typically, sugarcane requires an average of 1 800 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 (Inman-Bamber et al., 2008; Singels et al., 2019). Continuous access to nutrients and the absence of pests and disease are primary factors that limit the successful cultivation of sugarcane (Gasparatos et al., 2021), 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 (Chinsinga, 2017; Fundira & Henley, 2017).

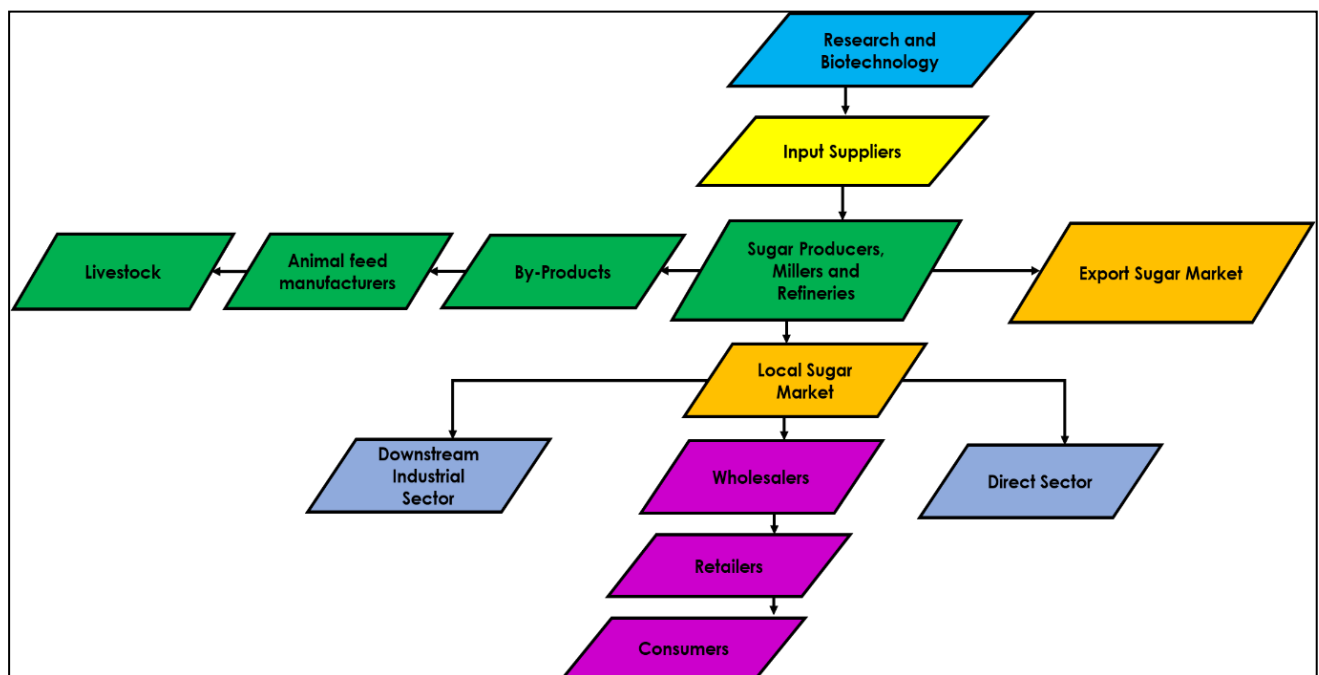


Figure 4.1 A typical southern African sugarcane production value chain (Modified from: (Booyesen et al., 2017 ; Harvest-Choice, 2019).

An estimated 785 000 Ha is under sugarcane across southern Africa (Harvest-Choice, 2019), 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 (Carr & Knox, 2011; Watson, 2011). As a consequence of these increases in water deficits, yields in the countries have correspondingly declined over the past 25 years (Jones et al., 2015; SADC Sugar Digest, 2019). There is considerable debate regarding these declines in yields, with some scholars suggesting water deficits as the main cause (Inman-Bamber et al., 2016), while others cite sub-optimum crop management driven by intensive monocropping (Olivier & Singels, 2015; Dias & Sentelhas, 2021) or suggesting a combination of nutrient management, variety selection and soil health

(Singels et al., 2021). 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 (Carrer et al., 2022; Dias & Sentelhas, 2018a; Marin et al., 2019; Raut & Bhagat, 2021; Yang et al., 2022). 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 (Knox et al., 2010a) but also to management-related factors that are currently transforming the global sugar industry (Oliveira et al., 2022). 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 (Knox et al., 2010a; Hennessy et al., 2022). By altering rainfall and temperature regimes, climatic changes projected for this region (IPCC, 2022) have the potential to significantly undercut yields and, as demonstrated by the drought of 2014-2017, devastate livelihoods (Bahta, 2022). 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 (Dias & Sentelhas, 2018b; Zu et al., 2018; Christina et al., 2021; Gasparotto et al., 2022), 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 (Olivier & Singels, 2015; Adetoro et al., 2020), combined with climatic conditions conducive to sugarcane production over the past 25 years (Jones et al., 2019), 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 (Dubb, 2015) and *Sporisorium scitamineum* or sugarcane smut (Devnarain et al., 2010; Potgieter et al.,

2013; Cockburn et al., 2014). 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 (Tweddle et al., 2021). 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 (Mhlanga et al., 2006; Knox et al., 2010b). 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 (Watson, 2011). Finally, in Malawi, government involvement in the sugar industry has led to yield declines by prioritising access to water resources for tea growers at the expense of sugarcane growers (Chinsinga, 2017; Kasambala Donga & Eklo, 2018; Adams et al., 2019). 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.

4.2 Study Sites

The Yield Gap (YG) analysis was conducted at the 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 (**Figure 4.2**) and catchment information are summarised (**Table 4.1**). 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 4.1**). 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 (Y_a), *simulated* maximum potential yields (Y_p) and water-limited yields (Y_w) represent the yield gaps (YG) for each mill (see **Figure 4.3**). The yields gaps were used to isolate the effects of water deficits and agronomic management from those of climatic extremes (Dias & Sentelhas, 2018b; Jones et al., 2015a; van den Berg & Singels, 2013; Zu et al., 2018)

4.3 Methods

4.3.1 Introduction

Yield gaps can be determined from field experiments, average annual yields as reported by mills or through crop simulation models. 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 (SA Canegrowers Association, 2018; Swaziland Sugar Association, 2018; Kasinthula Canegrowers Association, 2015; Illovo Sugar Africa, 2018; Illovo Malawi, 2018; Rabobank International, 2013; The Sugar Engineers, 2018). The justification for this approach rests on the fact that crop simulation models such as DSSAT/CANEGRO (Jones & Singels, 2018), APSIM-Sugarcane (Keating et al., 2003), and AquaCrop (Steduto et al., 2009; Raes et al., 2009; Raes et al., 2012; Vanuytrecht et al., 2014), have shown good performance when simulating sugarcane yields in the selected study catchments (van den Berg & Singels, 2013). 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 4.1**). 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 Jones & Singels (2018) and Dias & Sentelhas (2018b), crop simulation models provide the optimum 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.

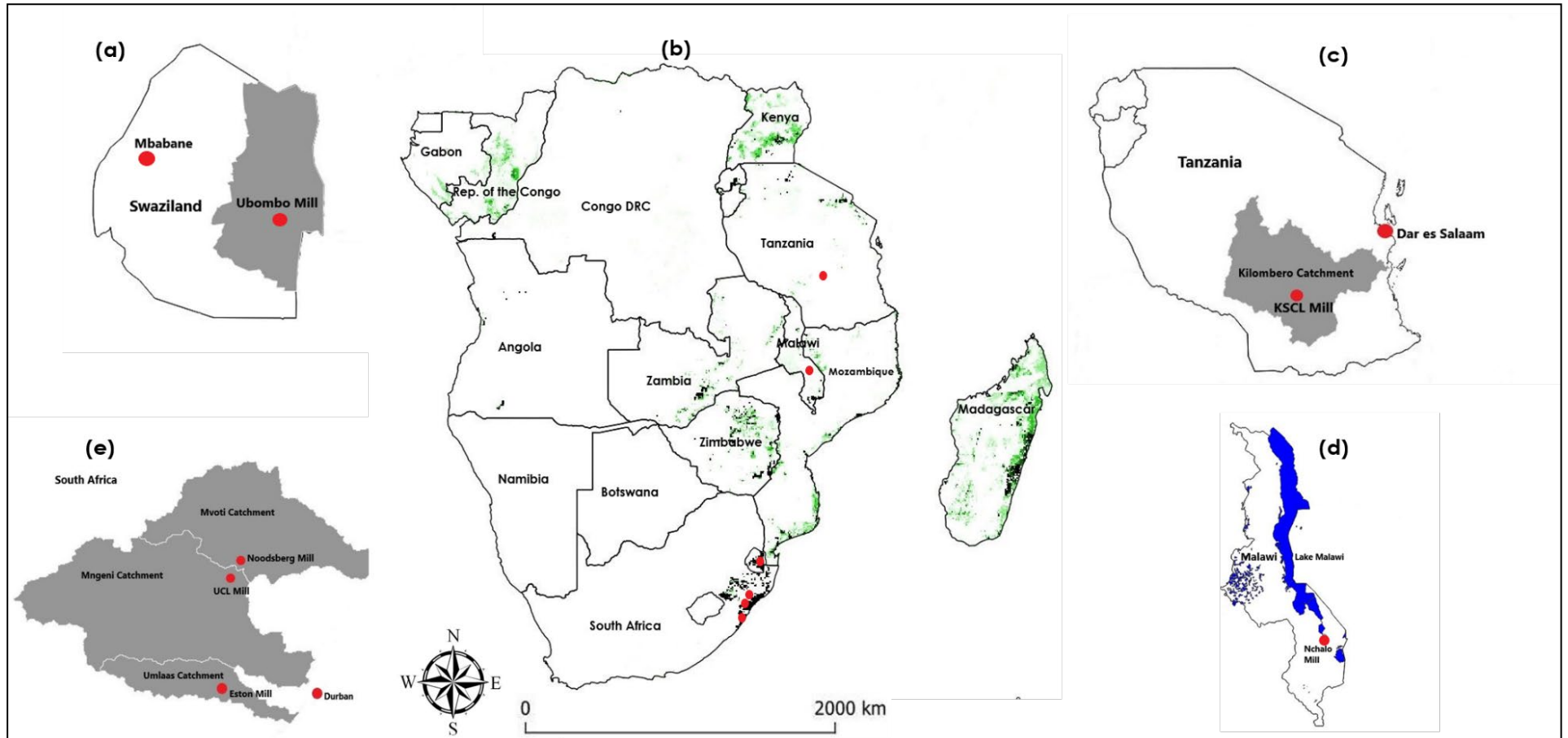


Figure 4.2 Mill locations within individual catchments and the spatial extent of the area under sugarcane across the region (Harvest-Choice, 2019). Clockwise from top-left: **a)** the Ubombo Catchment in Swaziland, **b)** The approximate spatial distribution of sugarcane production areas across southern African based on modelled data (Harvest-Choice, 2019), **c)** the Kilombero Catchment in Tanzania. **d)** the Shire Catchment in Malawi and **e)** the Mvoti, Umlaas and Mngeni Catchments in South Africa.

Table 4.1 Information on sugarcane mills and parent catchments (Sources: SA Canegrowers Association, 2018; Swaziland Sugar Association, 2018; Kasinthula Canegrowers Association, 2015; Illovo Sugar Africa, 2018; Illovo Malawi, 2018; The Sugar Engineers, 2018).

Mill	Catchment	MAP (mm/annum)	Production System	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) (TNZ)	Kilombero	1223	Irrigated and Rainfed	21 800	1 200 000	113	Ratooning	12

4.3.2 Yield Gap Analysis

Conducting a YG analysis requires information related to the following yield types: potential yield (Y_p), potential water-limited yield (Y_w) and observed long-term yield (Y_a) per growing cycle (Fischer, 2015; Jones & Singels, 2018) (**Figure 4.3**). 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 (Y_p 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.
2. Potential water-limited yield (Y_w 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 (Y_a in $t. ha^{-1}$) is the actual growing cycle and is reported as an accumulated annual value by the individual mills.

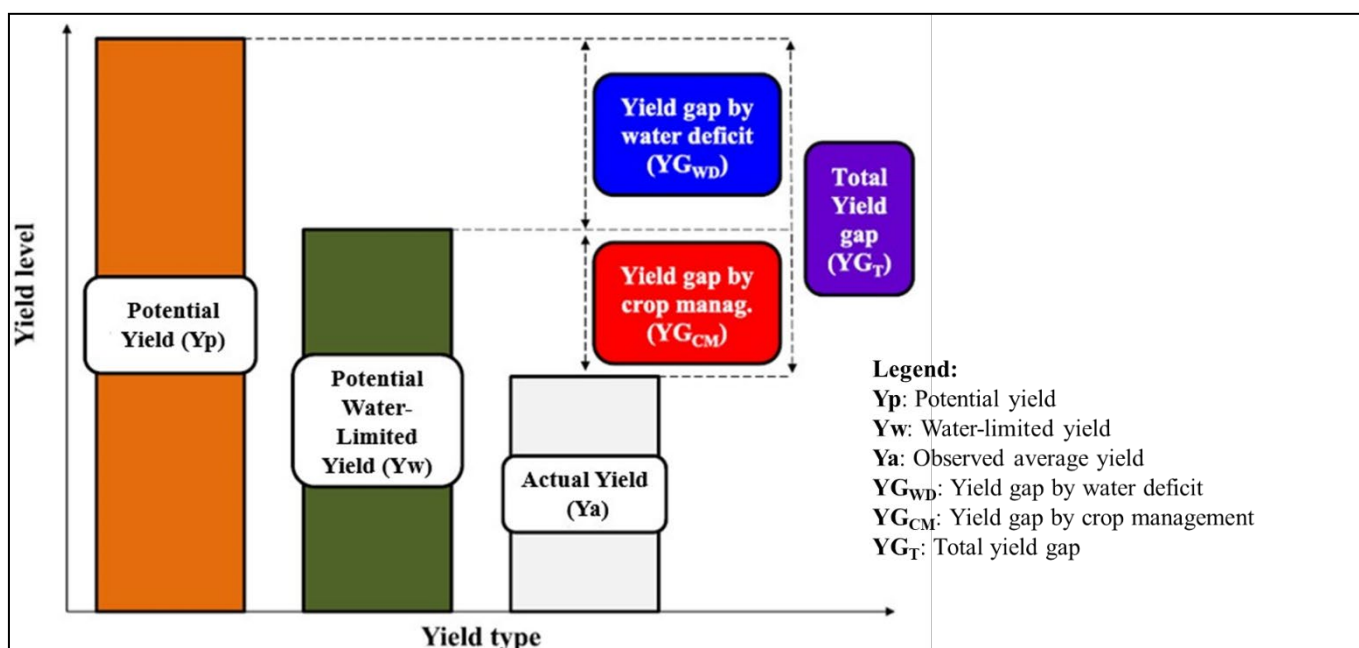


Figure 4.3 A conceptual framework describing the yield gap analysis and its components (Modified from: Dias & Sentelhas, 2018b).

The difference between Y_p and Y_w results in the YG caused by water deficit or $Y_{G_{WD}}$, while the difference between Y_w and Y_a results in the YG caused by crop management or $Y_{G_{CM}}$ (**Figure 4.3**). The sum of $Y_{G_{WD}}$ and $Y_{G_{CM}}$ yields the total yield gap or Y_{G_T} . This study was concerned with assessing $Y_{G_{WD}}$, $Y_{G_{CM}}$ and Y_{G_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 4.2**). These analyses were performed only for years where observed yields (Y_a) 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 year 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 Y_a . The KSCL and Nchalo mills, were missing nine and eight years of Y_a records, respectively (**Table 4.2**). This limitation was recorded in the modelling study and considered in the interpretation of the results. Regardless, several authors (*e.g.*, Bezuidenhout and Singels, 2007; van Ittersum *et al.*, 2013; Fischer *et al.*, 2015) recommend a minimum of 15 years of Y_a 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 Y_a 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 Y_{G_T} , $Y_{G_{WD}}$ and $Y_{G_{CM}}$ 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 12km 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.

4.3.3 Input Data Acquisition and Processing

Observed average annual yield (Y_a) 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 4.2**). 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 Y_a 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 validation.

Where necessary, the records were checked for errors using data profiling, identifying outliers, double-mass plots, and by using the ACRU-based Time Series Analysis (Schulze, 1995) tool to identify and correct errors. Following the quality control exercises, the records were robust enough for use in the crop yield modelling exercise. Missing daily climate data were infilled using data from weather stations closest to the mills and from other additional sources (**Table 4.2**). 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. These default values can be changed in the model as and when data becomes available. The AquaCrop model was used to generate ET_0 data from observed temperature records using the ET_0 calculator embedded within the model which is based on the FAO Penman-Monteith equation (Allen et al., 2006). 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 (Bezuidenhout & Singels, 2007). The results were a continuous set of daily and monthly climate records ranging from 1994 to 2019 for each mill area.

Table 4.2 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
Noodsberg	Mngeni (SA)	1994-2019	25	-	-	https://sasri.sasa.org.za/weatherweb_legacy/ 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/
Big Bend	Ubombo (SWA)	1996-2019	23	1994 and 1995	Ya data reliability	https://climateknowledgeportal.worldbank.org/download-data
Nchalo	Shire (MAL)	2000-2019	19	1994 and 1999	Climate and Ya data reliability	https://www.csag.uct.ac.za/climate-services/cip/ https://cip.csag.uct.ac.za/webclient2/app/
Kilombero Sugar Company (KSCL)	Kilombero (TNZ)	2000-2019	19	1994 and 1999	Climate and Ya data reliability	https://texasclimate.tamu.edu/research/data/index.html https://ihesp.github.io/archive/products/ds_archive/Datasets.html#regional-datasets https://gpm.nasa.gov/data

The remaining datasets, including soils and management data, were based on Best Management Practices for sugarcane production as suggested by researchers (e.g. Baez-Gonzalez et al., 2017; Singels, Donaldson, et al., 2005; Marin et al., 2019) and the USDA and the FAO-AGRIS databases.

4.3.4 Model Description

Developed by the Food and Agriculture Organization of the United Nations, AquaCrop is a crop growth model that simulates maximum potential yields as a function of total evaporation (Steduto et al., 2009; Raes et al., 2009; Raes et al., 2012; UN-FAO, 2018). It is a water-driven daily and monthly-time step, climate-driven crop simulation model (Steduto et al., 2009; UN-FAO, 2018) (**Figure 4.4**). The model simulates crop, soil, and available water interactions under different management practices (Ahmadi et al., 2022, 2022; Wellens et al., 2022), and predicts sugarcane growth, phenology, water management, potential and actual yield under various climatic regimes (Alvar-Beltrán et al., 2021). The model was selected due to its relative ease of use, accuracy, robustness and demonstrated reliability in simulating sugarcane yields (Rahimi Jamnani et al., 2022). The model has a relatively simple conceptual structure and requires few input parameters (Kelly & Foster, 2021). AquaCrop simulates four major parameters which govern crop yields: total evaporation, daily crop transpiration, crop water productivity and above-ground biomass (Alvar-Beltrán et al., 2021). The product of above-ground biomass and the harvest index (*HI*) resulted in potential yield (Y_p) for sugarcane assuming no climatic, agronomic or water-related limitations. The model was run in calendar days spanning the length of the growing cycle in the mill areas as opposed to growing degree days which only consider heat units required by the crop to reach senescence. The AquaCrop model uses local climate data to simulate daily crop growth and development and simulates crop responses to water stress using four coefficients, *viz*, canopy expansion, stomatal control, canopy senescence and harvest index (**Table 4.3**). Depending on the degree, duration and timing of water stress, the harvest index can be adjusted to improve biomass simulations and ultimately, yields. Owing to its relative simplicity, the AquaCrop model has been applied by hydrologists, environmental engineers, agricultural extension officers, governments and NGOs for a range of applications, including irrigation planning, climate change impact studies, crop yield projections, YG analyses and in water use efficiency assessments (Babel et al., 2018; Zu et al., 2018; Silva et al., 2017a; Rosa et al., 2019; Hadebe et al., 2020; Mubvuma et al., 2021).

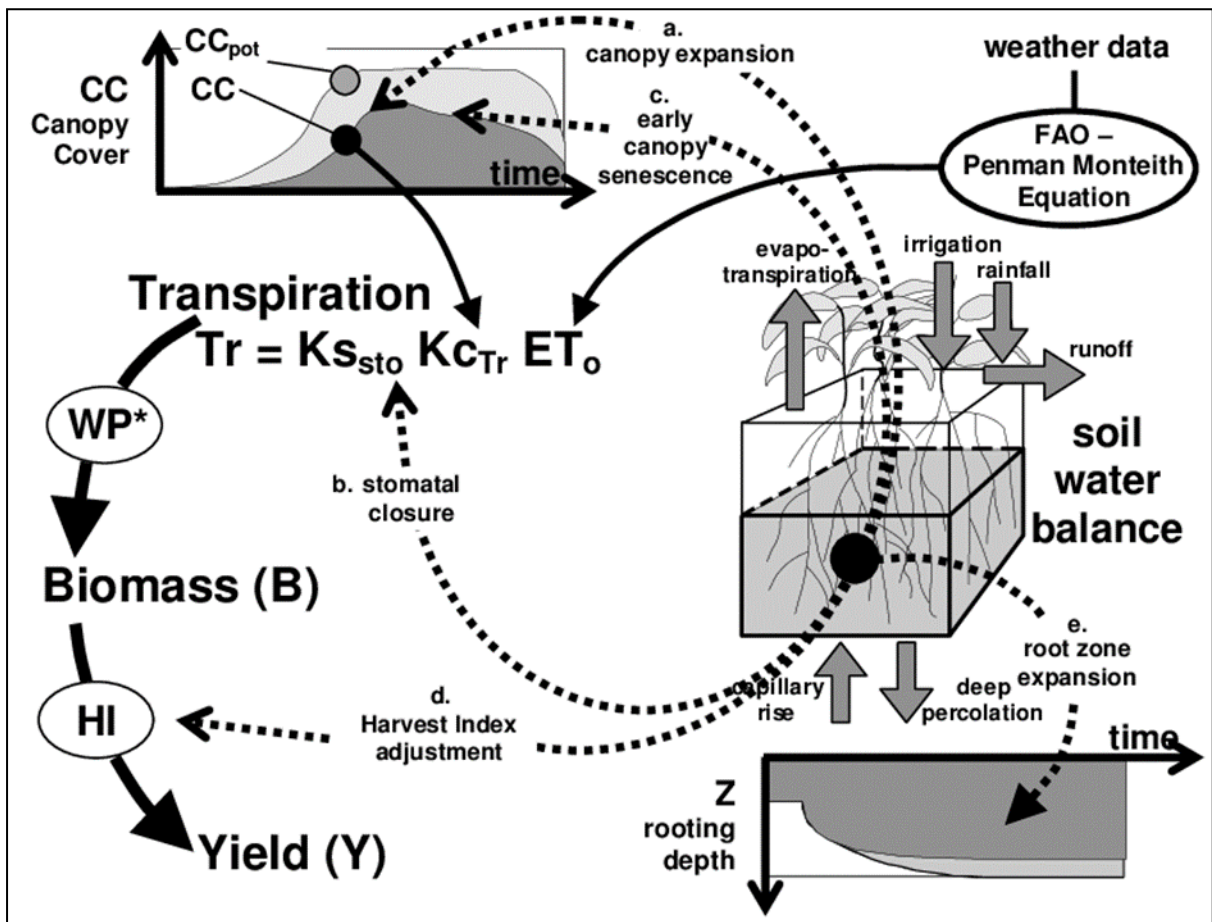


Figure 4.4 The AquaCrop calculation scheme indicating the various processes (indicated by the dotted lines) that are directly affected by water stress (Steduto et al., 2009; Raes et al., 2009; Raes et al., 2012; UN-FAO, 2018).

The model has been calibrated and verified in a number of studies conducted in Brazil for soybean and wheat (Silva et al., 2017a; Rosa et al., 2019), southern China for sugarcane (Zu et al., 2018), India for sugarcane (M. Babel et al., 2018) and in South Africa for sorghum and sugarcane (Hadebe et al., 2020; Mubvuma et al., 2021). In these geographically diverse studies, the model provided a sufficient level of accuracy 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 (Silva et al., 2017a; Singels et al., 2019). This ensures that a clear distinction can be made between yields obtained from rainfed, irrigated and mills which use a combination of both approaches.

4.3.5 Model Inputs

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 observed *or* derived 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 Y_p , Y_w and $Y_{G_{WD}}$ and $Y_{G_{CM}}$. This section describes the modules within the AquaCrop model, file setup and the procedures which were followed to simulate sugarcane yields (**Figure 4.5**).

4.3.6 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 CO₂ 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 non-conservative (*i.e.*, parameters that require adjustment for individual mill areas), and these are described in the following section and summarised in **Table 4.3**.

4.3.7 AquaCrop File Setup and Simulation Procedures

Since this study was conducted at mill area level and not at the scale of individual sugarcane estates or outgrower farms, the input files used observed data that best represented the mill area in question. It would have been impractical to use input data from each sugarcane estate as this would be beyond the scale objectives of the study and the data it would not be possible to

independently verify or quality control the data. Therefore, average observed data from each mill area was used as input. The actual input and menu files have been made available in Appendix A.

The AquaCrop model requires daily observed rainfall, minimum and maximum temperature, ET_O and atmospheric CO_2 concentration as inputs. The climate (CLI) module was set up for individual mill areas with the exception of the Noodsberg and UCL mills, which (as mentioned previously) were treated as a single mill owing to their proclivity to operate as one mill. The Eston, Noodberg and UCL mills in South Africa used observed climate data from various sources which are summarised in **Table 4.2**. Similarly, the Big Bend, Nchalo and KSCL mill areas also used observed climate data collected from various sources and a single climate file was created using data from these sources. While observed ET_O was not consistently available for all mill areas apart for limited periods from South Africa and eSwatini, it was estimated using the ET_O calculator embedded within the model for all mill areas. Default mean annual atmospheric CO_2 concentrations measured from Manua Loa Observatory were used as input and were not adjusted in the modelling exercise. The actual CLI files used as input in the model for individual mill areas have been included in Appendix A, **Table 4A.1**.

Due to the scale at which the study was conducted i.e., mill area level, observed soils data (SOL) at mill area level was not directly available due to the variation in soil types across individual sugarcane production estates and outgrowers. However, soils data such as saturated hydraulic conductivity, volumetric water content, field capacity, permanent wilting points and data on soil horizons were based on indicative values provided by AquaCrop and from locally determined and published data (*e.g.* Allen et al., 1998; Singels et al., 2003; Steduto et al., 2009; Raes et al., 2009; Raes et al., 2012; UN-FAO, 2018). The soils module was thus set up using both published and locally derived data already embedded as default within the model. The non-conservative parameters were kept constant for the duration of the simulation periods. The SOL files used as input are included in the Appendix, **Table 4A.1**.

Since the study was conducted at mill area level, default non-location specific but sugarcane-specific crop (CRO), field management (MAN) and irrigation management (IRR) values were used as input to initialize the module. The non-conservative parameters within these modules, i.e., CRO, MAN and IRR, were subsequently fine-tuned to best reflect the management philosophies of sugarcane production as observed within the mill areas. Specifically, the

modules were adjusted to reflect as closely as possible the current approaches of sugarcane production in South Africa, eSwatini, Malawi and Tanzania. Each mill area has its own philosophy regarding cultivar types, field management (ratooning vs. direct sowing) and production systems (irrigation vs. rainfed). The parameters were, therefore, adjusted within AquaCrop to reflect as far as possible the current methodologies being adopted within mill areas to maximize sugarcane yields. The actual CRO, MAN, IRR files including the actual input values are detailed in the Appendix, **Table 4A.1**.

Once input files were correctly formatted, the data quality controlled and reliable records of sufficient length established for each mill area, they were used as input into the model.

Table 4.3 Non-conservative parameters adjusted in the AquaCrop to simulate yields*.

Parameter	Unit
Crop Water Productivity (WP)	g. m ⁻²
Rainfall (RFL)	mm
Temperature (TMP)	°C
ET ₀	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
Water stress coefficient	Dimensionless
Irrigation Management	Return to Field Capacity

***Appendix A includes the actual values used in the crop files as input in 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 1.00m and plant spacings of 0.05m (Mubvuma et al., 2021; Singels, Donaldson, et al., 2005). 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 UN-FAO (2018) and Singels (2003). 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 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_0 stress, soil salinity and fertility stress. Non-conservative coefficients related to ET_0 , 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 six mill areas. As mentioned before, the actual input values including the full set of menu files for non-conservative parameters for all mill areas are indicated in the Appendix, **Table 4A.1**.

It is crucial to note that each mill area was simulated individually, and the actual data files used as input into AquaCrop are summarised in **Table 4A.1**. This table also presents, in full, the actual non-conservative parameters used for each mill area to generate the results presented in this study.

4.3.8 Yield Estimation

The AquaCrop model simulates maximum potential yields (Y_p) 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:

$$B = WP \times \sum_{i=0}^n \left(\frac{T_r}{ET_O} \right) \quad (\text{Eq. 4.1})$$

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 model estimates maximum potential yields from the product of above-ground biomass and the harvest index using Equation 4.2:

$$Y_p = HI \times B \quad (\text{Eq. 4.2})$$

where:

Y_p is the potential yield ($\text{t}\cdot\text{ha}^{-1}$) 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 ($\text{t}\cdot\text{ha}^{-1}$). 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 (Y_w) is the yield that would be achieved provided the crop is not affected by access to water from rainfall, irrigation and soil moisture. Y_w was simulated by specifying no water stress, regardless of prevailing rainfall and irrigation conditions. Y_{GWD} and Y_{GCM} were not simulated directly in the model. Y_{GWD} was calculated as the difference between Y_p and Y (*i.e.* $Y_p - Y_w$) and Y_{GCM} was calculated from the difference between Y_w and Y_a (*i.e.* $Y_w - Y_a$).

4.3.9 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 selected 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 (**Figure 4.5** and **Figure 4.6**), 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 (Y_a), simulated (Y_p) yields and total yield gaps (Y_{GT}) are as two-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 a RMSE of 0.88, a R^2 of 0.96 and a MAPE of 5.74. Mill areas in the Ubombo catchment reported a RMSE of 0.98, a R^2 of 0.61 and a MAPE of 14.76. In this regard, the AquaCrop model was adequate for simulating sugarcane yields in the remainder of selected catchments.

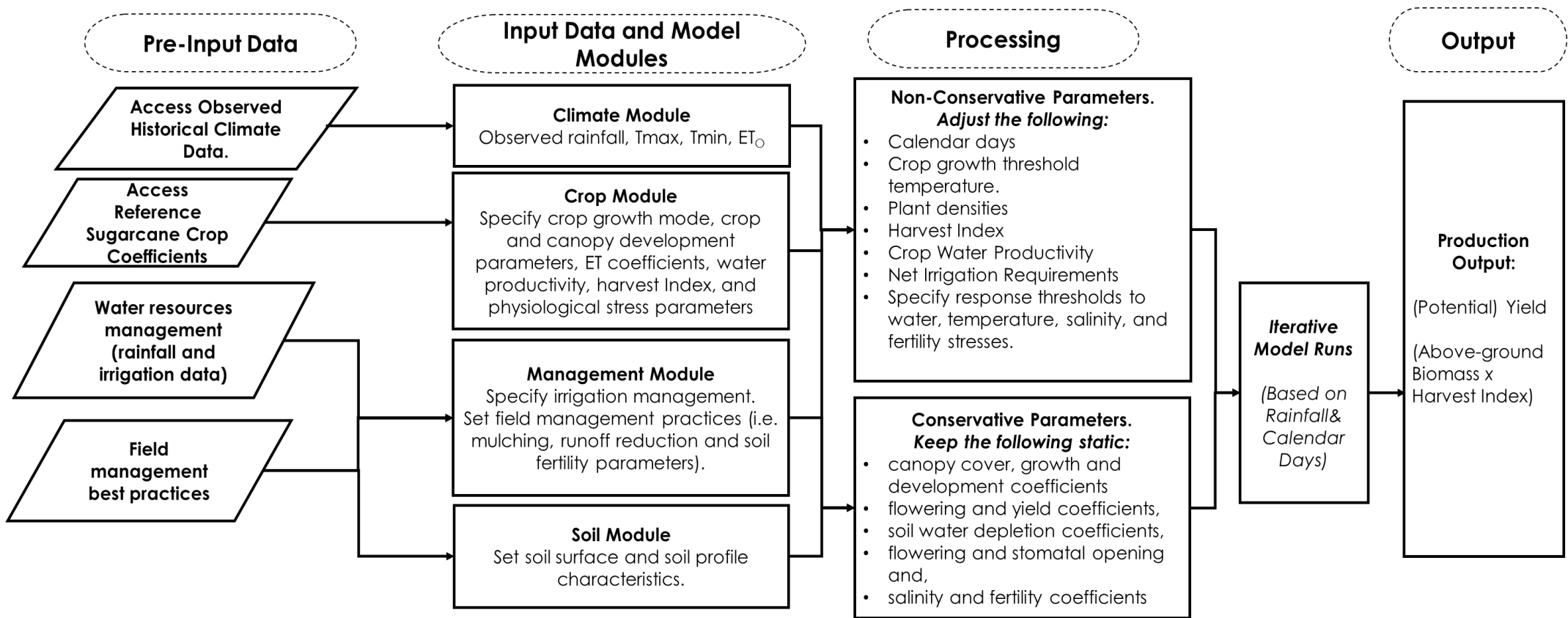


Figure 4.5 A summary of the modelling procedures in the AquaCrop model adopted in this study to determine yield gaps.

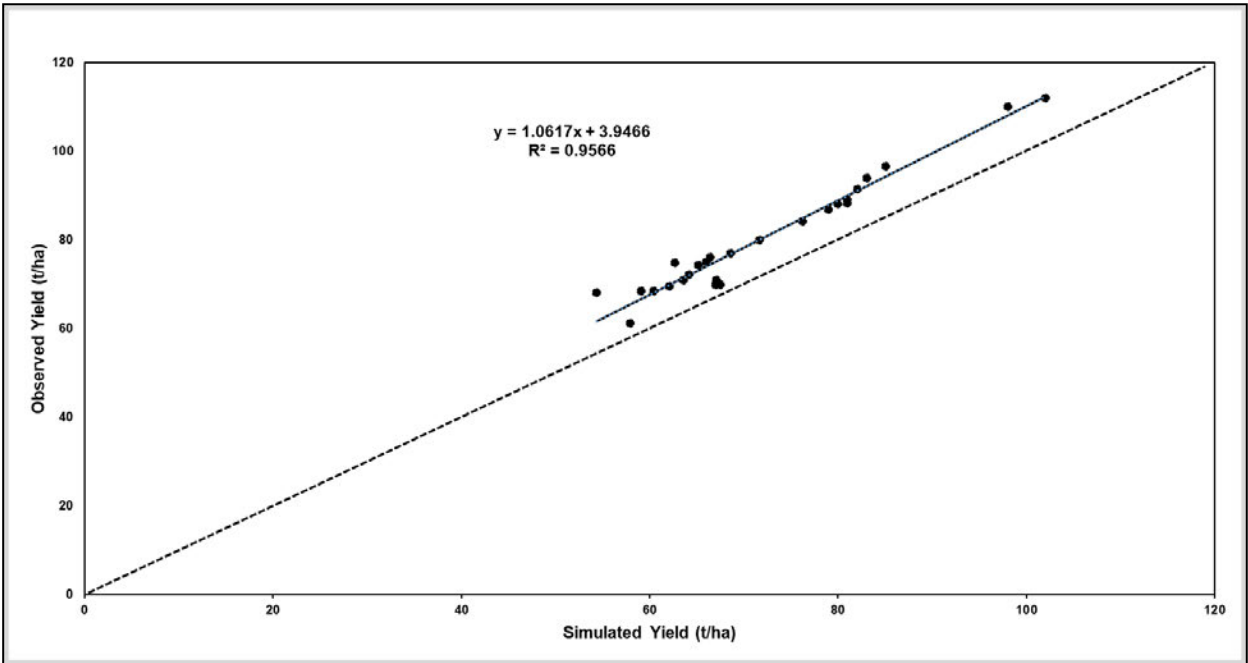


Figure 4.6 AquaCrop verification results based on average (*i.e.* combined) observed (Y_a) and simulated (Y_p) sugarcane yield data for the mill areas in South Africa.

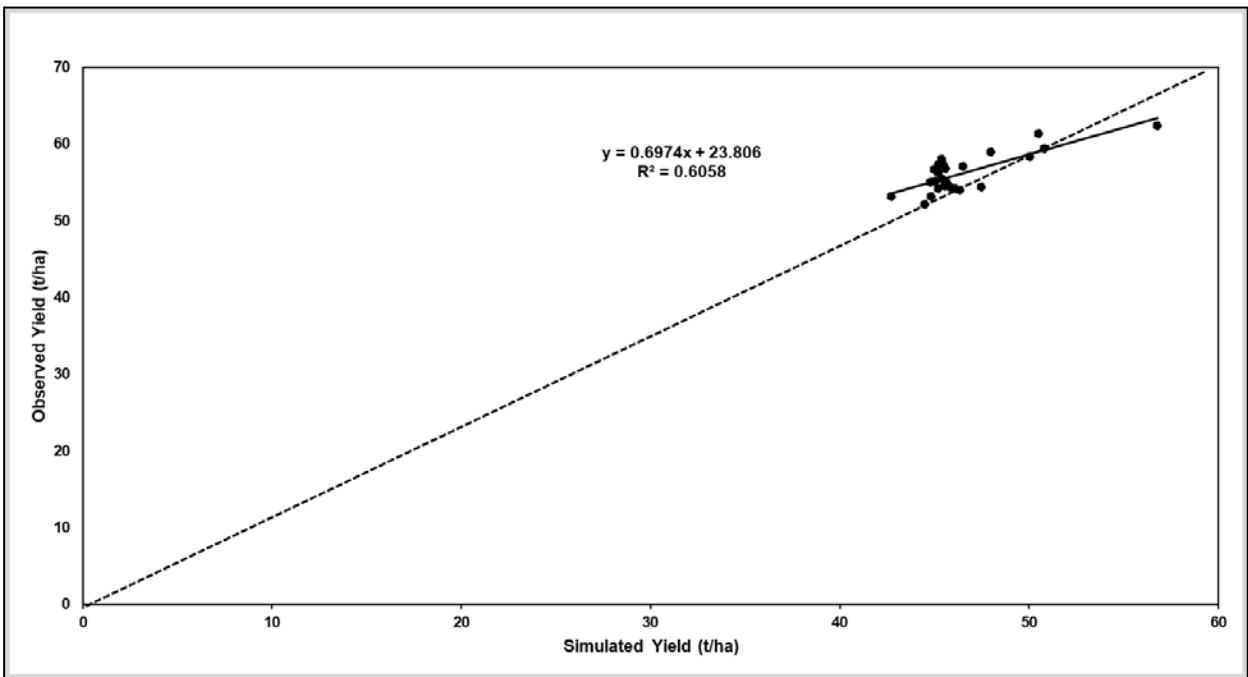


Figure 4.7 AquaCrop verification results based on observed (Y_a) and simulated (Y_p) sugarcane yield data for the Big Bend mill area in the Ubombo catchment.

4.4 Results and Discussion

4.4.1 Sugarcane Yield Trends and Yield Gaps

The average Y_a simulated by AquaCrop for mills in South Africa, the Ubombo Catchment, the Shire Catchment and the Kilombero Catchment were, respectively, 71.95t/ha, 46.50t/ha, 71.48t/ha and 113.09t/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 two-year moving average to provide comparable annual yields. In the irrigated Big Bend mill area in the Ubombo catchment, Y_a 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 Y_a trend during the 2005-2015 period was considered to be cause 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 Y_a by the mill or, potentially, the diversion of harvested sugarcane to nearby mills for processing. In any case, Y_p in this mill area was consistently higher than Y_a by at least 10% per annum. This was because no limitations regarding crop growth parameters were invoked for this 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 Y_p relative to Y_a , Ubombo had the lowest average Y_p of all the mill areas in the study. This, again, was attributed to widespread irrigation and the use of the drought-tolerant N41 and N26 varieties which, in part, prevented yield declines and kept yields fairly constant (Illovo Sugar, 2018) (**Figure 4.8a**). The implication of the constant Y_p 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 Y_{GT} for this mill area averaged 9.83t/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 (Y_p) 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 (**Figure 4.8b**). This suggests that, despite the reported increases in Y_a , 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. Y_{GT} 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 (Adams et al., 2019; Dal Belo Leite et al., 2020). 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 Y_p 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 (**Figure 4.9a**). Y_a and Y_p for these mill areas averaged 71.95t/ha and 80.34t/ha respectively for the period under study. The relatively high average Y_p 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 (Van den Berg and Singels, 2013). Further, these high Y_p 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 Y_a for the 2000-2006 period and minor, yet consistent Y_a declines over the 2007-2019 period (**Figure 4.9b**). 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. Y_a and Y_p were estimated at 71.48t/ha and 82.53t/ha respectively. The

implication is that growers in this catchment can 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. Y_{GT} was increasing for the 2001-2007 period but had since been steadily declining for the 2007-2019 period.

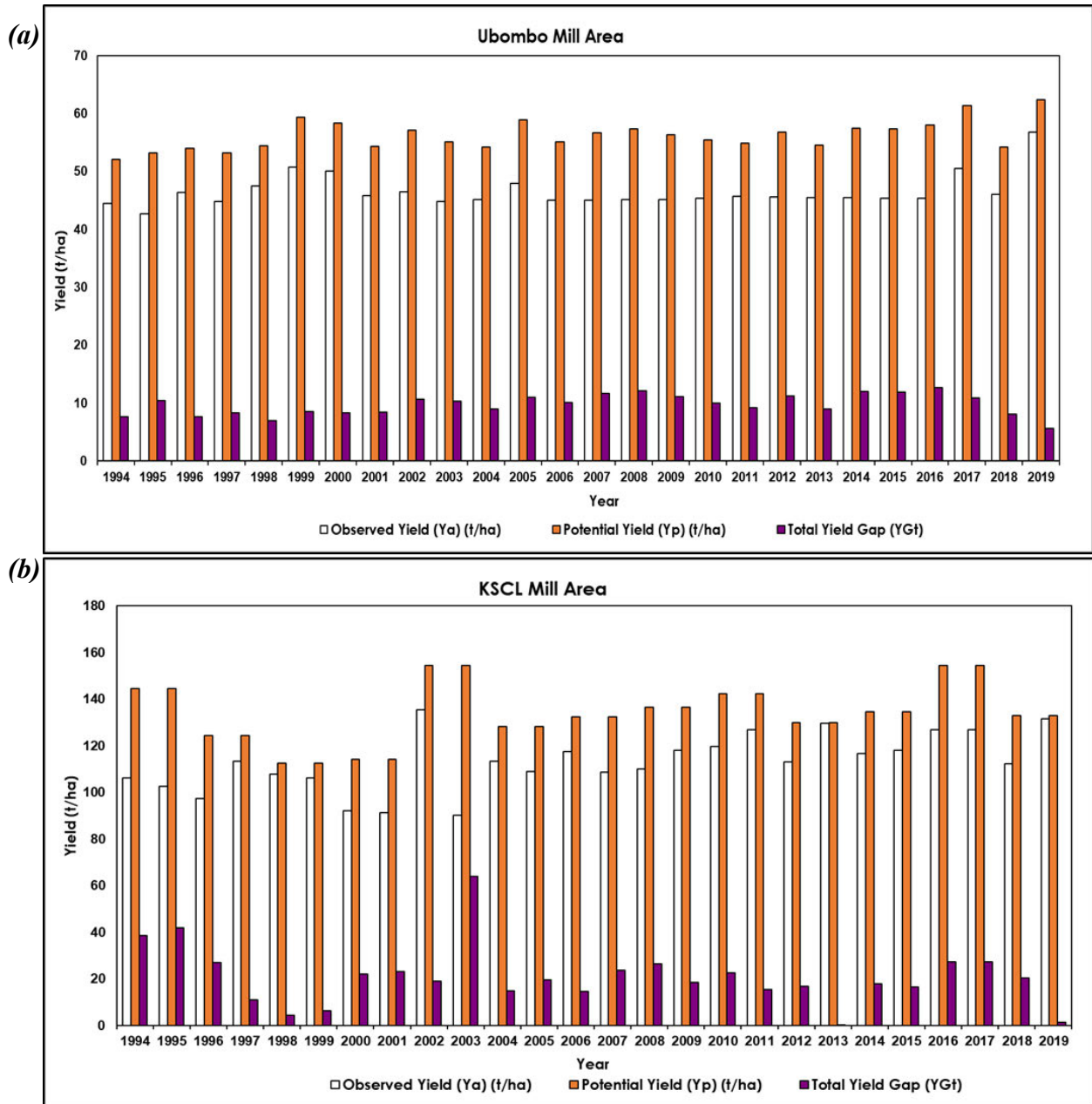
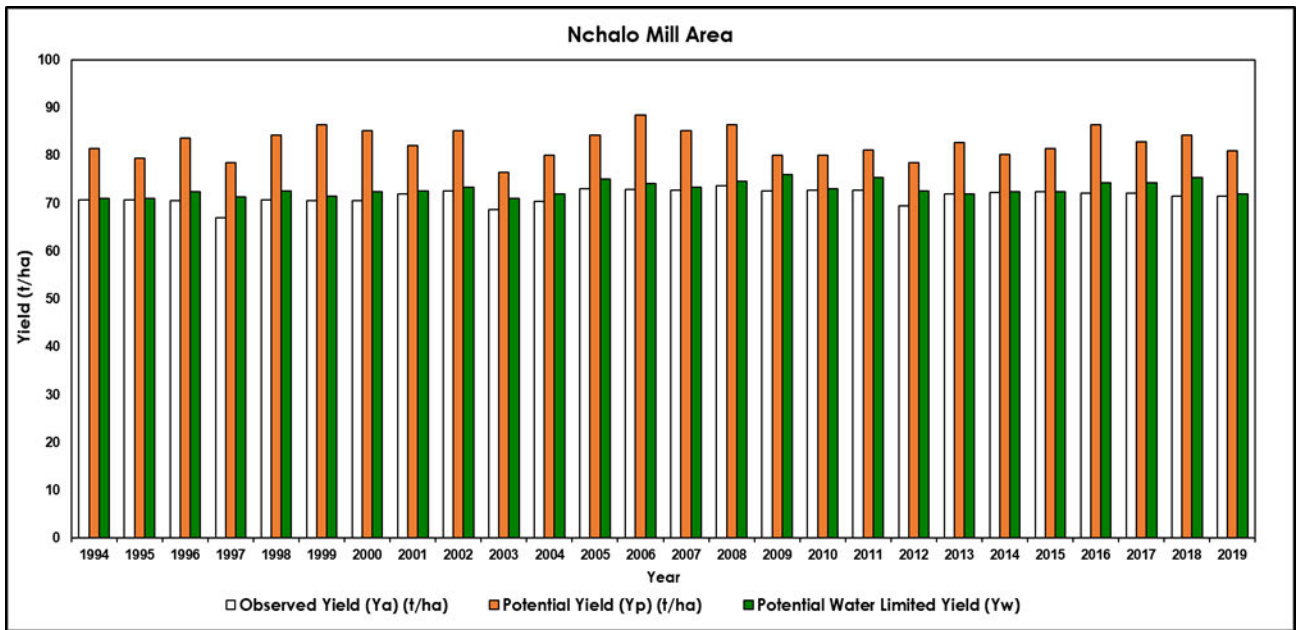


Figure 4.8 (a) Observed (Y_a) and simulated (Y_p) yield for the irrigated Big Bend mill in the Ubombo catchment and (b) the KSCL mill area in the Kilombero catchment. The total yield gaps (Y_{GT}) per year are reported here indicating, on average, an increase in yield gaps over the 1996-2015 period and a subsequent decrease in yield gaps from 2016-2019.

(a)



(b)

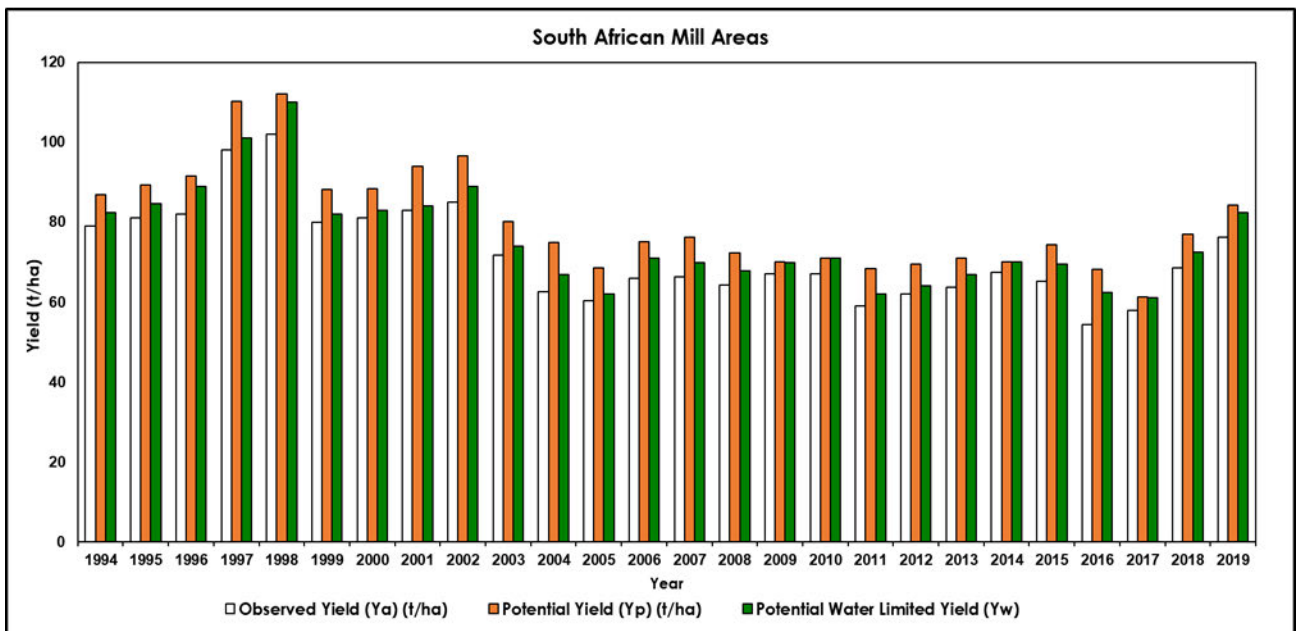


Figure 4.9 Potential water-limited yield (Y_w) for the (a) South African and (b) Nchalo mill areas compared to observed (Y_a) and potential (Y_p) yields. Y_w for these mills area averaged 75.69t/ha over the course of the study as a result of lower water deficits.

The KSCL mill area had the highest average water-limited yield (Y_w) of 123.3t/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 presented high average Y_w yields of 75.69t/ha and 73.00t/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 Y_w at 47.92t/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 Y_a as reported by the individual mills and various sources averaged 71.95t/ha for the South African mills, 46.50t/ha for the Big Bend mill, 71.48t/ha for the Nchalo mill and 113.09t/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 (**Figure 4.10**). These differences in Y_a can be attributed to, *inter alia*, recent variations in rainfall and temperature (Singels et al., 2005; Jones et al., 2015c), access to supplementary irrigation (Morita, 2021), changes in areas under sugarcane and changes in agronomic management (particularly the use of drought and pest-resistant sugarcane cultivars) (Sexton et al., 2017; 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 maximum potential yields (Y_p) and reductions in Y_{G_T} (van den Berg & Singels, 2013).

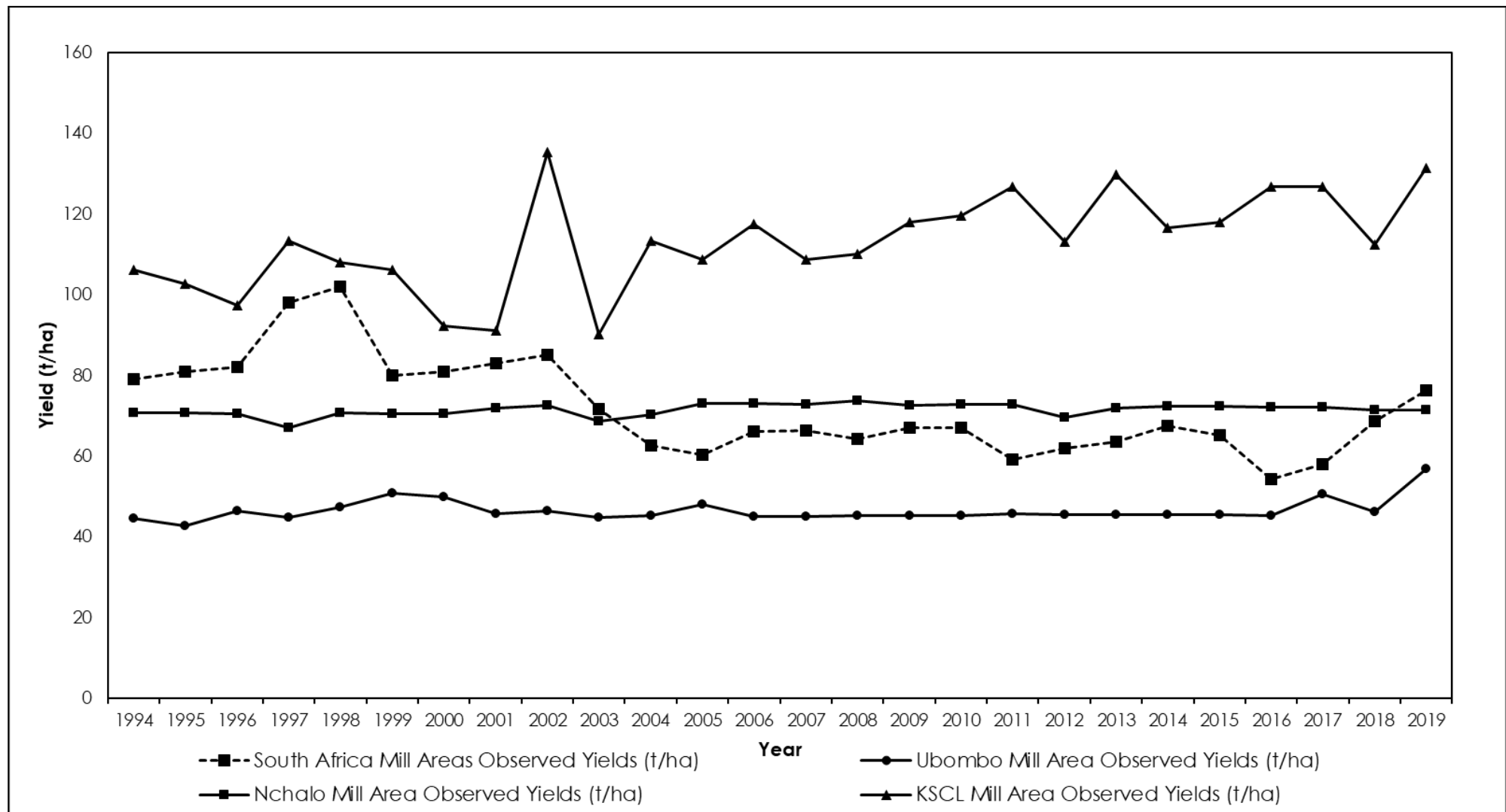


Figure 4.10 Observed yield trends for all mill areas under study between 1994 and 2019.

4.5 Drivers of Yield Gaps

Yield gaps are primarily driven by access to water resources (YG_{WD}) 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 (Dubb, 2015; Richardson, 2009). 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 Y_p and Y_{GT} , 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 Y_p and Y_w) was increasing at an average of 8.20t/ha/annum between 1996 and 2014, and declined to an average of 8.13t/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 (Knox et al., 2010b), which implies that there is limited scope for improving YG_{WD} . YG_{CM} (*i.e.* the difference between Y_w and Y_a) declined from an average of 1.46t/ha/annum between 1994 and 2006 to 1.12t/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 such as the N41 and N26 variants (Illovo Sugar, 2008), and, in some cases, increases in areas under sugarcane (Mhlanga et al., 2022). It is, therefore, apparent that access to water resources (*i.e.* YG_{WD}) assumes a more important role than YG_{CM} in the Y_{GT} for this mill area. Further, Y_a and Y_p 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 Y_a and Y_p 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 $Y_{G_{WD}}$ and $Y_{G_{CM}}$ resulted in increased Y_p . It should be noted that the actual Y_a 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 sugarcane and limited sunshine hours caused by high cloud cover, which contribute to a lower sucrose content of sugarcane. Despite these limitations, $Y_{G_{WD}}$ and $Y_{G_{CM}}$ and, therefore, Y_{G_T} have been consistently declining. This is possible due to two main reasons: i) the Kilombero catchment has high rainfall seasonality (MAP averages 1200mm during the rainy seasons and 990mm 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 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 Y_a .

The three mill areas in South Africa have experienced consistent declines in yields over the past 25 years. For these mills, Y_a and Y_p have been in decline since the early 2000s. However, $Y_{G_{WD}}$ has been in decline since the 2001-2002 cycle, 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 $Y_{G_{CM}}$ 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, Jones and Singels (2015) 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 (Jones and Singels, 2015). 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 (Adams et al., 2019), 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.

4.6 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 (**Figure 4.11** and **Figure 4.12**). 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) (Styles et al., 2012) 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 (Inman-Bamber et al., 2008). Mulching can assist in minimizing soil surface evaporation and overall decrease total evaporation which will result in lower crop transpiration rates.

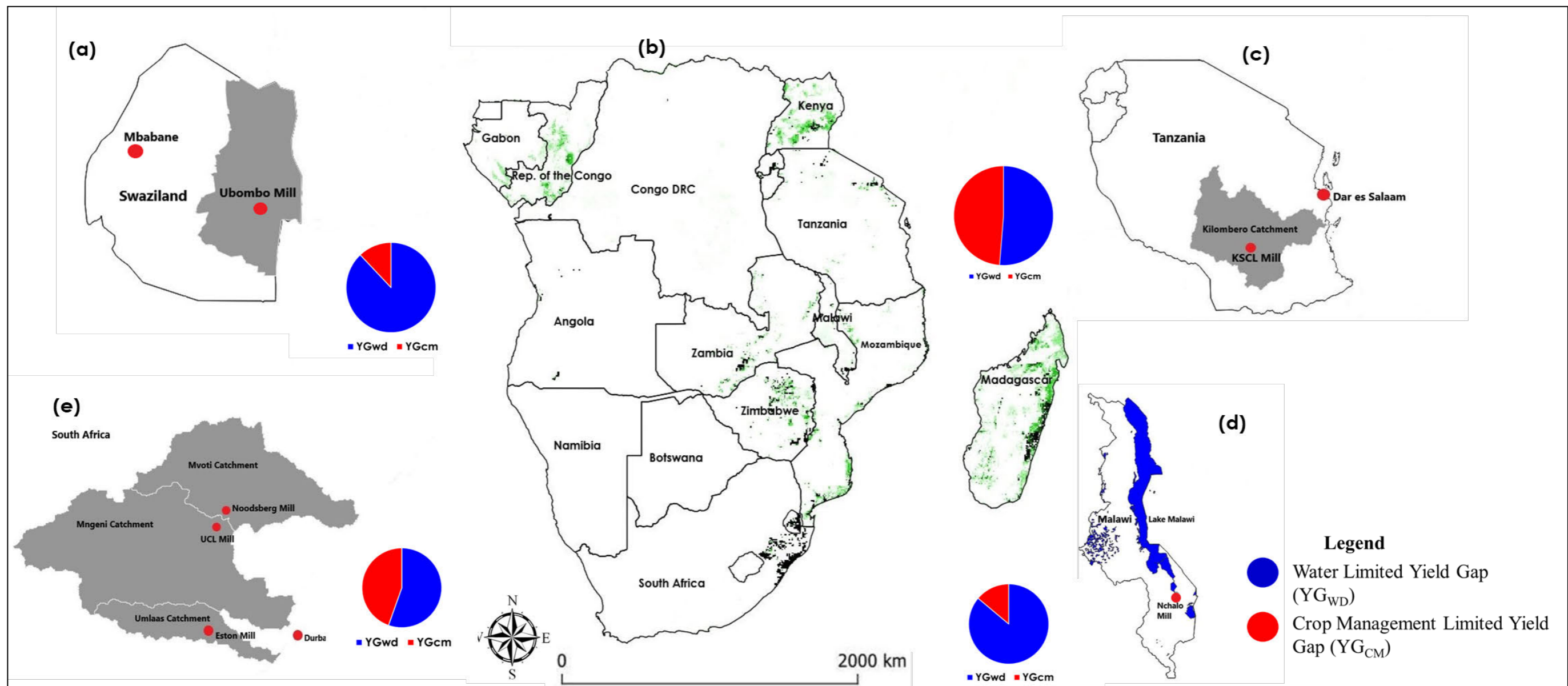


Figure 4.11 Access to water resources and crop management as the main causes of sugarcane yield gaps across the study catchments.

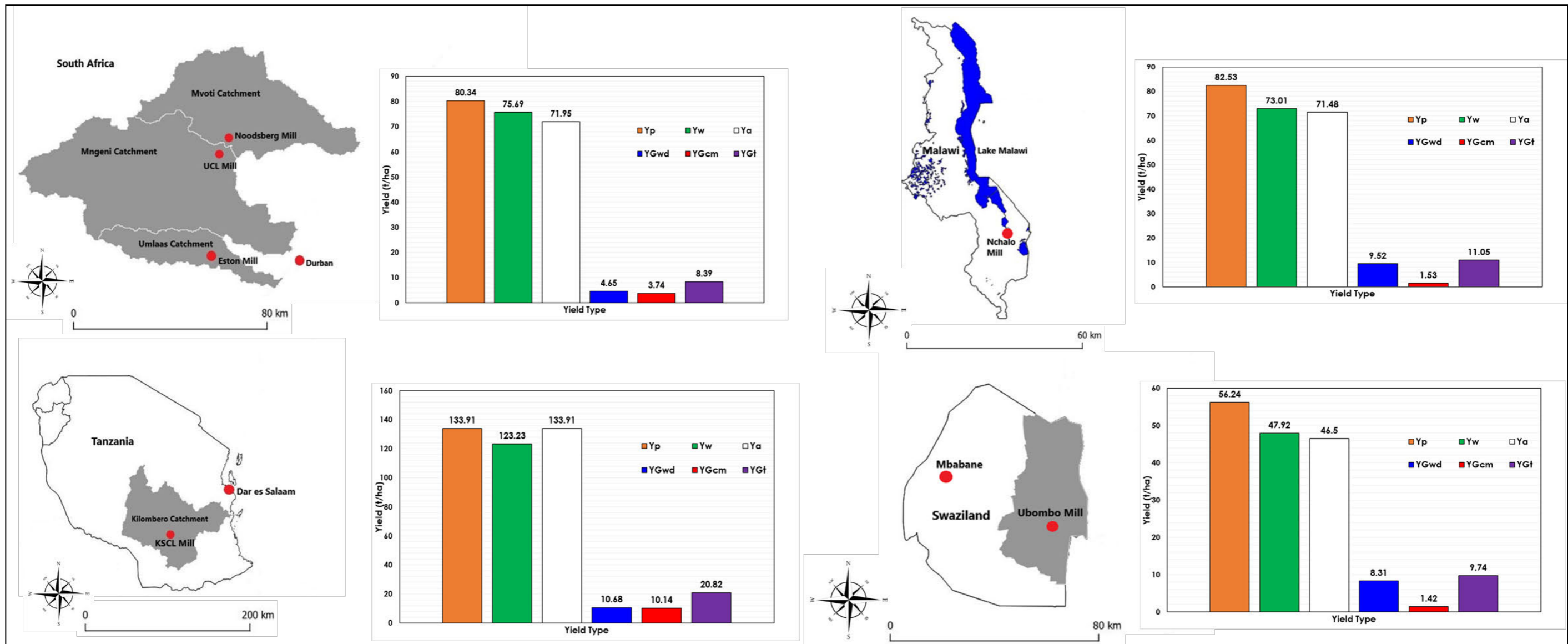


Figure 4.12 Yield gap analysis results for the mill areas under study based on the conceptual framework.

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 (Field et al., 2008). Finally, retaining post-harvest crop residues can increase effective rainfall by increasing soil moisture through increased infiltration (Valim et al., 2016). Minimizing in-field traffic, such as is being undertaken in the Noodsberg and UCL mill areas of South Africa (SA Canegrowers Association, 2018), 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 as 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.

4.7 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 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 to 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 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.

Acknowledgements

This study was supported by the University of KwaZulu-Natal’s Centre for Water Resources Research (CWRR) and the Global Challenges Research Fund - Uncertainty reduction in Models for Understanding Development Applications (GRCF-UMFULA). The author would like to thank the following organizations for permitting access to otherwise restricted datasets: The South African Sugar Research Institute; Illovo Sugar Africa; and The Sugar Engineers.

References

- Abayomi, Y. A., & Lawal, O. J. (1998). Effect of water stress on growth and biomass yield of contrasting genotypes of sugarcane (*Saccharum officinarum*). *Ghana Journal of Agricultural Science*, 31(1), Article 1. <https://doi.org/10.4314/gjas.v31i1.1948>
- Abbas, H. A., Bond, W. J., & Midgley, J. J. (2019). The worst drought in 50 years in a South African savannah: Limited impact on vegetation. *African Journal of Ecology*, 57(4), 490–499. <https://doi.org/10.1111/aje.12640>

- Adams, T., Gerber, J.-D., & Amacker, M. (2019). Constraints and opportunities in gender relations: Sugarcane outgrower schemes in Malawi. *World Development*, *122*, 282–294. <https://doi.org/10.1016/j.worlddev.2019.05.029>
- Adetoro, A. A., Abraham, S., Paraskevopoulos, A. L., Owusu-Sekyere, E., Jordaan, H., & Orimoloye, I. R. (2020). Alleviating water shortages by decreasing water footprint in sugarcane production: The impacts of different soil mulching and irrigation systems in South Africa. *Groundwater for Sustainable Development*, *11*, 100464. <https://doi.org/10.1016/j.gsd.2020.100464>
- Adger, W. N., Lorenzoni, I., & O'Brien, K. L. (2009). *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press.
- Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of impact on major crops. *Food and Energy Security*, *4*(2), 110–132. <https://doi.org/10.1002/fes3.61>
- Ahmadi, S. H., Reis Ghorra, M. R., & Sepaskhah, A. R. (2022). Parameterizing the AquaCrop model for potato growth modeling in a semi-arid region. *Field Crops Research*, *288*, 108680. <https://doi.org/10.1016/j.fcr.2022.108680>
- Aleman, J. C., Blarquez, O., & Staver, C. A. (2016). Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Global Change Biology*, *22*(9), 3013–3025. <https://doi.org/10.1111/gcb.13299>
- Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., Yrisarry, J. B., Smith, M., Pereira, L. S., Raes, D., Perrier, A., Alves, I., Walter, I., & Elliott, R. (2006). A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method. *Agricultural Water Management*, *81*(1), 1–22. <https://doi.org/10.1016/j.agwat.2005.03.007>
- Alvar-Beltrán, J., Heureux, A., Soldan, R., Manzanar, R., Khan, B., & Dalla Marta, A. (2021). Assessing the impact of climate change on wheat and sugarcane with the AquaCrop model along the Indus River Basin, Pakistan. *Agricultural Water Management*, *253*, 106909. <https://doi.org/10.1016/j.agwat.2021.106909>
- Archer, E., Landman, W., Malherbe, J., Tadross, M., & Pretorius, S. (2019). South Africa's winter rainfall region drought: A region in transition? *Climate Risk Management*, *25*, 100188. <https://doi.org/10.1016/j.crm.2019.100188>
- Babel, M., Deb, P., & Soni, P. (2018). Performance Evaluation of AquaCrop and DSSAT-CERES for Maize Under Different Irrigation and Manure Application Rates in the Himalayan Region of India. *Agricultural Research*, *8*. <https://doi.org/10.1007/s40003-018-0366-y>
- Babel, M. S., Deb, P., & Soni, P. (2019). Performance Evaluation of AquaCrop and DSSAT-CERES for Maize Under Different Irrigation and Manure Application Rates in the Himalayan Region of India. *Agricultural Research*, *8*(2), 207–217. <https://doi.org/10.1007/s40003-018-0366-y>
- Baez-Gonzalez, A. D., Kiniry, J. R., Meki, M. N., Williams, J., Alvarez-Cilva, M., Ramos-Gonzalez, J. L., Magallanes-Estala, A., & Zapata-Buenfil, G. (2017). Crop Parameters for Modeling Sugarcane under Rainfed Conditions in Mexico. *Sustainability*, *9*(8), Article 8. <https://doi.org/10.3390/su9081337>
- Bahta, Y. T. (2022). Social vulnerability to agricultural drought: Insights from Northern Cape, South Africa. *Scientific African*, *17*, e01324. <https://doi.org/10.1016/j.sciaf.2022.e01324>
- Bakker, H. (2012). *Sugar Cane Cultivation and Management*. Springer Science & Business Media.

- Baskin, C. C. (2022). Chapter 16 - Effects of climate change on annual crops: The case of maize production in Africa. In C. C. Baskin & J. M. Baskin (Eds.), *Plant Regeneration from Seeds* (pp. 213–228). Academic Press. <https://doi.org/10.1016/B978-0-12-823731-1.00020-2>
- Bezuidenhout, C. N., & Singels, A. (2007). Operational forecasting of South African sugarcane production: Part 1 – System description. *Agricultural Systems*, 92(1), 23–38. <https://doi.org/10.1016/j.agsy.2006.02.001>
- Bezuidenhout, C., & Singels, A. (2007). Operational forecasting of South African sugarcane production: Part 1 – System description. *Agricultural Systems*, 92, 23–38. <https://doi.org/10.1016/j.agsy.2006.02.001>
- Biggs, J. S., Thorburn, P. J., Crimp, S., Masters, B., & Attard, S. J. (2013). Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region, Australia. *Agriculture, Ecosystems & Environment*, 180, 79–89. <https://doi.org/10.1016/j.agee.2011.11.005>
- Booyesen, K. C., Foxon, K. M., & Davis, S. B. (2017). The development of a screening tool to identify new products for the South African sugarcane industry. *Proceedings of the Annual Congress - South African Sugar Technologists' Association, No.90*, 431–454. <https://www.cabdirect.org/cabdirect/abstract/20183262257>
- Braidwood, R. J. (1960). The Agricultural Revolution. *Scientific American*, 203(3), 130–152. <https://www.jstor.org/stable/24940620>
- Cairns, J. E., Chamberlin, J., Rutsaert, P., Voss, R. C., Ndhlela, T., & Magorokosho, C. (2021). Challenges for sustainable maize production of smallholder farmers in sub-Saharan Africa. *Journal of Cereal Science*, 101, 103274. <https://doi.org/10.1016/j.jcs.2021.103274>
- Carr, M. K. V., & Knox, J. W. (2011). The Water Relations and Irrigation Requirements Of Sugar Cane (*Saccharum Officinarum*): A Review. *Experimental Agriculture*, 47(1), 1–25. <https://doi.org/10.1017/S0014479710000645>
- Carrer, M. J., Filho, H. M. de S., Vinholis, M. de M. B., & Mozambani, C. I. (2022). Precision agriculture adoption and technical efficiency: An analysis of sugarcane farms in Brazil. *Technological Forecasting and Social Change*, 177, 121510. <https://doi.org/10.1016/j.techfore.2022.121510>
- Change, I. P. on C. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Chinsinga, B. (2017). The Green Belt Initiative, Politics and Sugar Production in Malawi. *Journal of Southern African Studies*, 43(3), 501–515. <https://doi.org/10.1080/03057070.2016.1211401>
- Christina, M., Jones, M.-R., Versini, A., Mézino, M., Le Mézo, L., Auzoux, S., Soulié, J. C., Poser, C., & Gérardaux, E. (2021). Impact of climate variability and extreme rainfall events on sugarcane yield gap in a tropical Island. *Field Crops Research*, 274, 108326. <https://doi.org/10.1016/j.fcr.2021.108326>
- Cockburn, J., Coetzee, H., Van den Berg, J., & Conlong, D. (2014). Large-scale sugarcane farmers' knowledge and perceptions of *Eldana saccharina* Walker (Lepidoptera: Pyralidae), push-pull and integrated pest management. *Crop Protection*, 56, 1–9. <https://doi.org/10.1016/j.cropro.2013.10.014>
- Crutzen, P. J. (2006). The “Anthropocene.” In E. Ehlers & T. Krafft (Eds.), *Earth System Science in the Anthropocene* (pp. 13–18). Springer. https://doi.org/10.1007/3-540-26590-2_3

- Dai, A., Zhao, T., & Chen, J. (2018). Climate Change and Drought: A Precipitation and Evaporation Perspective. *Current Climate Change Reports*, 4(3), 301–312. <https://doi.org/10.1007/s40641-018-0101-6>
- Dal Belo Leite, J. G., Langa, F. M., von Maltitz, G., Lima Verde Leal, M. R., & Barbosa Cortez, L. A. (2020). Sugarcane outgrower schemes model: Friend or foe? A question for smallholder farmers in Mozambique. *World Development Perspectives*, 19, 100232. <https://doi.org/10.1016/j.wdp.2020.100232>
- Daroub, S. H., Van Horn, S., Lang, T. A., & Diaz, O. A. (2011). Best Management Practices and Long-Term Water Quality Trends in the Everglades Agricultural Area. *Critical Reviews in Environmental Science and Technology*, 41(sup1), 608–632. <https://doi.org/10.1080/10643389.2010.530905>
- de Fátima Rodrigues de Souza, R., Dutra, E. D., Leite, F. C. B., Cadete, R. M., Rosa, C. A., Stambuk, B. U., Stamford, T. L. M., & de Moraes, M. A. (2018). Production of ethanol fuel from enzyme-treated sugarcane bagasse hydrolysate using d-xylose-fermenting wild yeast isolated from Brazilian biomes. *3 Biotech*, 8(7), 312. <https://doi.org/10.1007/s13205-018-1340-x>
- Deressa, T., Hassan, R., & Poonyth, D. (2005). Measuring The Impact Of Climate Change On South African Agriculture: The Case Of Sugarcane Growing Regions. *Agrekon*, 44(4), 524–542. <https://doi.org/10.1080/03031853.2005.9523726>
- Devnarain, N., Snyman, S. J., Hunter, C., McFarlane, S. A., & Rutherford, R. S. (2010). The establishment of in vitro screening methods for evaluating sugarcane (*Saccharum* spp. Hybrids) susceptibility to *Ustilago scitaminea* H. & P. Sydow and *Eldana saccharina* Walker. *South African Journal of Botany*, 76(2), 409. <https://doi.org/10.1016/j.sajb.2010.02.062>
- Dias, H. B., & Sentelhas, P. C. (2018a). Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. *Science of The Total Environment*, 637–638, 1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
- Dias, H. B., & Sentelhas, P. C. (2018b). Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. *Science of The Total Environment*, 637–638, 1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
- Dias, H. B., & Sentelhas, P. C. (2021). Assessing the performance of two gridded weather data for sugarcane crop simulations with a process-based model in Center-South Brazil. *International Journal of Biometeorology*, 65(11), 1881–1893. <https://doi.org/10.1007/s00484-021-02145-6>
- Dlamini, P. J. (2021). Drought stress tolerance mechanisms and breeding effort in sugarcane: A review of progress and constraints in South Africa. *Plant Stress*, 2, 100027. <https://doi.org/10.1016/j.stress.2021.100027>
- Dubb, A. (2015). Dynamics of decline in small-scale sugarcane production in South Africa: Evidence from two ‘rural’ wards in the Umfolozi region. *Land Use Policy*, 48, 362–376. <https://doi.org/10.1016/j.landusepol.2015.06.029>
- Dubb, A., Scoones, I., & Woodhouse, P. (2017). The Political Economy of Sugar in Southern Africa – Introduction. *Journal of Southern African Studies*, 43(3), 447–470. <https://doi.org/10.1080/03057070.2016.1214020>
- Dunkelberg, E., Finkbeiner, M., & Hirschl, B. (2014). Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions. *Biomass and Bioenergy*, 71, 37–45. <https://doi.org/10.1016/j.biombioe.2013.10.006>
- Eksteen, A., Singels, A., & Ngxaliwe, S. (2014). Water relations of two contrasting sugarcane genotypes. *Field Crops Research*, 168, 86–100. <https://doi.org/10.1016/j.fcr.2014.08.008>

- Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: The scale of the potential resource. *Trends in Ecology & Evolution*, 23(2), 65–72. <https://doi.org/10.1016/j.tree.2007.12.001>
- Fischer, K., & Hajdu, F. (2015). Does raising maize yields lead to poverty reduction? A case study of the Massive Food Production Programme in South Africa. *Land Use Policy*, 46, 304–313. <https://doi.org/10.1016/j.landusepol.2015.03.015>
- Fischer, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research*, 182, 9–18. <https://doi.org/10.1016/j.fcr.2014.12.006>
- Forsell, N., Turkovska, O., Gusti, M., Obersteiner, M., Elzen, M. den, & Havlik, P. (2016). Assessing the INDCs' land use, land use change, and forest emission projections. *Carbon Balance and Management*, 11(1), 26. <https://doi.org/10.1186/s13021-016-0068-3>
- Fundira, T., & Henley, G. (2017). *Biofuels in Southern Africa: Political economy, trade, and policy environment* (WIDER Working Paper Series wp-2017-48). World Institute for Development Economic Research (UNU-WIDER). <https://econpapers.repec.org/paper/unuwpaper/wp-2017-48.htm>
- Gasparatos, A., Maltitz, G. von, Roland, N., Ahmed, A., Mudombi, S., & Jarzebski, M. P. (2021). Institutional and socioeconomic transformation from sugarcane expansion in northern Eswatini. In *Political Ecology of Industrial Crops*. Routledge.
- Gasparotto, L. G., Rosa, J. M., Grassini, P., & Marin, F. R. (2022). Developing an operational framework to diagnose yield gaps in commercial sugarcane mills. *Field Crops Research*, 278, 108433. <https://doi.org/10.1016/j.fcr.2022.108433>
- German, L. A., Hepinstall-Cymerman, J., Biggs, T., Parker, L., & Salinas, M. (2020). The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. *Applied Geography*, 121, 102240. <https://doi.org/10.1016/j.apgeog.2020.102240>
- Gleick, P. (2000). The Changing Water Paradigm—A Look at Twenty-First Century Water Resources Development. *Water International*, 25, 127–138. <https://doi.org/10.1080/02508060008686804>
- Hadebe, S. T., Mabhaudhi, T., & Modi, A. T. (2020). Sorghum best practice management recommendations based on AquaCrop modeling scenario analysis in various agro-ecologies of KwaZulu Natal, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 117, 102866. <https://doi.org/10.1016/j.pce.2020.102866>
- Hennessy, K., Lawrence, J., & Mackey, B. (2022). *IPCC Sixth Assessment Report (AR6): Climate Change 2022 - Impacts, Adaptation and Vulnerability: Regional Factsheet Australasia*. https://policycommons.net/artifacts/2264302/ipcc_ar6_wgii_factsheet_australasia/3023355/
- Hess, T. M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Montegudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A., Marin, F., & Knox, J. W. (2016). A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change*, 39, 181–194. <https://doi.org/10.1016/j.gloenvcha.2016.05.003>
- Hiloidhari, M., Banerjee, R., & Rao, A. B. (2021). Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. *Journal of Cleaner Production*, 290, 125170. <https://doi.org/10.1016/j.jclepro.2020.125170>
- Houghton, J. (2005). Global warming. *Reports on Progress in Physics*, 68(6), 1343. <https://doi.org/10.1088/0034-4885/68/6/R02>

- Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). Climate change: The IPCC scientific assessment. *American Scientist; (United States)*, 80:6. <https://www.osti.gov/biblio/6819363>
- Inman-Bamber, N., Bonnett, G., Thorburn, P., Garside, A., Berding, N., & Attard, S. (2008). Inman-Bamber NG et al. Pointers for Better Farming and Research From Sugarcane Physiology. *Proceedings Australian Society of Sugar Cane Technologists*, 30, 231–240.
- Inman-Bamber, N. G. (2004). Sugarcane water stress criteria for irrigation and drying off. *Field Crops Research*, 89(1), 107–122. <https://doi.org/10.1016/j.fcr.2004.01.018>
- Inman-Bamber, N. G., Jackson, P. A., Stokes, C. J., Verrall, S., Lakshmanan, P., & Basnayake, J. (2016). Sugarcane for water-limited environments: Enhanced capability of the APSIM sugarcane model for assessing traits for transpiration efficiency and root water supply. *Field Crops Research*, 196, 112–123. <https://doi.org/10.1016/j.fcr.2016.06.013>
- Inman-Bamber, N. G., Muchow, R. C., & Robertson, M. J. (2002). Dry matter partitioning of sugarcane in Australia and South Africa. *Field Crops Research*, 76(1), 71–84. [https://doi.org/10.1016/S0378-4290\(02\)00044-8](https://doi.org/10.1016/S0378-4290(02)00044-8)
- Inman-Bamber, N. G., & Smith, D. M. (2005). Water relations in sugarcane and response to water deficits. *Field Crops Research*, 92(2), 185–202. <https://doi.org/10.1016/j.fcr.2005.01.023>
- Iqbal, M. A., Shen, Y., Stricevic, R., Pei, H., Sun, H., Amiri, E., Penas, A., & del Rio, S. (2014). Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation. *Agricultural Water Management*, 135, 61–72. <https://doi.org/10.1016/j.agwat.2013.12.012>
- Ishtiaque, A., Estoque, R. C., Eakin, H., Parajuli, J., & Rabby, Y. W. (2022). IPCC’s current conceptualization of ‘vulnerability’ needs more clarification for climate change vulnerability assessments. *Journal of Environmental Management*, 303, 114246. <https://doi.org/10.1016/j.jenvman.2021.114246>
- James, P., & Woodhouse, P. (2017). Crisis and Differentiation among Small-Scale Sugar Cane Growers in Nkomazi, South Africa. *Journal of Southern African Studies*, 43(3), 535–549. <https://doi.org/10.1080/03057070.2016.1197694>
- Jewitt, G., & Kunz, R. (2011). The impact of biofuel feedstock production on water resources: A developing country perspective. *Biofuels, Bioproducts and Biorefining*, 5(4), 387–398. <https://doi.org/10.1002/bbb.314>
- Jones, M. R., & Singels, A. (2018). Refining the Canegro model for improved simulation of climate change impacts on sugarcane. *European Journal of Agronomy*, 100, 76–86. <https://doi.org/10.1016/j.eja.2017.12.009>
- Jones, M. R., Singels, A., Chinorumba, S., Patton, A., Poser, C., Singh, M., Martiné, J. F., Christina, M., Shine, J., Annandale, J., & Hammer, G. (2019). Exploring process-level genotypic and environmental effects on sugarcane yield using an international experimental dataset. *Field Crops Research*, 244, 107622. <https://doi.org/10.1016/j.fcr.2019.107622>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015a). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015b). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>

- Jones, M. R., Singels, A., & Ruane, A. C. (2015c). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, *139*, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Kalantari, Z., Ferreira, C. S. S., Keesstra, S., & Destouni, G. (2018). Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. *Current Opinion in Environmental Science & Health*, *5*, 73–78. <https://doi.org/10.1016/j.coesh.2018.06.003>
- Kasambala Donga, T., & Eklo, O. M. (2018). Environmental load of pesticides used in conventional sugarcane production in Malawi. *Crop Protection*, *108*, 71–77. <https://doi.org/10.1016/j.cropro.2018.02.012>
- Kaufmann, R. K., Kauppi, H., Mann, M. L., & Stock, J. H. (2011). Reconciling anthropogenic climate change with observed temperature 1998–2008. *Proceedings of the National Academy of Sciences*, *108*(29), 11790–11793. <https://doi.org/10.1073/pnas.1102467108>
- Kayiwa, R., Kasedde, H., Lubwama, M., & Kirabira, J. B. (2021). The potential for commercial scale production and application of activated carbon from cassava peels in Africa: A review. *Bioresource Technology Reports*, *15*, 100772. <https://doi.org/10.1016/j.biteb.2021.100772>
- Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., ... Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, *18*(3), 267–288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- Kelly, T. D., & Foster, T. (2021). AquaCrop-OSPy: Bridging the gap between research and practice in crop-water modeling. *Agricultural Water Management*, *254*, 106976. <https://doi.org/10.1016/j.agwat.2021.106976>
- Kerridge, E. (2013). *The Agricultural Revolution*. Routledge.
- Knapp, A. K., Ciais, P., & Smith, M. D. (2017). Reconciling inconsistencies in precipitation–productivity relationships: Implications for climate change. *New Phytologist*, *214*(1), 41–47. <https://doi.org/10.1111/nph.14381>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010a). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, *103*(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010b). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, *103*(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Koo, J., Pardey, P. G., & Kubik, Z. (2020). *HarvestChoice: Supporting strategic investment choices in agricultural technology development and adoption* (0 ed.). International Food Policy Research Institute. <https://doi.org/10.2499/p15738coll2.133807>
- Laing, A. G., Carbone, R. E., & Levizzani, V. (2011). Cycles and Propagation of Deep Convection over Equatorial Africa. *Monthly Weather Review*, *139*(9), 2832–2853. <https://doi.org/10.1175/2011MWR3500.1>
- Laurie, S., Faber, M., Adebola, P., & Belete, A. (2015). Biofortification of sweet potato for food and nutrition security in South Africa. *Food Research International*, *76*, 962–970. <https://doi.org/10.1016/j.foodres.2015.06.001>
- Linnenluecke, M. K., Nucifora, N., & Thompson, N. (2018). Implications of climate change for the sugarcane industry. *WIREs Climate Change*, *9*(1), e498. <https://doi.org/10.1002/wcc.498>

- Lumsden, T. G., Schulze, R. E., Lecler, N. L., & Schmidt, E. J. (2000). Assessing the potential for improved sugarcane yield forecasting using seasonal rainfall forecasts and crop yield models. *Proceedings of the Annual Congress - South African Sugar Technologists' Association*, No.74, 131–139. <https://www.cabdirect.org/cabdirect/abstract/20023018386>
- Mabhaudhi, T., Modi, A. T., & Beletse, Y. G. (2014). Parameterisation and evaluation of the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. *Agricultural and Forest Meteorology*, 192–193, 132–139. <https://doi.org/10.1016/j.agrformet.2014.03.013>
- Marin, F. R., Rattalino Edreira, J. I., Andrade, J., & Grassini, P. (2019). On-farm sugarcane yield and yield components as influenced by number of harvests. *Field Crops Research*, 240, 134–142. <https://doi.org/10.1016/j.fcr.2019.06.011>
- Mason, S. J., Waylen, P. R., Mimmack, G. M., Rajaratnam, B., & Harrison, J. M. (1999). Changes in Extreme Rainfall Events in South Africa. *Climatic Change*, 41(2), 249–257. <https://doi.org/10.1023/A:1005450924499>
- Matsa, M., & Muyemeki, L. (2010). Matsa Mark and Muyemeki Luckson (2010) The Relationship Between Satellite Derived and Ground Measurement Sugar-cane Water Use: The Case of Hippo Valley Estates in Zimbabwe. *Journal of Sustainable Development in Africa*, Vol. 12, No.8 2010 Pages 191-216. *Journal of Sustainable Development in Africa*, 12, 191–216.
- McKay, B., Sauer, S., Richardson, B., & Herre, R. (2016). The political economy of sugarcane flexing: Initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies*, 43(1), 195–223. <https://doi.org/10.1080/03066150.2014.992016>
- Mekonnen, M. M., & Hoekstra, A. Y. (2010). *The green, blue and grey water footprint of crops and derived crops products*. <https://research.utwente.nl/en/publications/the-green-blue-and-grey-water-footprint-of-crops-and-derived-crop-3>
- Meyer, J., & Antwerpen, R. (2021). *Soil Degradation As A Factor In Yield Decline In The South African Sugar Industry*.
- Meyfroidt, P., Lambin, E. F., Erb, K.-H., & Hertel, T. W. (2013). Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability*, 5(5), 438–444. <https://doi.org/10.1016/j.cosust.2013.04.003>
- Mhlanga, B., Ercoli, L., Thierfelder, C., & Pellegrino, E. (2022). Conservation agriculture practices lead to diverse weed communities and higher maize grain yield in Southern Africa. *Field Crops Research*, 289, 108724. <https://doi.org/10.1016/j.fcr.2022.108724>
- Mhlanga, B. F. N., Ndlovu, L. S., & Senzanje, A. (2006). Impacts of irrigation return flows on the quality of the receiving waters: A case of sugarcane irrigated fields at the Royal Swaziland Sugar Corporation (RSSC) in the Mbuluzi River Basin (Swaziland). *Physics and Chemistry of the Earth, Parts A/B/C*, 31(15), 804–813. <https://doi.org/10.1016/j.pce.2006.08.028>
- Mirza, M. M. Q. (2003). Climate change and extreme weather events: Can developing countries adapt? *Climate Policy*, 3(3), 233–248. <https://doi.org/10.3763/cpol.2003.0330>
- Morita. (2021). Chapter 9—Constraints of improving crop water productivity in rainfed and irrigated systems in South Asia and Sub-Saharan Africa. In M. D. Kumar (Ed.), *Current Directions in Water Scarcity Research* (Vol. 3, pp. 197–218). Elsevier. <https://doi.org/10.1016/B978-0-323-91277-8.00004-6>

- Mubvuma, Michael. T., Ogola, J. B. O., & Mhizha, T. (2021). AquaCrop model calibration and validation for chickpea (*Cicer arietinum*) in Southern Africa. *Cogent Food & Agriculture*, 7(1), 1898135. <https://doi.org/10.1080/23311932.2021.1898135>
- Mudombi, S., Ochieng, C., Johnson, F. X., von Maltitz, G., Luhanga, D., Dompreeh, E. B., Romeu-Dalmau, C., & Gasparatos, A. (2021). Fuelling rural development? The impact of biofuel feedstock production in southern Africa on household income and expenditures. *Energy Research & Social Science*, 76, 102053. <https://doi.org/10.1016/j.erss.2021.102053>
- Musakwa, W., & Niekerk, A. V. (2013). Implications of land use change for the sustainability of urban areas: A case study of Stellenbosch, South Africa. *Cities*, 32, 143–156. <https://doi.org/10.1016/j.cities.2013.01.004>
- Näschen, K., Diekkrüger, B., Leemhuis, C., Steinbach, S., Seregina, L. S., Thonfeld, F., & Van der Linden, R. (2018). Hydrological Modeling in Data-Scarce Catchments: The Kilombero Floodplain in Tanzania. *Water*, 10(5), Article 5. <https://doi.org/10.3390/w10050599>
- Ngcobo, S., & Jewitt, G. (2017). Multiscale drivers of sugarcane expansion and impacts on water resources in Southern Africa. *Environmental Development*, 24, 63–76. <https://doi.org/10.1016/j.envdev.2017.07.004>
- Ngcobo, S., Jewitt, G., Stuart-Hill, S., & Warburton, M. (2013). Impacts of global change on southern African water resources systems. *Current Opinion in Environmental Sustainability*, 5(6), 655–666. <https://doi.org/10.1016/j.cosust.2013.10.002>
- Ofori, S. A., Cobbina, S. J., & Obiri, S. (2021). Climate Change, Land, Water, and Food Security: Perspectives From Sub-Saharan Africa. *Frontiers in Sustainable Food Systems*, 5. <https://www.frontiersin.org/articles/10.3389/fsufs.2021.680924>
- O’Gorman, P. A. (2015). Precipitation Extremes Under Climate Change. *Current Climate Change Reports*, 1(2), 49–59. <https://doi.org/10.1007/s40641-015-0009-3>
- Oliveira, K. D., Tomasella, J., Caram, R. de O., Falck, A. S., & Sanches, I. D. (2022). Impacts of sugarcane expansion on water availability in a river basin in southeastern Brazil. *CATENA*, 216, 106437. <https://doi.org/10.1016/j.catena.2022.106437>
- Olivier, F. C., & Singels, A. (2015). Increasing water use efficiency of irrigated sugarcane production in South Africa through better agronomic practices. *Field Crops Research*, 176, 87–98. <https://doi.org/10.1016/j.fcr.2015.02.010>
- Oosterveer, P., & Mol, A. P. J. (2010). Biofuels, trade and sustainability: A review of perspectives for developing countries. *Biofuels, Bioproducts and Biorefining*, 4(1), 66–76. <https://doi.org/10.1002/bbb.194>
- Potgieter, L., van Vuuren, J. H., & Conlong, D. E. (2013). A reaction–diffusion model for the control of Eldana saccharina Walker in sugarcane using the sterile insect technique. *Ecological Modelling*, 250, 319–328. <https://doi.org/10.1016/j.ecolmodel.2012.11.019>
- Pryor, S. W., Smithers, J., Lyne, P., & van Antwerpen, R. (2017). Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. *Journal of Cleaner Production*, 141, 137–145. <https://doi.org/10.1016/j.jclepro.2016.09.069>
- Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal*. 101 (3), 438:447. <https://doi.org/10.2134/agronj2008.0140s>
- Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2012. Reference Manual AquaCrop (Version 4.0). AquaCrop Website <http://www.fao.org/nr/water/aquacrop.html>

- Rahimi Jamnani, M., Mirzaei, F., & Liaghat, A. (2022). Evaluation of sugarcane irrigation using AquaCrop model and remote sensing. *Irrigation and Drainage*, *71*(4), 1034–1047. <https://doi.org/10.1002/ird.2718>
- Raut, S. U., & Bhagat, P. R. (2021). Sugarcane bio-refinery products: An efficient one umbrella approach for synthesis of biofuel and value-added compounds using metal-free photo-catalyst. *Fuel*, *303*, 121154. <https://doi.org/10.1016/j.fuel.2021.121154>
- Revathy, R., & Balamurali, S. (2022). *Developing an efficient irrigation scheduling system using hybrid machine learning algorithm to enhance the sugarcane crop productivity* [Preprint]. In Review. <https://doi.org/10.21203/rs.3.rs-1504824/v1>
- Rice, R. W., Izuno, F. T., & Garcia, R. M. (2002). Phosphorus load reductions under best management practices for sugarcane cropping systems in the Everglades Agricultural Area. *Agricultural Water Management*, *56*(1), 17–39. [https://doi.org/10.1016/S0378-3774\(01\)00196-2](https://doi.org/10.1016/S0378-3774(01)00196-2)
- Richardson, A. E. (2009). Regulating the phosphorus nutrition of plants: Molecular biology meeting agronomic needs. *Plant and Soil*, *322*(1–2), 17–24. <https://doi.org/10.1007/s11104-009-0071-5>
- Rosa, S. L. K., Souza, J. L. M. de, & Tsukahara, R. Y. (2019). Performance of the AquaCrop model for the wheat crop in the subtropical zone in Southern Brazil. *Pesquisa Agropecuária Brasileira*, *55*. <https://doi.org/10.1590/S1678-3921.pab2020.v55.01238>
- Roudier, P., Muller, B., d'Aquino, P., Roncoli, C., Soumaré, M. A., Batté, L., & Sultan, B. (2014). The role of climate forecasts in smallholder agriculture: Lessons from participatory research in two communities in Senegal. *Climate Risk Management*, *2*, 42–55. <https://doi.org/10.1016/j.crm.2014.02.001>
- Ruddiman, W. F. (2013). The Anthropocene. *Annual Review of Earth and Planetary Sciences*, *41*(1), 45–68. <https://doi.org/10.1146/annurev-earth-050212-123944>
- Sandhu, S. S., Mahal, S. S., & Kaur, P. (2015). Calibration, validation and application of AquaCrop model in irrigation scheduling for rice under northwest India. *Journal of Applied and Natural Science*, *7*(2), Article 2. <https://doi.org/10.31018/jans.v7i2.668>
- Schulze, R. E. (2000). Modelling Hydrological Responses to Land Use and Climate Change: A Southern African Perspective. *Ambio*, *29*(1), 12–22. <https://www.jstor.org/stable/4314988>
- Sexton, J., Everingham, Y. L., & Inman-Bamber, G. (2017). A global sensitivity analysis of cultivar trait parameters in a sugarcane growth model for contrasting production environments in Queensland, Australia. *European Journal of Agronomy*, *88*, 96–105. <https://doi.org/10.1016/j.eja.2015.11.009>
- Sezen, S. M., Yazar, A., Daşgan, Y., Yucel, S., Akyıldız, A., Tekin, S., & Akhoundnejad, Y. (2014). Evaluation of crop water stress index (CWSI) for red pepper with drip and furrow irrigation under varying irrigation regimes. *Agricultural Water Management*, *143*, 59–70. <https://doi.org/10.1016/j.agwat.2014.06.008>
- Shavazipour, B., Stray, J., & Stewart, T. J. (2020). Sustainable planning in sugar-bioethanol supply chain under deep uncertainty: A case study of South African sugarcane industry. *Computers & Chemical Engineering*, *143*, 107091. <https://doi.org/10.1016/j.compchemeng.2020.107091>
- Silva, V. de P. R. da, Silva, R. A. e, Maciel, G. F., Braga, C. C., Silva, J. L. C. da, Souza, E. P. de, Almeida, R. S. R., Silva, M. T., & Holanda, R. M. de. (2017a). Calibration and validation of the AquaCrop model for the soybean crop grown under different levels of irrigation in the Motopiba region, Brazil. *Ciência Rural*, *48*. <https://doi.org/10.1590/0103-8478cr20161118>

- Silva, V. de P. R. da, Silva, R. A. e, Maciel, G. F., Braga, C. C., Silva, J. L. C. da, Souza, E. P. de, Almeida, R. S. R., Silva, M. T., & Holanda, R. M. de. (2017b). Calibration and validation of the AquaCrop model for the soybean crop grown under different levels of irrigation in the Motopiba region, Brazil. *Ciência Rural*, 48. <https://doi.org/10.1590/0103-8478cr20161118>
- Singels, A., Donaldson, R. A., & Smit, M. A. (2005). Improving biomass production and partitioning in sugarcane: Theory and practice. *Field Crops Research*, 92(2), 291–303. <https://doi.org/10.1016/j.fcr.2005.01.022>
- Singels, A., Jackson, P., & Inman-Bamber, G. (2021). Sugarcane. In *Crop Physiology Case Histories for Major Crops* (pp. 674–713). Elsevier. <https://doi.org/10.1016/B978-0-12-819194-1.00021-9>
- Singels, A., Jones, M., Marin, F., Ruane, A., & Thorburn, P. (2014). Predicting Climate Change Impacts on Sugarcane Production at Sites in Australia, Brazil and South Africa Using the Canegro Model. *Sugar Tech*, 16(4), 347–355. <https://doi.org/10.1007/s12355-013-0274-1>
- Singels, A., Paraskevopoulos, A. L., & Mashabela, M. L. (2019). Farm level decision support for sugarcane irrigation management during drought. *Agricultural Water Management*, 222, 274–285. <https://doi.org/10.1016/j.agwat.2019.05.048>
- Singels, A., Smit, M. A., Redshaw, K. A., & Donaldson, R. A. (2005). The effect of crop start date, crop class and cultivar on sugarcane canopy development and radiation interception. *Field Crops Research*, 92(2), 249–260. <https://doi.org/10.1016/j.fcr.2005.01.028>
- Singels, A., van den Berg, M., Smit, M. A., Jones, M. R., & van Antwerpen, R. (2010). Modelling water uptake, growth and sucrose accumulation of sugarcane subjected to water stress. *Field Crops Research*, 117(1), 59–69. <https://doi.org/10.1016/j.fcr.2010.02.003>
- Smithers, J. C., Rowe, T. J., Horan, M. J. C., & Schulze, R. E. (2018). Development and assessment of rules to parameterise the ACRU model for design flood estimation. *Water SA*, 44(1), Article 1. <https://doi.org/10.4314/wsa.v44i1.11>
- Srivastava, A. K., & Rai, M. K. (2012). Review: Sugarcane production: Impact of climate change and its mitigation. *Biodiversitas Journal of Biological Diversity*, 13(4), Article 4. <https://doi.org/10.13057/biodiv/d130407>
- Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal*, 101(3), 426–437. <https://doi.org/10.2134/agronj2008.0139s>
- Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. (2011). The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1938), 842–867. <https://doi.org/10.1098/rsta.2010.0327>
- Stokes, C. J., Inman-Bamber, N. G., Everingham, Y. L., & Sexton, J. (2016). Measuring and modelling CO2 effects on sugarcane. *Environmental Modelling & Software*, 78, 68–78. <https://doi.org/10.1016/j.envsoft.2015.11.022>
- Styles, D., Schoenberger, H., & Galvez-Martos, J.-L. (2012). Environmental improvement of product supply chains: A review of European retailers' performance. *Resources, Conservation and Recycling*, 65, 57–78. <https://doi.org/10.1016/j.resconrec.2012.05.002>
- Sulle, E. (2017). Social Differentiation and the Politics of Land: Sugar Cane Outgrowing in Kilombero, Tanzania. *Journal of Southern African Studies*, 43(3), 517–533. <https://doi.org/10.1080/03057070.2016.1215171>

- Sulle, E., & Dancer, H. (2020). Gender, politics and sugarcane commercialisation in Tanzania. *The Journal of Peasant Studies*, 47(5), 973–992. <https://doi.org/10.1080/03066150.2019.1632294>
- Suresh, K. R., & Nagesh, M. A. (2015). Experimental Studies on Effect of Water and Soil quality on Crop Yield. *Aquatic Procedia*, 4, 1235–1242. <https://doi.org/10.1016/j.aqpro.2015.02.161>
- Tesfay, T., Berhane, A., & Gebremariam, M. (2019). Optimizing Irrigation Water and Nitrogen Fertilizer Levels for Tomato Production. *The Open Agriculture Journal*, 13(1). <https://doi.org/10.2174/1874331501913010198>
- The Anthropocene: Conceptual and historical perspectives | Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. (n.d.). Retrieved January 5, 2023, from <https://royalsocietypublishing.org/doi/full/10.1098/rsta.2010.0327>
- Thornton, P. K., Ericksen, P. J., Herrero, M., & Challinor, A. J. (2014). Climate variability and vulnerability to climate change: A review. *Global Change Biology*, 20(11), 3313–3328. <https://doi.org/10.1111/gcb.12581>
- Tongwane, M. I., & Moeletsi, M. E. (2018). A review of greenhouse gas emissions from the agriculture sector in Africa. *Agricultural Systems*, 166, 124–134. <https://doi.org/10.1016/j.agsy.2018.08.011>
- Trambauer, P., Dutra, E., Maskey, S., Werner, M., Pappenberger, F., van Beek, L. P. H., & Uhlenbrook, S. (2014). Comparison of different evaporation estimates over the African continent. *Hydrology and Earth System Sciences*, 18(1), 193–212. <https://doi.org/10.5194/hess-18-193-2014>
- Tweddle, P. B., Lyne, P. W. L., van Antwerpen, R., & Lagerwall, G. L. (2021). Chapter Three—A review and synthesis of sugarcane losses attributed to infield traffic. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 166, pp. 197–250). Academic Press. <https://doi.org/10.1016/bs.agron.2020.10.002>
- Valim, W. C., Panachuki, E., Pavei, D. S., Alves Sobrinho, T., & Almeida, W. S. (2016). Effect of sugarcane waste in the control of interrill erosion. *Semina: Ciências Agrárias (Londrina)*, 37(3), 1155–1164. <https://www.cabdirect.org/cabdirect/abstract/20163226955>
- van den Berg, M., & Singels, A. (2013). Modelling and monitoring for strategic yield gap diagnosis in the South African sugar belt. *Field Crops Research*, 143, 143–150. <https://doi.org/10.1016/j.fcr.2012.10.009>
- van Eekelen, M. W., Bastiaanssen, W. G. M., Jarmain, C., Jackson, B., Ferreira, F., van der Zaag, P., Saraiva Okello, A., Bosch, J., Dye, P., Bastidas-Obando, E., Dost, R. J. J., & Luxemburg, W. M. J. (2015). A novel approach to estimate direct and indirect water withdrawals from satellite measurements: A case study from the Incomati basin. *Agriculture, Ecosystems & Environment*, 200, 126–142. <https://doi.org/10.1016/j.agee.2014.10.023>
- Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T. C., Fereres, E., Heng, L. K., Garcia Vila, M., & Mejias Moreno, P. (2014). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling & Software*, 62, 351–360. <https://doi.org/10.1016/j.envsoft.2014.08.005>
- Veldkamp, A., & Lambin, E. F. (2001). Predicting land-use change. *Agriculture, Ecosystems & Environment*, 85(1), 1–6. [https://doi.org/10.1016/S0167-8809\(01\)00199-2](https://doi.org/10.1016/S0167-8809(01)00199-2)
- von Maltitz, G. P., Henley, G., Ogg, M., Samboko, P. C., Gasparatos, A., Read, M., Engelbrecht, F., & Ahmed, A. (2019). Institutional arrangements of outgrower sugarcane production in Southern Africa. *Development Southern Africa*, 36(2), 175–197. <https://doi.org/10.1080/0376835X.2018.1527215>

- Warburton Toucher, M., Schulze, R., & Jewitt, G. (2010). Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences*, 7. <https://doi.org/10.5194/hess-14-2399-2010>
- Watson, H. K. (2011). Potential to expand sustainable bioenergy from sugarcane in southern Africa. *Energy Policy*, 39(10), 5746–5750. <https://doi.org/10.1016/j.enpol.2010.07.035>
- Wellens, J., Raes, D., Fereres, E., Diels, J., Coppys, C., Adiele, J. G., Ezui, K. S. G., Becerra, L.-A., Selvaraj, M. G., Dercon, G., & Heng, L. K. (2022). Calibration and validation of the FAO AquaCrop water productivity model for cassava (*Manihot esculenta* Crantz). *Agricultural Water Management*, 263, 107491. <https://doi.org/10.1016/j.agwat.2022.107491>
- Wendimu, M. A., Henningsen, A., & Gibbon, P. (2016). Sugarcane Outgrowers in Ethiopia: “Forced” to Remain Poor? *World Development*, 83, 84–97. <https://doi.org/10.1016/j.worlddev.2016.03.002>
- World Bank. (2019). *The World Bank Annual Report 2019: Ending Poverty, Investing in Opportunity*. Washington, DC: World Bank. <https://doi.org/10.1596/978-1-4648-1470-9>
- Yang, L., Zhou, Y., Meng, B., Li, H., Zhan, J., Xiong, H., Zhao, H., Cong, W., Wang, X., Zhang, W., Lakshmanan, P., Deng, Y., Shi, X., Chen, X., & Zhang, F. (2022). Reconciling productivity, profitability and sustainability of small-holder sugarcane farms: A combined life cycle and data envelopment analysis. *Agricultural Systems*, 199, 103392. <https://doi.org/10.1016/j.agsy.2022.103392>
- Zhou, M. (2013). *Conventional Sugarcane Breeding in South Africa: Progress and Future Prospects*. 2013. <https://doi.org/10.4236/ajps.2013.42025>
- Zu, Q., Mi, C., Liu, D. L., He, L., Kuang, Z., Fang, Q., Ramp, D., Li, L., Wang, B., Chen, Y., Li, J., Jin, N., & Yu, Q. (2018). Spatio-temporal distribution of sugarcane potential yields and yield gaps in Southern China. *European Journal of Agronomy*, 92, 72–83. <https://doi.org/10.1016/j.eja.2017.10.005>
- Zulu, N. S., Sibanda, M., & Tlali, B. S. (2019). Factors Affecting Sugarcane Production by Small-Scale Growers in Ndwedwe Local Municipality, South Africa. *Agriculture*, 9(8), 170. <https://doi.org/10.3390/agriculture9080170>

Appendix 4A: Observed and Supplementary Input Data

```

Eston Mill Season 1
  6.0      : AquaCrop Version (March 2017)
30762     : First day of simulation period - 22 March 1985
31301     : Last day of simulation period - 12 September 1986
30762     : First day of cropping period - 22 March 1985
31301     : Last day of cropping period - 12 September 1986
  4        : Evaporation decline factor for stage II
  1.10    : Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil surface
  5        : Threshold for green CC below which HI can no longer increase (% cover)
  70       : Starting depth of root zone expansion curve (% of Zmin)
  5.00    : Maximum allowable root zone expansion (fixed at 5 cm/day)
  -6       : Shape factor for effect water stress on root zone expansion
  20       : Required soil water content in top soil for germination (% TAW)
  1.0      : Adjustment factor for FAO-adjustment soil water depletion (p) by ETo
  3        : Number of days after which deficient aeration is fully effective
  1.00    : Exponent of senescence factor adjusting drop in photosynthetic activity of dying crop
  12       : Decrease of p(sen) once early canopy senescence is triggered (% of p(sen))
  10       : Thickness top soil (cm) in which soil water depletion has to be determined
  30       : Depth [cm] of soil profile affected by water extraction by soil evaporation
  0.30    : Considered depth (m) of soil profile for calculation of mean soil water content for CN adjustment
  1        : CN is adjusted to Antecedent Moisture Class
  20       : salt diffusion factor (capacity for salt diffusion in micro pores) [%]
  100      : salt solubility [g/liter]
  16       : shape factor for effect of soil water content gradient on capillary rise
  12.0     : Default minimum temperature (°C) if no temperature file is specified
  28.0     : Default maximum temperature (°C) if no temperature file is specified
  3        : Default method for the calculation of growing degree days
-- 1. Climate (CLI) file
EstonMill.CLI
C:\MODELLING\AQUACROP\DATA\
1.1 Temperature (Tnx or TMP) file
EstonMill.TMP
C:\MODELLING\AQUACROP\DATA\
1.2 Reference ET (Eto) file
EstonMill.ETO
C:\MODELLING\AQUACROP\DATA\

```

Figure 4A.1 Example of a project data file (CLI) for the 1st season in the Eston Mill Area in South Africa.

```

EstonMill, South Africa 1Jan1984-31Dec2019
  6.1      : AquaCrop Version (May 2018)
EstonMill.TMP
EstonMill.ETO
EstonMill.PLU
MaunaLoa.CO2
|

```

Figure 4A.2 Example of an AquaCrop build menu. This menu contains all the climate parameter files that can only be edited within the model. This build menu specifies the available files and their extensions and the model run times.

```

organic mulches, practices preventing runoff
 6.0      : AquaCrop Version (March 2016)
 25      : percentage (%) of ground surface covered by mulches IN growing period
 50      : effect (%) of mulches on reduction of soil evaporation
 0       : Non-limiting soil fertility
 0.00    : height (m) of soil bunds
 0       : surface runoff NOT affected by field surface practices
 0       : N/A (surface runoff is not affected or completely prevented)
 0       : relative cover of weeds at canopy closure (%)
 0       : increase of relative cover of weeds in mid-season (+%)
 100.00  : shape factor of the CC expansion function in a weed infested field

```

Figure 4A.3 Example of a field management data file (MAN) Eston Mill Area in South Africa

```

a particular schedule
 3.2    : AquaCrop Version (January 2011)
 4      : Surface irrigation: Furrow
 90     : Percentage of soil surface wetted by irrigation
 1      : Irrigation schedule

  Day    Depth (mm)    ECw (dS/m)
  =====
  1      20            0.0
  5      20            0.0
 10      50            0.0
 20      50            0.0
 30      50            0.0
 40      50            0.0
 50      50            0.0
 60      50            0.0
 70      50            0.0

```

Figure 4A.4 Example of an irrigation input menu file (IRR) that can only be edited within AquaCrop.

```

1      : File not protected
1      : leafy vegetable crop
0      : Crop is transplanted
0      : Determination of crop cycle : by growing degree-days
1      : Soil water depletion factors (p) are adjusted by ETo
9.0    : Base temperature (°C) below which crop development does not progress
32.0   : Upper temperature (°C) above which crop development no longer increases with an increase in temperature
4267   : Total length of crop cycle in growing degree-days
0.20   : Soil water depletion factor for canopy expansion (p-exp) - Upper threshold
0.55   : Soil water depletion factor for canopy expansion (p-exp) - Lower threshold
3.0    : Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)
0.50   : Soil water depletion fraction for stomatal control (p - sto) - Upper threshold
3.0    : Shape factor for water stress coefficient for stomatal control (0.0 = straight line)
0.60   : Soil water depletion factor for canopy senescence (p - sen) - Upper threshold
3.0    : Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)
0      : Sum(ETo) during stress period to be exceeded before senescence is triggered
0.90   : Soil water depletion factor for pollination (p - pol) - Upper threshold
5      : Vol% for Anaerobiotic point (* (SAT - [vol%]) at which deficient aeration occurs *)
50     : Considered soil fertility stress for calibration of stress response (%)
25.00  : Response of canopy expansion is not considered
25.00  : Response of maximum canopy cover is not considered
25.00  : Response of crop Water Productivity is not considered
25.00  : Response of decline of canopy cover is not considered
-9     : dummy - Parameter no longer required
8      : Minimum air temperature below which pollination starts to fail (cold stress) (°C)
40     : Maximum air temperature above which pollination starts to fail (heat stress) (°C)
12.0   : Minimum growing degrees required for full crop transpiration (°C - day)
2      : Electrical Conductivity of soil saturation extract at which crop starts to be affected by soil salinity (dS/m)
19     : Electrical Conductivity of soil saturation extract at which crop can no longer grow (dS/m)
-9     : Dummy - no longer applicable
25     : Calibrated distortion (%) of CC due to salinity stress (Range: 0 (none) to +100 (very strong))
100    : Calibrated response (%) of stomata stress to ECsw (Range: 0 (none) to +200 (extreme))
1.10   : Crop coefficient when canopy is complete but prior to senescence (KcTr,x)
0.150  : Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.
0.30   : Minimum effective rooting depth (m)
1.80   : Maximum effective rooting depth (m)

```

```

6.50   : Canopy size of individual plant (re-growth) at 1st day (cm2)
140000 : Number of plants per hectare
0.07798 : Canopy growth coefficient (CGC): Increase in canopy cover (fraction soil cover per day)
-9      : Maximum decrease of Canopy Growth Coefficient in and between seasons - Not Applicable
-9      : Number of seasons at which maximum decrease of Canopy Growth Coefficient is reached - Not Applicable
-9.0    : Shape factor for decrease Canopy Growth Coefficient - Not Applicable
0.95    : Maximum canopy cover (CCx) in fraction soil cover
0.07839 : Canopy decline coefficient (CDC): Decrease in canopy cover (in fraction per day)
10      : Calendar Days: from transplanting to recovered transplant
94      : Calendar Days: from transplanting to maximum rooting depth
322     : Calendar Days: from transplanting to start senescence
500     : Calendar Days: from transplanting to maturity
0       : Calendar Days: from transplanting to flowering
0       : Length of the flowering stage (days)
0       : Crop determinancy unlinked with flowering
20      : Building up of Harvest Index (% of growing cycle)
100     : Building up of Harvest Index starting at sowing/transplanting (days)
30.0    : Water Productivity normalized for ETo and CO2 (WP*) (gram/m2)
100     : Water Productivity normalized for ETo and CO2 during yield formation (as % WP*)
50      : Crop performance under elevated atmospheric CO2 concentration (%)
35      : Reference Harvest Index (HIo) (%)
-9      : Possible increase (%) of HI due to water stress before flowering
-9.0    : No impact on HI of restricted vegetative growth during yield formation
-9.0    : No effect on HI of stomatal closure during yield formation
-9      : Allowable maximum increase (%) of specified HI
82      : GDDays: from transplanting to recovered transplant
673     : GDDays: from transplanting to maximum rooting depth
2773    : GDDays: from transplanting to start senescence
4267    : GDDays: from transplanting to maturity
0       : GDDays: from transplanting to flowering
0       : Length of the flowering stage (growing degree days)
0.011209 : CGC for GGDays: Increase in canopy cover (in fraction soil cover per growing-degree day)
0.006549 : CDC for GGDays: Decrease in canopy cover (in fraction per growing-degree day)
709     : GDDays: building-up of Harvest Index during yield formation

```

Figure 4A.5 Example of a crop data file (CRO) for the 1st season in the Eston Mill Area in South Africa.

```
Nearly totals (Climate file: UnionMill.CLI; Crop file: SugarCaneEston.CRO; Tbase: 9.0°C and Tupper: 32.0°C)
AquaCrop 6.0 (March 2017) - Output created on (date) : 2018/09/20 at (time) : 18:00:13

Rainfall expressed in mm/year - (Rainfall file: UnionMill.PLU): 35 complete years
ETo expressed in mm/year - (ETo file: UnionMill.ETO): incomplete first and last year
```

Year	Rain	ETo
1984	1065.1	897.9
1985	1044.1	1831.2
1986	870.1	1958.0
1987	1596.8	1821.5
1988	1146.5	1555.1
1989	943.1	1619.4
1990	908.7	1691.1
1991	1066.8	1536.2
1992	705.0	1724.4
1993	875.1	1780.7
1994	849.6	1789.9
1995	845.0	1851.5
1996	1041.9	1964.0
1997	1206.8	1679.1
1998	1081.7	1635.9
1999	861.4	1614.2
2000	732.4	1662.9
2001	956.5	1667.0
2002	873.6	1504.6
2003	866.3	1853.5
2004	630.4	1687.9
2005	789.7	1716.4
2006	813.2	1522.8
2007	1124.3	1469.6
2008	943.2	1628.4
2009	790.4	1396.5
2010	1000.9	1413.1
2011	809.3	1461.4
2012	1027.8	1514.6

Figure 4A.6 Example of an observed climate data file (CLI) for the Union Mill Area in South Africa.

Figure 4A.713 Example of an observed climate data file (CLI) for the Eston Mill

```
AquaCrop 6.0 (March 2017) - Output created on (date) : 2021/10/21 at (time) : 08:45:02
Climate input data
```

** Run number: 1										
Day	Month	Year	DAP	Stage	Rain mm	ETo mm	Tmin °C	Tavg °C	Tmax °C	CO2 ppm
1	1	1985	1	1	0.0	4.3	16.3	20.9	25.5	346.77
2	1	1985	2	1	0.0	5.3	16.7	24.1	31.6	346.77
3	1	1985	3	1	3.7	2.7	17.5	22.6	27.6	346.77
4	1	1985	4	1	6.8	2.9	15.9	19.1	22.2	346.77
5	1	1985	5	1	1.4	3.0	16.4	22.5	28.7	346.77
6	1	1985	6	1	0.0	2.0	19.2	24.8	30.4	346.77
7	1	1985	7	1	0.0	1.8	17.3	23.5	29.6	346.77
8	1	1985	8	1	0.0	5.0	17.7	26.2	34.7	346.77
9	1	1985	9	1	0.0	5.3	19.6	25.6	31.5	346.77
10	1	1985	10	1	0.5	3.5	19.7	24.4	29.2	346.77
11	1	1985	11	1	0.0	4.3	20.7	24.8	28.8	346.77
12	1	1985	12	1	0.0	9.0	16.8	17.6	18.5	346.77
13	1	1985	13	1	0.5	4.3	16.3	20.2	24.1	346.77
14	1	1985	14	1	0.0	4.0	17.5	23.3	29.1	346.77
15	1	1985	15	1	30.4	6.5	14.9	16.4	17.8	346.77
16	1	1985	16	1	28.9	7.3	14.5	17.9	21.4	346.77
17	1	1985	17	1	16.9	4.8	15.8	21.7	27.6	346.77
18	1	1985	18	1	4.3	1.3	16.7	24.2	31.7	346.77
19	1	1985	19	1	2.6	3.5	19.4	25.9	32.5	346.77
20	1	1985	20	1	1.2	2.8	18.5	23.5	28.5	346.77
21	1	1985	21	1	0.0	3.5	15.5	19.1	22.6	346.77
22	1	1985	22	1	0.0	3.5	16.3	23.4	30.5	346.77
23	1	1985	23	1	0.0	0.5	18.8	21.0	23.1	346.77
24	1	1985	24	1	6.5	1.0	17.9	22.7	27.5	346.77
25	1	1985	25	1	0.2	5.3	18.1	23.9	29.7	346.77
26	1	1985	26	1	0.0	4.8	18.4	21.8	25.2	346.77
27	1	1985	27	1	0.2	4.8	17.4	22.3	27.1	346.77
28	1	1985	28	1	0.0	5.5	17.8	26.3	34.8	346.77
29	1	1985	29	1	0.0	4.5	21.1	27.5	33.9	346.77
30	1	1985	30	1	0.2	5.8	20.4	24.2	28.0	346.77

Area in South Africa for the year 1985. This climate file spanned 1984-2019.

GD	Z	StExp	StSto	StSen	StSalt	StWleed	CC	CCw	StTr	Kc(Tr)	Trx	Tr	TrW	Tr/Trx	WP	Biomass	HI	YieldPart	Brelative	WPet
°C-day	m	%	%	%	%	%	%	%	%	-	mm	mm	mm	%	g/m2	ton/ha	%	ton/ha	%	kg/m3
11.9	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.1	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
13.6	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
10.1	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
13.5	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.8	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
14.5	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.9	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
16.6	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.4	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.8	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
8.6	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
11.2	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
14.3	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
7.4	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
8.9	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
12.7	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.2	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
16.7	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
14.5	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
10.1	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
14.4	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
12.0	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
13.7	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
14.9	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
12.8	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
13.3	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
15.9	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00
17.6	0.30	-9	-9	-9	0	-9	0.0	0.0	0	-9.00	0.0	0.0	0.0	100	29.1	0.000	-9.9	0.000	-9	0.00

Figure 4A.8 Example output data file (OUT) for the Eston Mill Area in South Africa for the year 1996.

Table 4A.1 The full set of AquaCrop observed files used in this study have been made available in the links indicated.

Mill Area	File Type					
	Menu (PLU)	Climate (CLI)	Soil (SOL)	Crop (CRO)	Field Management (MAN)	Irrigation (IRR)
Eston	https://doi:10.5061/dryad.2547d7wz1					
UCL	https://datadryad.org/stash/share/SAc7269mjkZNv3OvnvqIV2bpNRVuoqOHyclIsb4v8DI					
Noodsberg	https://www.dropbox.com/home/AquaCrop%20Menu%20Inputs?di=left_nav_browse					
Ubombo	https://www.dropbox.com/home/AquaCrop%20Menu%20Inputs/AquaCrop%20Data%20Files?di=left_nav_browse					
Nchalo	https://www.dropbox.com/home/Reference%20Data?di=left_nav_browse					
Kilombero	https://www.dropbox.com/home/Reference%20Data?di=left_nav_browse					

CHAPTER FIVE
AN ASSESSMENT OF THE VULNERABILITY AND ADAPTATION
POTENTIAL OF SUGARCANE PRODUCTION TO WATER STRESS
ACROSS SOUTHERN AFRICA

Ngcobo, S.I.^{1*}, Jewitt, G^{2,3.}, Hill, T.R^{4.}, Archer, E^{5.}

¹ 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.

² Department Water Resources and Ecosystems, IHE Delft Institute for Water Education, PO Box 3015, 2601DA Delft, The Netherlands.

³ Water Management, Civil Engineering & Geosciences, TU Delft, PO Box 5048, 2600 GA Delft, The Netherlands.

⁴ Discipline of Geography, School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg Campus, King Edward Avenue, Scottsville, Pietermaritzburg, 3209, South Africa.

⁵ Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Hatfield 0028, South Africa.

**Corresponding author.*

E-mail address: ngcobos21@ukzn.ac.za (S. Ngcobo)

Abstract

The high spatial variability of rainfall in southern Africa presents significant challenges for sugarcane production. An increase in the frequency of droughts has been observed in the recent past and this has increased the risk of exposure to water stress for the sugarcane production value chain. Regardless, the economic and social importance of this activity for supporting livelihoods has seen the rapid expansion and intensification of this activity in the past few decades. However, despite this, sugarcane yields have been consistently declining as a result of challenges related to water resources management, climatic change and the agronomic management of sugarcane. By amplifying precipitation variability, climate change will increase the vulnerability of sugarcane to water stress and is likely to negatively impact sugarcane yields. Using a combination of crop simulations and a relationship between actual sugarcane water use and observed rainfall over 25 growing cycles, this study introduces a crop productivity ratio (CPR) which seeks to assess sugarcane water stress for six sugarcane mills located across four catchments in southern Africa. The combination of the CPR and simulation results was used to assess the adaptation space or potential for individual mill areas. Results showed that various mill areas have differing rates of exposure to water stress and thus have different abilities to adapt and respond to the effects of water stress. Simulation results combined with the CPR were used to determine the long-term adaption potential of individual mill areas and the actual cause of yield declines. The safe and unsafe adaptation spaces were directly correlated to the simulation results and the CPR. By amplifying inter-annual precipitation variability, it is not unreasonable to estimate that climate change will amplify water stress within the individual mill areas included in this study. It was concluded that adapting to a changing climate is a multifaceted exercise that requires a holistic approach that includes every aspect of sugarcane value chain. Improving the understanding of the impacts of climatic extremes across the sugarcane value chain, *i.e.* from planting to cultivation to processing, is crucial in reducing the vulnerability of sugarcane to water stress.

Key words: Crop Productivity Ratio, Adaptation Spaces, Water Stress, Vulnerability, Sugarcane Production.

5.1 Introduction

Sugarcane production from commercial and small-scale outgrowers is a crucial component of economic and social wellbeing for a number of countries across southern Africa. Outgrowers are defined in this study as small-scale sugarcane producers that primarily grow sugarcane from smallholdings to supply larger commercial growers through binding long-term contractual agreements (Wendimu et al., 2016; Sulle, 2017; von Maltitz et al., 2019). The viability and sustainability of sugarcane production, however, is under threat due to the increased frequency of extreme hydrological events that include prolonged droughts and extreme floods (Hennessy et al., 2022). The SADC region produces approximately 58% of total African sugar production, exporting over 1.2 million tonnes of refined sugar annually and in the 2018/2019 growing cycle generated revenues in excess of \$2.15 billion (SADC Sugar Digest, 2019; South African Sugar Research Institute, 2019). Between 2015 and 2020 the number of outgrowers and commercial sugarcane producers has grown by nearly 7% in southern Africa (Marais, 2022; Syngenta, 2022;) and this growth has created thousands of indirect and direct employment opportunities in this job starved region (Dubb et al., 2017). Over the same time period, regional sugar production accounted for approximately 11% of total earnings from agricultural commodities (Dal Belo Leite et al., 2020). This is despite a consistent decline in global sugar demand and the increased frequency of interruptions in the sugarcane supply chain (Shavazipour et al., 2020). 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 numerous countries across southern Africa.

Sugarcane is harvested in over 785 000Ha across southern Africa under complex hydrological, agronomic and socio-economic conditions (Hess et al., 2016; Chinsinga, 2017). In catchments where sugarcane is grown, the crop can consume as much as 40% of available water resources (Mekonnen & Hoekstra, 2010; Singels et al., 2021). 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 (Gleick, 2000; Schulze, 2000; Laing et al., 2011). 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, a complex hybrid of the *Saccharum* species, is a water use intensive crop, with reported mean annual crop water use/actual evapotranspiration (ET_C) rates ranging between 1 100 and 1 800mm.annum⁻¹ for a full canopy crop (Carr & Knox, 2011) and requires approximately 850mm of water per growing cycle for sustainable rainfed production (Jones et al., 2015b). These water use estimates should be seen in the context of potential evapotranspiration (ET_O) rates ranging between 1 610 and 2 800mm.annum⁻¹ across the region (Watson, 2011; FAO Aquastat, 2020). Considering the high sensitivity of sugarcane yields to water stress (Bezuidenhout & Singels, 2007; Dunkelberg et al., 2014; Olivier & Singels, 2015; Inman-Bamber et al., 2016), these estimates present important implications for the sustainability of both the sugar industry and for the severely pressured water resources across the region, particularly under a changing climate.

The current and projected changes to climatic patterns (IPCC, 2022) 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, 2022), increase drought risks (Archer et al., 2019), undermine water availability (Jones et al., 2015b) and increase the risks of diminished sugarcane yields (Knox et al., 2010a). By increasing the variability of an already highly variable hydroclimatic environment and ultimately impacting the seasonality and availability of water resources, climate change could negatively impact the sugar industry. Climate change is already affecting runoff generation (Roudier et al., 2014), total evaporation rates (Trambauer et al., 2014), nutrient retention (Ofori et al., 2021), and is expected to increase the exposure of sugarcane to water stress and directly impact sugarcane yields (Knox et al., 2010a; Jones et al., 2015c). Since all mill areas in this study adopt multiyear growing cycles spanning 18 to 24 months, the focus will be on inter-annual precipitation variability as the fundamental 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. 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 (van den Berg & Singels, 2013) (**Figure 5.1**), as stated earlier, access to adequate amounts of water at the correct intervals required 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 (Silva et al., 2017a) which can affect the economic viability of cultivating the crop in the region.

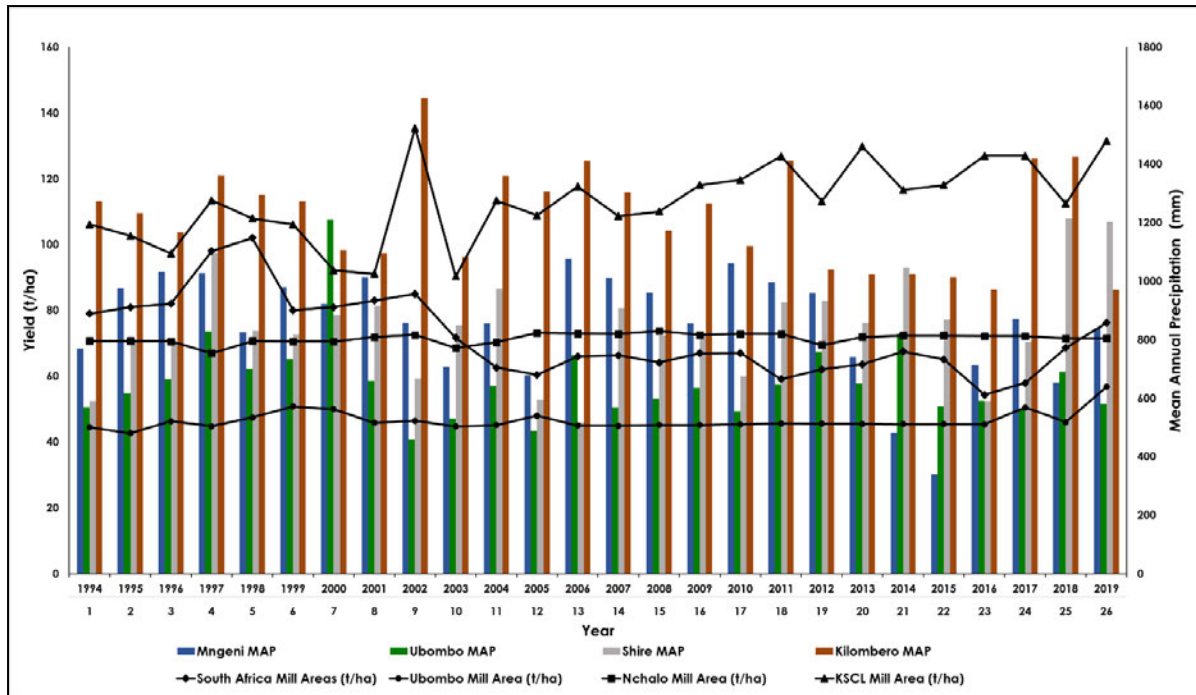


Figure 5.1 Average sugarcane yields ($\times 000t/annum$) and mean annual precipitation (MAP) for individual mill areas between 1994 and 2019 (Data Sources: FAO-Aquastat, 2020; Illovo Sugar Africa, 2020; NASA POWER Project, 2021).

Water stress of irrigated and rain-fed sugarcane production systems is detrimental to above-ground biomass accumulation and yields (Inman-Bamber et al., 2002; Olivier & Singels, 2015). In instances where sugarcane is subjected to water stress, crucial processes such as the rate of photosynthesis, nutrient uptake and structural growth can be curtailed leading to a decline in yield quantity (C. Bezuidenhout & Singels, 2007; Matsa & Muyemeki, 2010; Dunkelberg et al., 2014; van Eekelen et al., 2015). 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, 2019), but for enhancing the adaptive capacity of outgrowers and commercial producers with the aim of improving agronomic management and planning (Lumsden et al., 2000;

Bezuidenhout & Singels, 2007; Suresh & Nagesh, 2015). As a consequence of their limitations related to access to finances, current climate change data and information, crop modelling and 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 (Baskin, 2022; Cairns et al., 2021; Fischer & Hajdu, 2015; B. Mhlanga et al., 2022). 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. For instance, increased production costs during seasonal droughts can have a significantly damaging effect on the ability of outgrowers to break-even and maintain a viable sugarcane production enterprise.

Despite the recognition of the effects of water stress caused by seasonal droughts, field and other agronomic management practices on important commodity crops such as maize (Cairns et al., 2021), cassava (Kayiwa et al., 2021) and sweet potatoes (Laurie et al., 2015), there is limited research that addresses the vulnerability and adaptation potential of sugarcane to water stress in southern Africa. Although several studies (Knox et al., 2010a; Srivastava & Rai, 2012; Singels et al., 2014; Adhikari et al., 2015; Linnenluecke et al., 2018) have addressed the impacts of climate change on sugarcane production in the region, 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. There are currently few studies that have performed a regional assessment of the vulnerability of sugarcane to inter-annual dry periods over sufficient temporal scales. This is an important research gap since such studies would provide important insights derived from unique sugarcane production systems and from different perspectives that can address the vulnerability and adaptation potential of sugarcane.

To address this research gap, the aims of this study were to assess the vulnerability and adaptation potential of sugarcane production to climate and management-related water stress in selected mill areas across southern Africa, and to recommend viable adaptation strategies to ensure the sustainability of sugarcane production. These strategies would necessarily need to be applicable across the majority of the southern African sugarcane production industry. The objectives of this study were:

- 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,
- 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 finally,
- to define the adaptation potential or adaptation ‘space’ for outgrowers and commercial sugarcane producers and make recommendations regarding adaptation to climatic extremes in selected mill areas across southern Africa.

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

5.2 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). 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 (**Figure 5.2**) were selected specifically owing to their varied hydroclimatic conditions, relatively high sugarcane production levels (**Figure 5.1**), distinctive management approaches, access to long-term climate and production data (**Table 5.1**) 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 crop growth model, simulations, the determination of actual sugarcane water use and the identification of adaptation spaces are described in the following sections. 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.

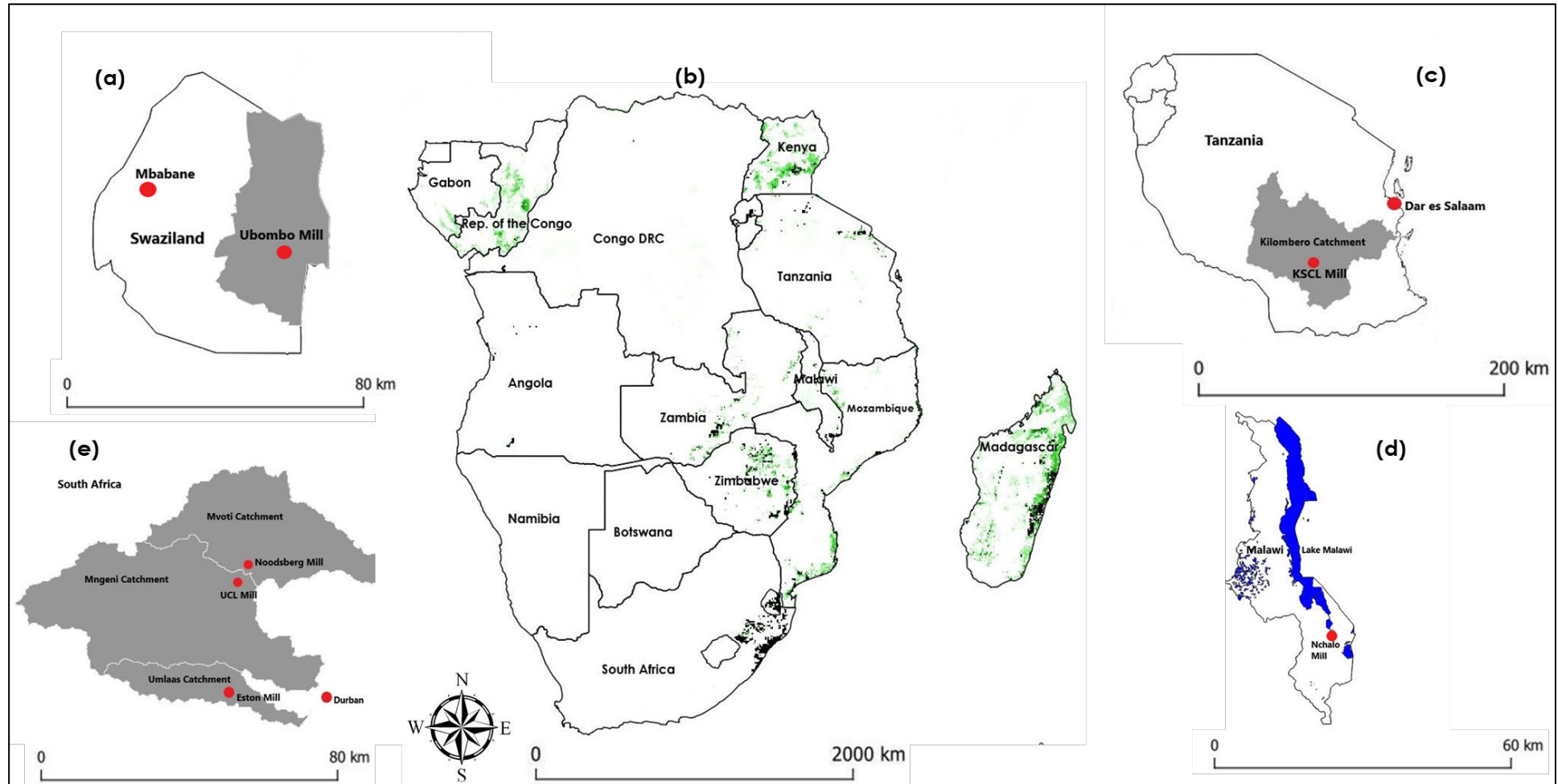


Figure 5.2 Clockwise from top-left: **a)** the Ubombo Catchment in Swaziland, **b)** Spatial distribution of sugarcane production areas across Southern African based on modelled data (Harvest-Choice, 2015), **c)** the Kilombero Catchment in Tanzania. **d)** the Shire Catchment in Malawi and **e)** the Mvoti, Umlaas and Mngeni Catchments in South Africa. Mill locations within individual catchments and the spatial extent of the area under sugarcane across the region are also reflected (Harvest-Choice, 2019).

Table 5.1 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	1 570 – 1 740	Rainfed	36 728	1 124 488
Noodsberg	Mngeni (SA)	787	1 570 – 1 740	Rainfed	29 917	1 326 214
Union Cooperative Limited (UCL)	Mngeni (SA)	893	1 570 – 1 740	Rainfed	18 433	712 257
Big Bend	Ubombo (SWA)	659	2000 – 2 200	Irrigated	10 987	1 303 750
Nchalo	Shire (MAL)	814	1 500- 1 800	Irrigated and Rainfed	19 520	1 680 000
Kilombero	Morogoro (TNZ)	1223	1 600 – 1 800	Irrigated and Rainfed	21 800	1 200 000

5.3 Methods

5.3.1 Introduction

The vulnerability of sugarcane to extended dry conditions, and thus water stress, can be determined by correlating observed yield data with annual sugarcane water use. Sustained reductions in plant-available water (PAW) resulting from low rainfall, high total evaporation rates and poor irrigation management can potentially lead to reduced yields and enhance the vulnerability of sugarcane to water stress resulting from dry conditions. Crop simulation models such as the AquaCrop model (Steduto et al., 2009; **Section 5.3.2**) can be used to simulate the variables required to determine the vulnerability of sugarcane to water stress instigated by extreme climatic conditions.

This study used a combination of the AquaCrop model and average observed sugarcane yields reported by primary and secondary sources to determine maximum potential sugarcane yields (**Section 5.3.3**). 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’ (see **Section 5.3.6**) 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.

The methodology adopted in this study may be summarised in the following narrative:

- 1) Use the AquaCrop model to simulate the maximum potential yields that would be achieved under ideal agronomic growing conditions for each mill area, *i.e.* assuming no climatic, crop, water or other field management related limitations,
- 2) Use observed sugarcane yields from the mill areas to determine the annualized actual sugarcane water use following the Thompson (1976) and Bezuidenhout *et al.*, (2006) empirical water use equations for mill areas,
- 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.

The observed yield data reported for each mill area in any growing cycle represents a yield deficit and does not reflect the maximum potential yield that can be achieved under ideal agronomic growing conditions. Sugarcane yields have been steadily declining over the past 25 years across southern Africa (**Figure 5.1**) owing to a combination of factors which include, but are not limited to, increased pest outbreaks, increased frequency of seasonal droughts leading to increased competition for water resources and high operational costs (Jones *et al.*, 2015a; Pryor *et al.*, 2017; Zulu *et al.*, 2019; Meyer & Antwerpen, 2021). These factors suggest that sugarcane production is becoming increasingly vulnerable to the adverse hydroclimatic, socio-political and economic landscape in the southern African sugarcane industry.

Further, the anticipated increases in inter-annual rainfall variability and the corresponding changes to rainfall seasonality caused by the increased frequency of droughts will potentially increase PAW deficits and enhance sugarcane vulnerability to water stress in the region (Hennessy et al., 2022).

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 $6\text{mm}\cdot\text{day}^{-1}$ required for phenological development (Eksteen et al., 2014), the stress this can induce can reduce above-ground biomass by up to 8% depending on the timing, severity and duration of water stress (Abayomi & Lawal, 1998) thus necessitating increases in supplementary irrigation. Similarly, if rainfall or effective irrigation over a growing cycle does not exceed the critical threshold required to prevent the onset of water stress, total yields may be compromised which can further undermine the viability of sugarcane production (Jangpromma et al., 2012). Furthermore, the outbreak of pests as a consequence of high maximum temperatures, weather changes, loss of habitat and the absence of pest control measures over a growing cycle can enhance vulnerability and potentially suppress yields (Olivier & Singels, 2015). 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 (Singels et al., 2019; Adetoro et al., 2020; Singels et al., 2010) .

This study uses observed yields to determine actual sugarcane water use based on an empirical relationship proposed by Thompson (1976) and 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 incisiveness and flexibility of agronomic management and iii) the favourability of the sugarcane production landscape with respect to legislation governing agricultural production (*e.g.* tax breaks, access to global markets, incentives and subsidies). 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. Further, sugarcane production systems that are not effectively insulated from external shocks such as extreme hydrological events and sudden exclusions from international markets due to supply chain problems and the prioritization of commercial growers over outgrowers, among others, would need greater adaptation interventions.

5.3.2 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 (Steduto et al., 2009; Tesfay et al., 2019; Vanuytrecht et al., 2014) (**Figure 5.3**). 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.

AquaCrop simulates three major parameters which determine crop yields: total evaporation, canopy growth and development and crop water productivity (Revathy & Balamurali, 2022). In this study, the product of above-ground biomass and the harvest index (*HI*) (Vanuytrecht et al., 2014) 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 5.3**). 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.

AquaCrop uses a water stress coefficient to simulate the degree, duration and timing of water stress. This coefficient reflects the rate of water depletion in the root zone and, by extension, is indicative of PAW and soil water depletion. The volume of soil water content determines PAW deficits, which, as mentioned before, determines the exposure of the crop to water stress and has a significant impact on yields.

Table 5.2 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
Noodsberg	Mngeni (RSA)	1994-2019	25	https://sasri.sasa.org.za/rtwd/458/index.html , Accessed: August 2019 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

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 (**Figure 5.3**). The model has been calibrated and verified in a number of studies conducted in Brazil (Silva et al., 2017b; Rosa et al., 2019), southern China (Iqbal et al., 2014; Zu et al., 2018) , India (Sandhu et al., 2015; Babel et al., 2019) and in South Africa (Mabhaudhi et al., 2014; Hadebe et al., 2020; Mubvuma et al., 2021).

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 5.1**).

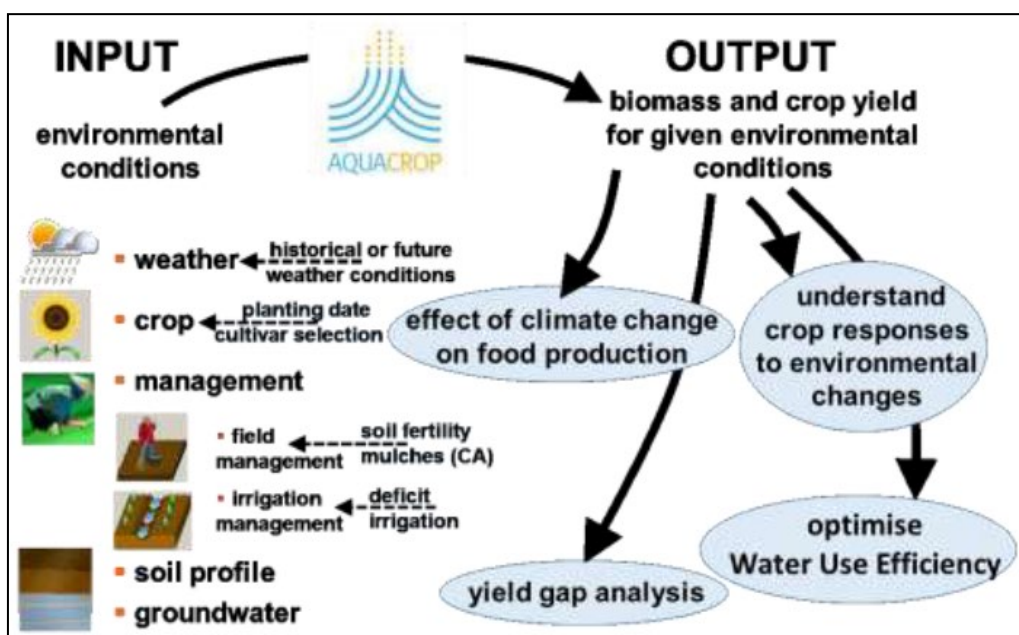


Figure 5.3 Examples of practical AquaCrop applications (Vanuytrecht et al., 2014).

4.7.1 Data Sources and Availability

Observed average seasonal yield data were obtained from FAO-Aquastat (2020), 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 5.3**). South Africa (1994-2019) and eSwatini (1996-2019) had the longest observed yield data. The majority of observed sugarcane yield data from Malawi and Tanzania had to be estimated from the total output per growing cycle and area under sugarcane as reported by the mills as there were either no known or reliable records prior to the year 2000. The main limitation with observed datasets from Malawi and Tanzania was the lack of independent verification; therefore, it was necessary to determine observed yields from available area and mill crush/production data to create a yield record from secondary sources.

Where necessary, the records from these sources were checked for errors using data profiling, identifying outliers, double-mass plots and third party tools such as the ACRU Time Series Analysis software to find and correct anomalous records (Smithers et al., 2018). Following these exercises, the datasets were considered to be a true reflection of observed records that could be used in the modelling exercise. Missing daily climate data had to be infilled using data from weather stations closest to the mills. Some missing data values that could not be infilled, quality controlled or sourced from veritable sources were defaulted to standard values 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_0 data from observed temperature records using the built-in approximation procedures embedded within the model. ET_0 was calculated within the model based on the FAO Penman-Monteith equation (Allen et al., 2006). 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 entire mill area (Bezuidenhout & Singels, 2007). The datasets generated 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 various researchers (Rice et al., 2002; Singels, Smit, et al., 2005; Daroub et al., 2011) and the USDA, Harvest-Choice and the FAO-AGRIS databases.

5.3.3 Simulation Procedures

The AquaCrop model requires daily observed rainfall, minimum and maximum temperature, ET_0 and atmospheric CO_2 concentration as input. The acquisition and processing of climate data is described in **Section 5.3.3**. The climate module was set up for individual mill areas with the exception of the Noodsberg and UCL mills which were combined as a single mill as they regularly 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, the records were used as input into the model.

The model was run with the assumption that the full set of crop development and production parameters was available. 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 small and progressively growing until maximum canopy cover was reached over the growing cycle.

Plant densities varied between mill areas with each mill area 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). Plant density estimates are a crucial component that directly influence overall above-ground biomass and harvestable yields, and these estimates were based on planting and seeding densities as reported by the mill areas and as recommended by SASRI (2019), the UN-FAO (2018) and Singels et al., (2005). 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. Days to reach emergence, maximum canopy cover, senescence and maturity were determined based on calendar days and seasonal growing length for each mill area. For instance, the Ubombo mill area adopts an 18-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 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 sensitive to any degree of soil water stress, total evaporation stress, and fertility stress, although the latter was not invoked. Non-conservative coefficients related to ET_0 , 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 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 PAW. It was assumed that once PAW reached or dropped below 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 mill areas. The Ubombo mill area is exclusively irrigated and the irrigation option was invoked assuming surface irrigation with an allowable PAW depletion of 10% required 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 all 6 mill areas spanning the length of the available data records (*i.e.* for 19 to 25 growing cycles) (**Figure 5.4**).

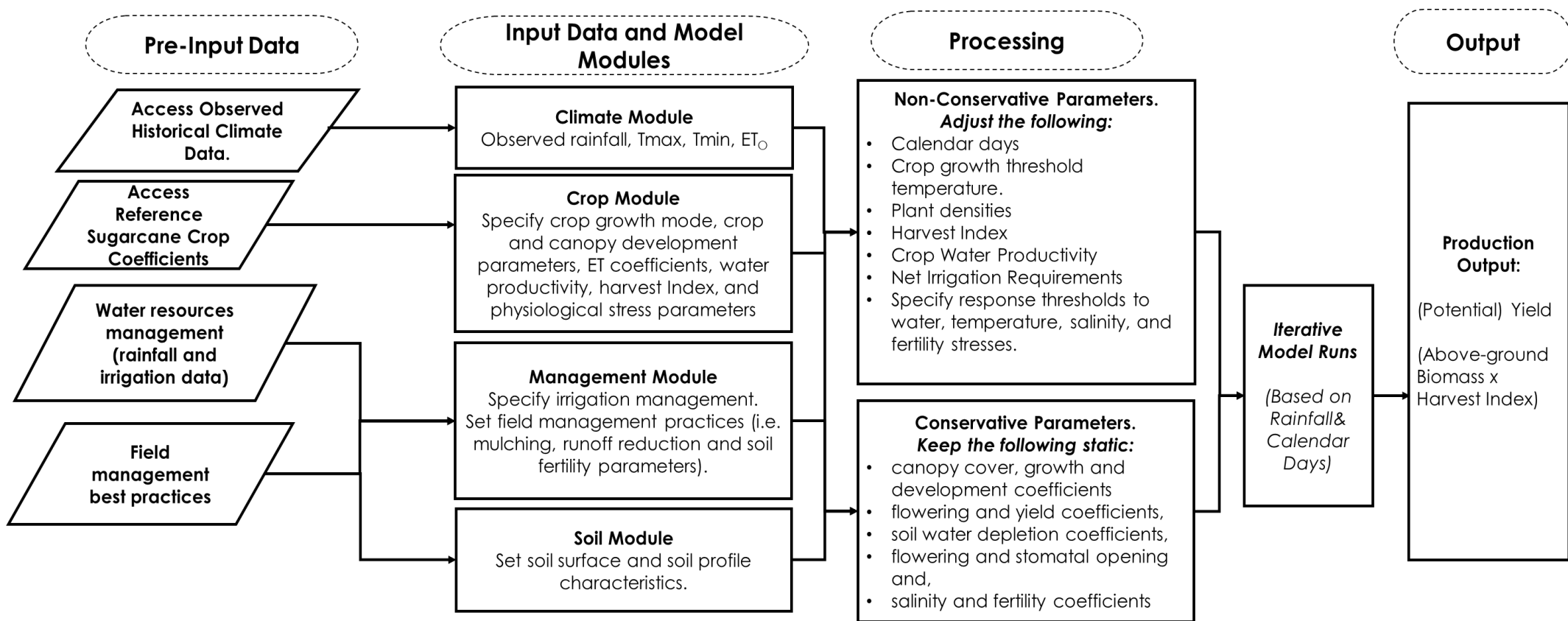


Figure 5.4 A summary of the modelling procedures in the AquaCrop model adopted in this study to simulate maximum potential sugarcane yields.

5.3.4 Seasonal Sugarcane Water Use

Total evaporation (ET_C in $\text{mm}\cdot\text{day}^{-1}$) reflects daily sugarcane water use. The parameter is limited by various factors which include, but are not limited to, crop height, leaf expansion rates, canopy and ground cover, plant available water (PAW), canopy temperature, and agronomic management. In the AquaCrop model, ET_C is obtained by relating the crop coefficient (K_C) with the reference evapotranspiration (ET_O) under suitable conditions *i.e.*, without limitations related to water, soil, and field management thus:

$$ET_C = K_C \times ET_O \quad (5.1)$$

In the AquaCrop model, the crop coefficient (K_C) for a full canopy crop was set to the standard 1.25 for sugarcane, and ET_O was derived from observed temperature records and estimated using the Penman-Monteith ET_O calculator embedded within the model (N. G. Inman-Bamber, 2004; N. G. Inman-Bamber & Smith, 2005) (**Equation 5.2**):

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_2 + 273} uD}{\Delta + \gamma(1 + 0.34\mu)} \quad (5.2)$$

Where R_n represents the net radiation ($\text{W}\cdot\text{m}^{-2}$), γ is the psychrometric constant ($\text{kPa}\cdot\text{°C}^{-1}$), Δ is the slope of the saturation vapour pressure curve ($\text{kPa}\cdot\text{°C}^{-1}$), T is the maximum air temperature (°C), u is the wind speed ($\text{m}\cdot\text{s}^{-1}$), G is soil heat storage ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) and D is the saturation vapor pressure deficit (kPa). Thompson (1976), Bakker (2012) 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 5.3**, thus:

$$Yield = 9.53 \frac{\sum ET_C}{100} - 2.36 \quad (5.3)$$

Where $Yield$ is the annualized observed sugarcane yield ($\text{t}\cdot\text{ha}^{-1}\cdot\text{annum}^{-1}$) and ET_C is the actual total evaporation ($\text{mm}\cdot\text{day}^{-1}$). The derivations from studies conducted by Thompson (1976) and (Bakker, 2012), Bezuidenhout *et al.*, (2006) were also 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 5.4**:

$$wu = \frac{100 (Yield+2.36)}{9.53} \quad (5.4)$$

It is important to note that wu and thus *Yield* as reflected in **Eq. 5.4** 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 is defining the vulnerability of sugarcane to water stress, understanding the relationship between observed yields, actual sugarcane water use and observed rainfall is vital. This relationship is expressed as the Crop Productivity Ratio and reflects the efficiency of water use in growing sugarcane over a growing cycle. The concept of the Crop Productivity Ratio is expanded on in the following section.

5.3.5 Crop Productivity Ratio

The Crop Productivity Ratio (hereafter the CPR) proposed in this study can assist 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 5.5** thus:

$$\text{Crop Productivity Ratio} = \frac{\text{Actual Water Use } (wu)}{\text{Annualised Observed Rainfall } (P)} \quad (5.5)$$

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 therefore 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. As mentioned before, 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. Regardless of whether the CPR is above or below 1, there is scope for improving efficiencies, reducing exposure to water stress and increasing the adaptation potential for each mill area.

5.4 Adaptation Spaces

Adaptation may be defined as the process of adjustment to actual or expected climatic stimuli and their effects in order to alleviate adverse impacts of change or take advantage of new opportunities (IPCC, 2001; Adger et al., 2009; 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 (**Figure 5.5**). 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. In this study, a mill area would exist in the unsafe or high-risk adaptation space if it consistently experiences a CPR lower than 1 and relatively low yields and in the safe adaptation space if it experiences a CPR above 1 and high yields. It is acknowledged that the positioning of a mill area in this adaptation space can change between growing cycles depending on the interventions applied as and when conditions become unfavourable. The purpose of this study was not to determine the positioning of a mill area in this space for individual growing cycles, but to assess the average long-term exposure to water stress based on the CPR and make conclusions regarding the vulnerability and adaptation potential of each mill area.

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 (**Figure 5.5**). 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 rapidly 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. A historically well-performing mill area can fall in the unsafe adaptation space due to inflexible management practices and increases in the frequency of extreme climatic events, while a

poorly performing mill area can have strong adaptation potential owing to a positive production environment reinforced by supportive policies necessitated by unfavorable climatic changes.

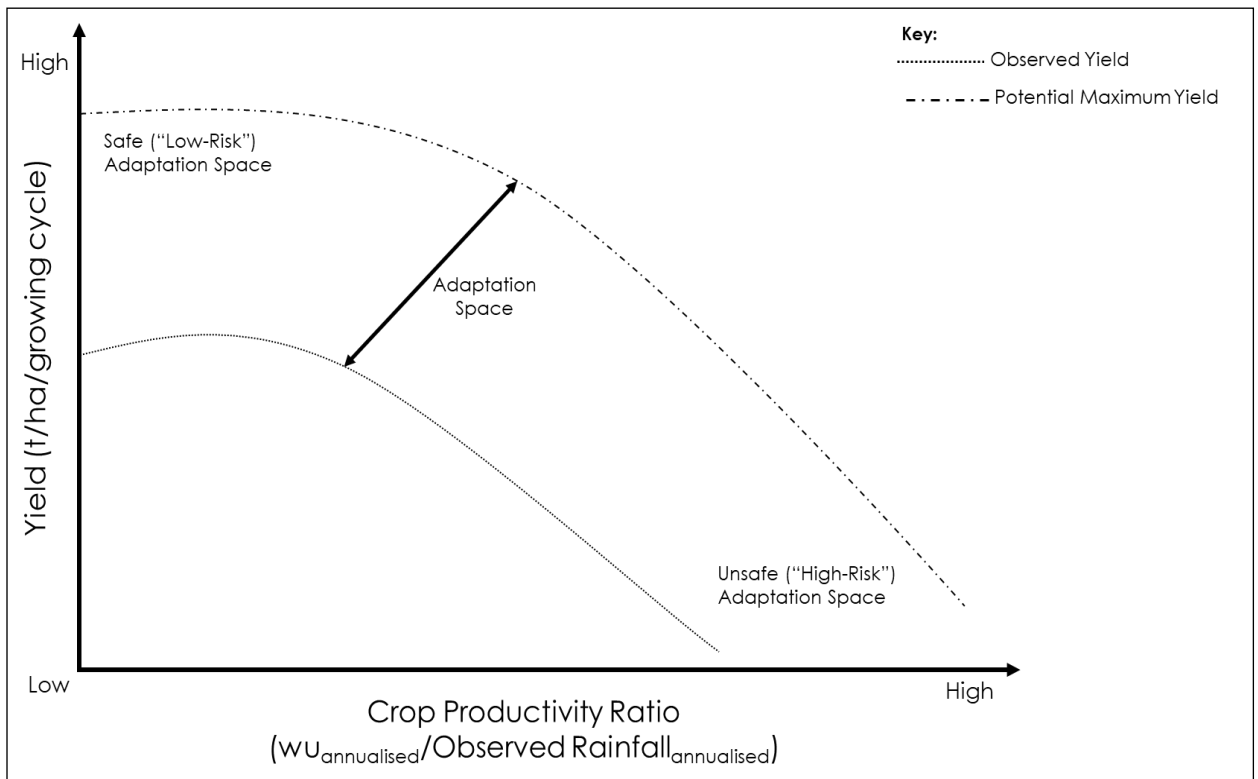


Figure 5.5 Defining safe and unsafe adaptation spaces based on the CPR concept and observed and simulated yields.

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 those management strategies that are currently being employed within each mill area that seek to maximize water use efficiency and reduce unnecessary losses. Defining the safe adaptation operating space for sugarcane can be complex owing to the diverse water resources management dynamics across the mill areas. In that regard, all mill areas were compared to one another to ascertain the best possible position that each mill area can be in to reduce vulnerability to water stress and increase adaptation potential. Lessons drawn from individual mill areas were used to develop the best possible adaptation strategies can suit the specific mill areas while also providing useful insights for the sugar industry across southern Africa.

5.5 Results and Discussion

5.5.1 Long Term Sugarcane Water Use

The estimated long-term mean (*i.e.* LTM) sugarcane water use for each mill area in relation to mean annual precipitation (MAP) is shown in **Figure 5.6**. The South African mill areas, Eston, Noodsberg and UCL have the advantage of being in catchments that experience relatively high MAP averaging 838mm/annum and can supplement their water supply with extensive irrigation schemes. However, it should be noted that sugarcane production in South Africa is a regulated activity that is considered a potential ‘Streamflow Reduction Activity’ or SFRA, grown predominantly in catchments prone to poor rainfall to runoff conversion ratios and high competition for limited water resources. A SFRA is defined in Section 36 of the South African National Water Act as “any activity, including the cultivation of any particular crop or vegetation which, in relation to a particular area, has a significant impact on water availability to other users, including the Reserve” (South African National Water Act, 1998). Further, 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. 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. As a consequence of the anticipated increases in rainfall variability and competition for water resources, it is clear that sugarcane will remain vulnerable to water stress in these mill areas.

Owing to the inherently high sugarcane water use relative to MAP, the Big Bend and Nchalo mill areas 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 an LTM water use approximating 1270mm/growing cycle, irrigation is imperative for the successful cultivation of sugarcane in this mill area (**Figure 5.6**). Irrigation systems will necessarily have to maintain pace with the rapid hydrological changes that will be engendered by climate change to avert exposure of sugarcane to water stress. Further, growers supplying the Big Bend mill are considered to be using the maximum available water resources in the Ubombo catchment (Knox et al., 2010a) suggesting high potential exposure to water stress and a strong need for adaptation to climatic extremes in this mill area.

Despite a LTM water use averaging 780mm per growing cycle against an MAP of 814mm, the Nchalo mill area 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. Intuitively, it may be suggested that 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 as discussed in **Section 5.5.2**.

Similar to the Nchalo mill area, the Kilombero (KSCL) mill area experiences high rainfall seasonality with high MAP estimates averaging 1200mm during the rainy seasons and 990mm during the dry seasons (Näschen et al., 2018) (**Figure 5.6**). Sugarcane water use averages 602mm/growing cycle in this mill area. Despite the relatively high MAP estimates and relatively low water use by sugarcane, however, yields in this mill areas remain below their potential. This is due to the limitations that sugarcane production faces which include 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. It is possible that 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.

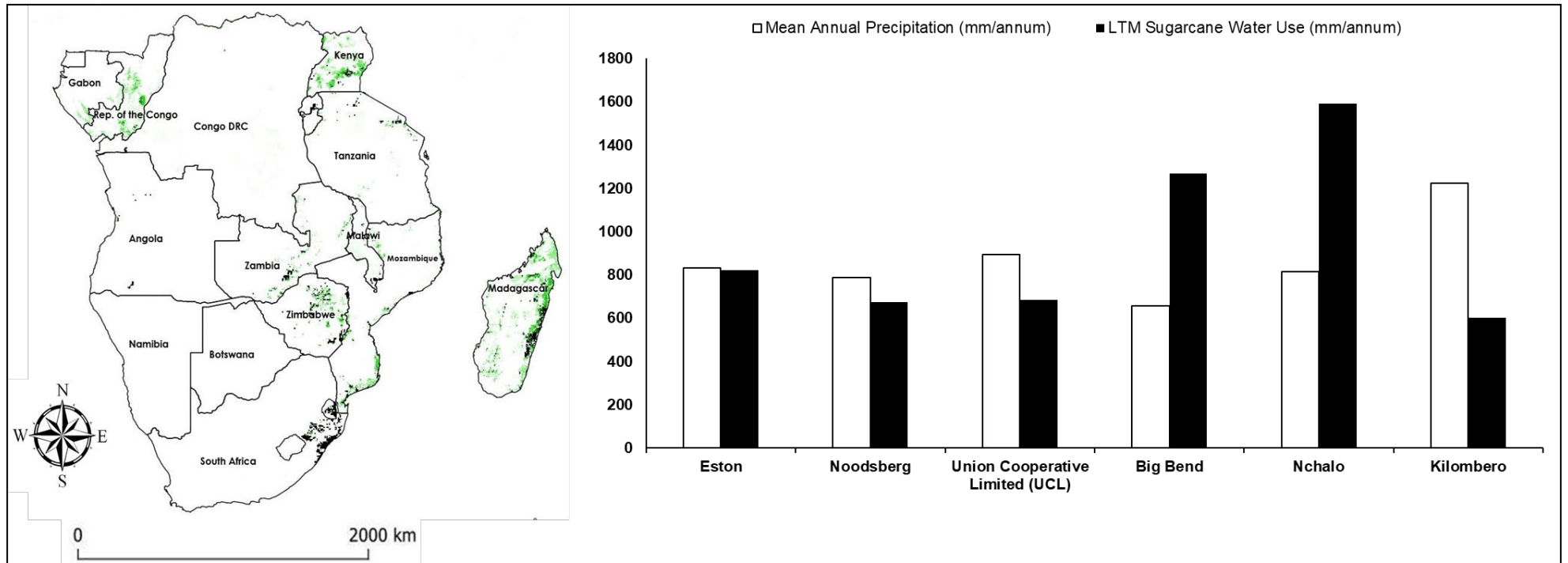


Figure 5.6 Long-term mean (LTM) sugarcane water use (*wu*) in relation to mean annual precipitation (MAP) for individual mill areas.

5.5.2 Sugarcane Yield and Water Use Relationships

Results for the LTM observed and simulated yields and water use estimates for the study period 1994-2019 are presented in this section. It should be noted that contributions by outgrowers were included in this exercise. 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 for every growing cycle.

The observed LTM yields as reported by the individual mills averaged 71.95t/ha/growing cycle for the South African mill areas *combined* (**Figure 5.7**), 46.50t/ha/growing cycle for the Big Bend mill area (**Figure 5.8**), 71.48t/ha/growing cycle for the Nchalo mill area (**Figure 5.9**) and 113.09t/ha/growing cycle for Kilombero mill area (**Figure 5.10**). On average, observed yields are declining for mills in the South African and Nchalo mill areas, and increasing in the Big Bend and Kilombero mill areas. The simulated LTM yields indicated a declining trend consistent with observed yield trends in the South African mill areas. These declines in yields 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. The AquaCrop model relies primarily on climate, crop and field management inputs and this implies that yield declines can only be caused by reductions in available water resources, both from rainfall and irrigation. 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 (*e.g.* soil degradation, increased soil compaction from high in-field traffic, increasing pest and weed pressures and declining sugarcane age at harvest) 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 5.4**, was consistently below observed rainfall for the duration of the study period (**Figure 5.7**). The exception to this was during the 2014-2016 period when most South African catchments were experiencing a 1 in 50-year drought (Abbas et al., 2019). 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.

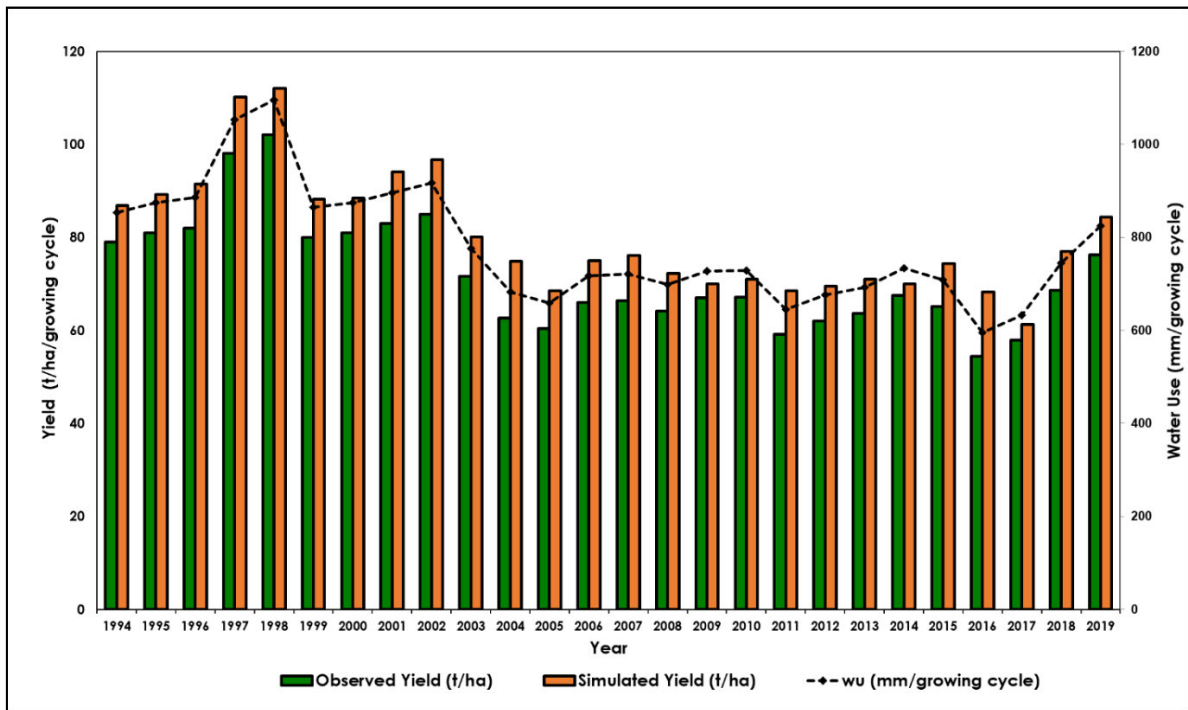


Figure 5.7 LTM observed and simulated yields for the South African mill areas and annualized water use per growing cycle.

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 period (**Figure 5.8**). This can be attributed to sugarcane being almost exclusively irrigated in this mill area which consequently buffers and limits yield declines. The reported near-constant yield trends over the 2006-2016 period was considered to be cause for further investigation. 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 (*e.g.* Simunye mill) 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 because water was not a limiting factor.

Rainfall for the Big Bend mill area is not sufficient to meet the requirements of commercial or small-scale sugarcane production, hence the need for irrigation. Further, rainfall in the Ubombo catchment averages approximately 659mm/annum, and the catchment is prone to intense, short-term droughts. Irrigation is therefore 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 in this mill area.

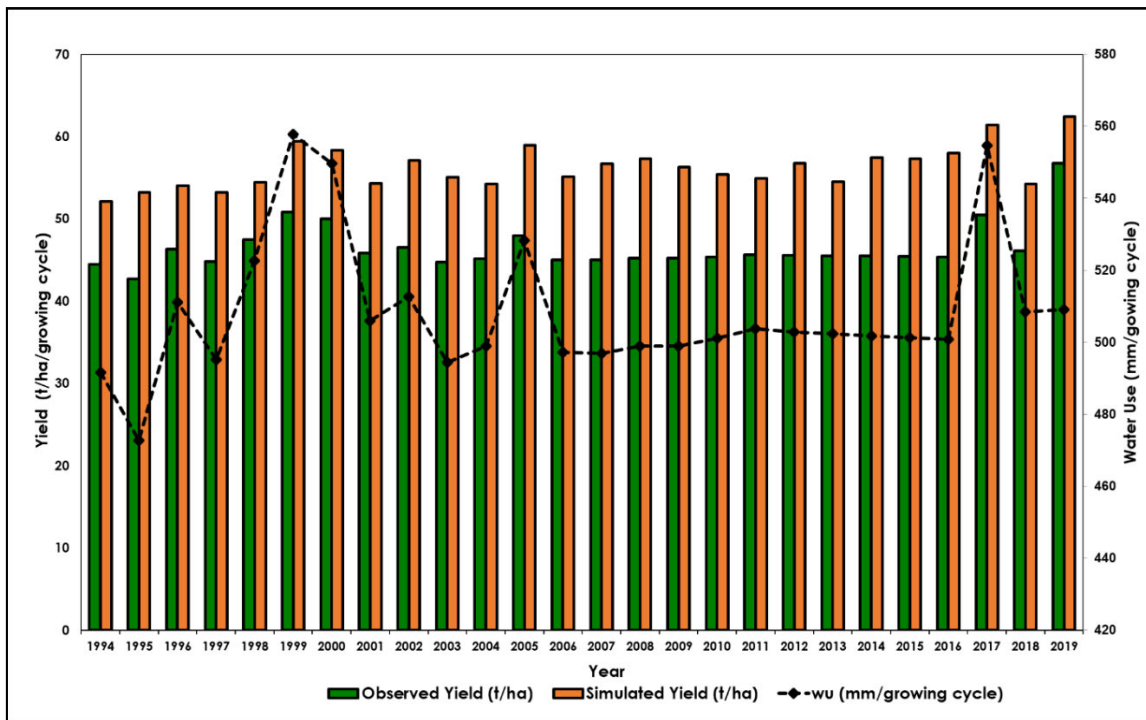


Figure 5.8 LTM observed and simulated yields for the Big Bend mill area and annualized water use per growing cycle.

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 (**Figure 5.9**). It is important to note that 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 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, particularly in the Nchalo mill area.

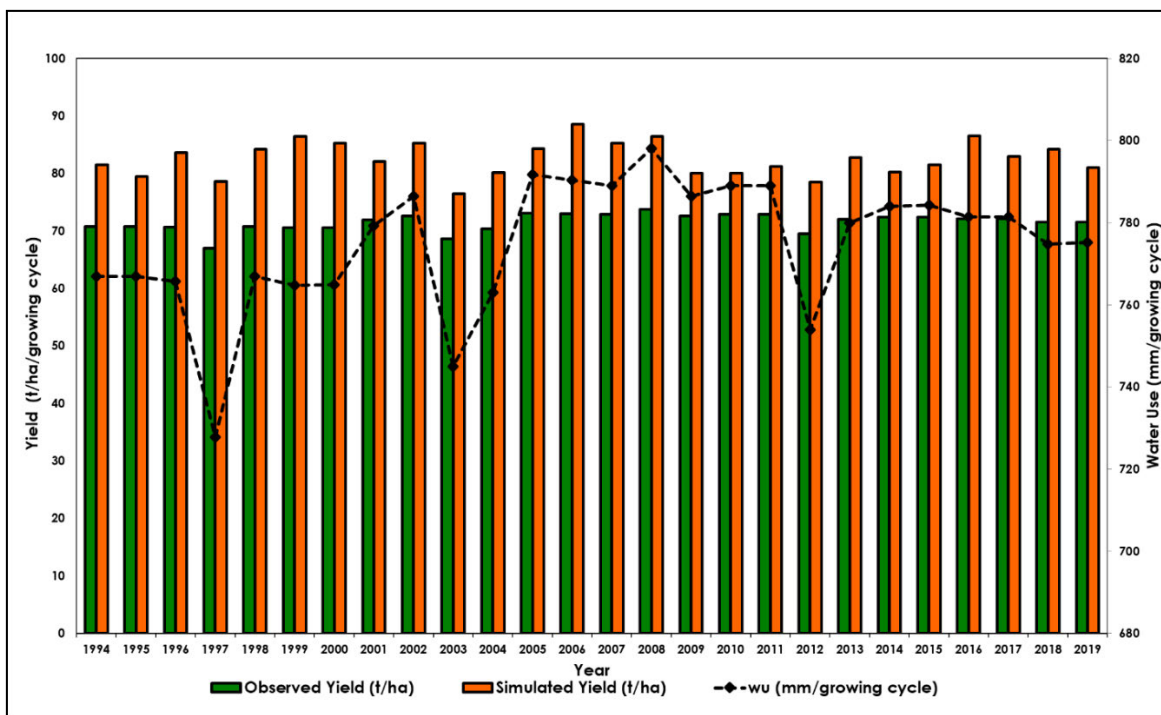


Figure 5.9 LTM observed and simulated yields for the Nchalo mill area and annualized water use per growing cycle.

LTM water use averaged 780mm/growing cycle and simulated yields were fairly constant for the Nchalo mill area, particularly after the 2011 growing cycle. The relatively high water use coupled with low rates of irrigation imply that this mill area is vulnerable to water stress and will increasingly rely on supplementary irrigation. The high seasonality of rainfall also serves to emphasize the importance of irrigation and the high exposure of sugarcane to water stress in this mill area. The LTM observed yields for the Kilombero mill area were 113.09t/ha/growing cycle over the study period as a result of increase

rainfall rates, which appear to have favoured increased sugarcane productivity (**Figure 5.10**). It should be noted that the actual observed yields for the period between 1994 and 2000 could not be independently verified, therefore the yield trends reported in **Figure 5.10** for this specific period are estimations based on yields reported by secondary sources (**Table 5.1**). 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.

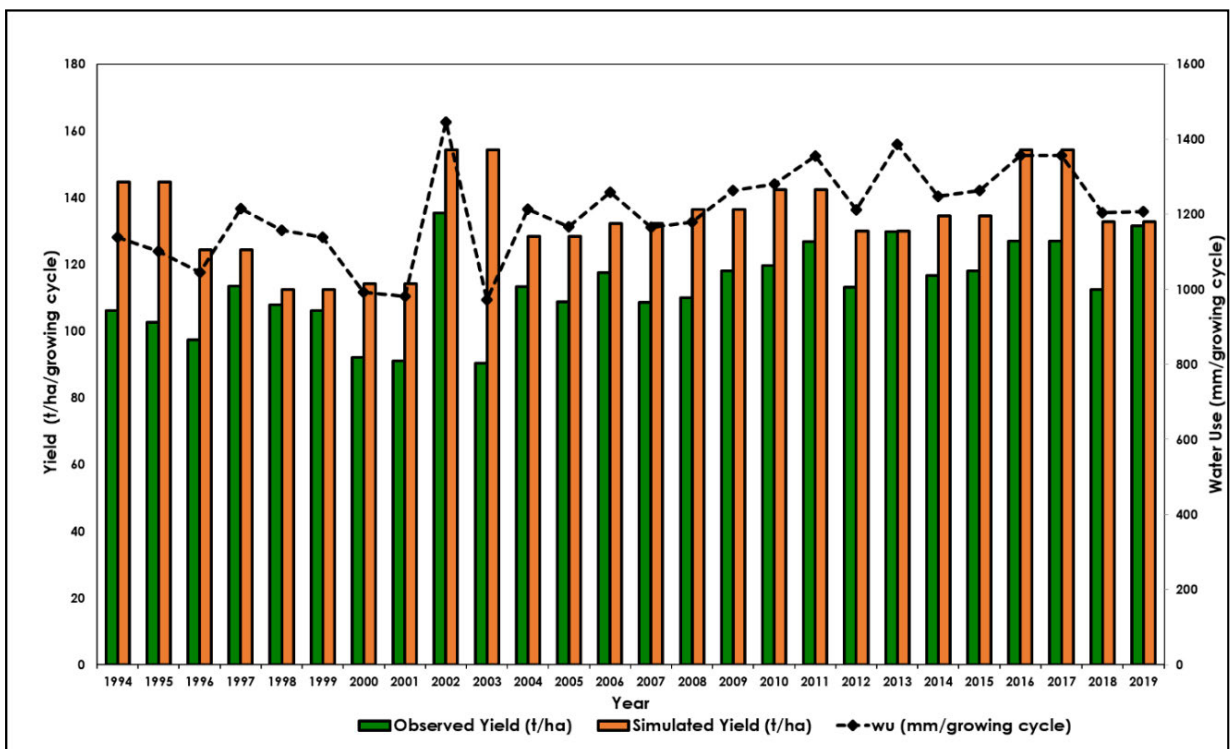


Figure 5.10 LTM observed and simulated yields for the Kilombero mill area and annualized water use per growing cycle.

Sugarcane water use is relatively high in the Kilombero mill area - averaging 1206mm/annum, against an 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.

5.5.3 Sugarcane Crop Productivity Ratio

This study sought to quantify the vulnerability of sugarcane to the impacts of increased climate variability and water stress. The sugarcane Crop Productivity Ratio (CPR, cf. [Section 5.3.6](#)), which aims to relate actual sugarcane water use with observed rainfall and thus quantify the potential vulnerability of sugarcane to water stress, was calculated for a 25-year period from 1994 to 2019. The CPR was calculated for each mill area and for each growing cycle using **Equation 5.5**. The CPR, in conjunction with the relationships between observed and simulated yields and water use per growing cycle were used to define the adaptation potential or ‘space’ for individual mill areas. The results of this assessment are intended to mitigate the vulnerability of sugarcane production systems to current and future ‘loss events’ associated with water stress resulting from extreme events and are presented in **Figure 5.11**. As mentioned before, 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.

It was accepted that 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 (**Figure 5.11a**) averaged 0.97 based on observed yields indicating that sugarcane water use consistently exceeded rainfall and thus supplementary irrigation was necessary to limit water stress and safeguard yields for the majority of growing cycles. While irrigation systems are highly 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 and this was necessary, once more, to prevent water stress. The observation that the CPR for South African mill areas is consistently below 1 suggests 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 (Change, 2012; Mason et al., 1999; Mirza, 2003; Thornton et al., 2014) and LTM yields are steadily declining, the advanced irrigation schemes coupled with large investments into research to create drought-tolerant varieties will further serve to reduce the vulnerability of sugarcane to water stress.

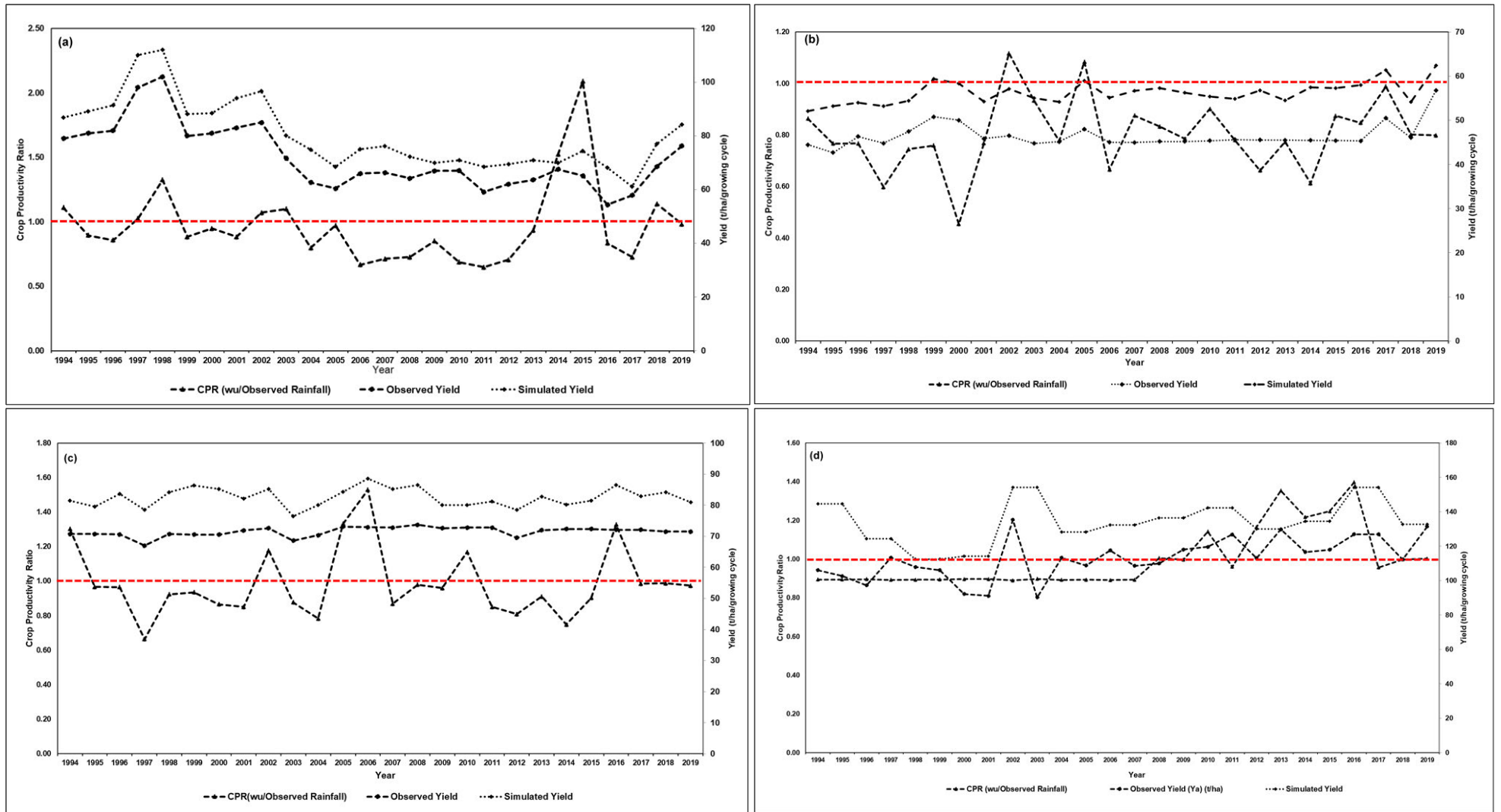


Figure 5.11 Long Term Mean (LTM) Crop Productivity Ratios (CPR) for a) South African, b) Big Bend, c) Nchalo and d) Kilombero mill areas relative to observed and simulated yields.

Therefore, despite the LTM CPR of 0.97, the relatively high observed and simulated yields suggest that the South African mill areas are still in the safe adaptation space, however some risks remain. It should be reiterated that the irrigation option was invoked in AquaCrop and this had the effect of increasing the CPR to an average of 1.07 which suggests that despite being in the safe adaptation space, some improvements can still be made in these mill areas to limit yield declines. 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 potentially assuming an important role in the reported yield declines in these 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 (**Figure 5.11b**). The CPR for this mill area was significantly below 1 for nearly all the growing cycles except for 2002 and 2005. This was a further indication that water stress poses a serious risk to sugarcane in this mill areas and is only countered by the high irrigation rates. The CPR highlights the central role that irrigation plays in this mill area. The LTM CPR suggests 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. There was a significant gap between observed and simulated yields due to the invocation of the irrigation option in AquaCrop. This highlighted the significant role that irrigation assumes and underscored the high vulnerability to water stress that sugarcane is subjected to.

Like the South African mill areas, the Nchalo mill area exhibited a CPR of 0.97 over the study period (**Figure 5.11c**). 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 be 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 because it is not a priority, the vulnerability of the sugarcane crop can be

amplified because during extreme events, water and other resources may be diverted to more economically important crops. This is evidenced by the low yields that have been experienced in this mill area since 2007. In that regard, the Nchalo mill area was operating in the high-risk and unsafe adaptation space despite the LTM CPR of 0.97.

The LTM CPR estimates for the Kilombero mill area were considered anomalous owing to poor and unverifiable data records between 1994 to 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 in the mill area. 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 in this mill area (**Figure 5.11d**). 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 in the safe adaptation space. While sugarcane water use is high, it is supplemented with irrigation and is grown in a mill area with high rainfall rates hence the LTM CPR that consistently exceeds 1 for the 2007-2019 growing cycles. Kilombero will require increased investments in irrigation to maintain high yields. The LTM CPR of 1.13 is indicative of the importance of irrigation in this mill area. While 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.

5.6 Adaptation Spaces for Sugarcane Production

The potential for adaptation is limited by the degree to which a system is vulnerable to external disturbances (Adger et al., 2009). 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 the adaptation potential will be based on the concept of adaptation spaces (Section 5.4, Figure 5.5). 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 (Figure 5.11) 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 rapidly increasing owing to changing 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* (Figure 5.11a). 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 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 regularly 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* as evidenced by the LTM CPR of 0.80 and the relationships between observed and simulated yields (**Figure 5.11b**). 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 high vulnerability to water stress; however, that can only be minimised by extensive research into drought resistant sugarcane varieties and highly efficient irrigation systems. The financial resources to achieve this would be substantial and can potentially affect the long-term sustainability of sugarcane production. With increases in the frequency of extremes, a proportionally large 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. Despite the LTM CPR of 0.97, the differences between observed and simulated yields were significant enough to suggest that improvements can be made to improve yields (**Figure 5.11c**). 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* (**Figure 5.11c**). 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 seen an upsurge and has enjoyed significant increases yields in the past few growing cycles (**Figure 5.11d**). 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 particularly after the 2011 growing cycle. This is evidenced by increasing yields under a highly seasonal hydroclimate, and an increase in the area under sugarcane across the Kilombero catchment (**Figure 5.11d**). 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 disproportionately 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.

It is clear that despite the current relatively successful cultivation of sugarcane production in all 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.

5.7 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 and they include:

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 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.

5.8 Conclusions

This study proposed a crop productivity ratio based on actual sugarcane water use in relation to actual observed rainfall over a growing cycle. Findings show that despite the inherent vulnerabilities to water stress there remains scope for adaptation for all the mill areas. 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 a few 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 nearly all 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 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. Further studies are required that will include the entire complement of the sugarcane production value chain for individual mill areas. For instance, the distance to ports can be a crucial aspect that limits the sustainability of sugarcane production, as the transportation costs can increase proportionally to the distance from the mill area. Increasing production costs can increase vulnerability by forcing growers to forgo purchasing newly developed varieties to afford exporting their product. There are numerous other factors that affect the vulnerability of sugarcane to climatic extremes. 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.

Acknowledgements

This study was supported by the University of KwaZulu-Natal's Centre for Water Resources Research (CWRR). The author would like to thank the following organizations for permitting access to otherwise restricted datasets:

- The South African Sugar Research Institute
- The Sugar Engineers.
- University of Cape Town Climate System Analysis Group.

References

- Abayomi, Y. A., & Lawal, O. J. (1998). Effect of water stress on growth and biomass yield of contrasting genotypes of sugarcane (*Saccharum officinarum*). *Ghana Journal of Agricultural Science*, 31(1), Article 1. <https://doi.org/10.4314/gjas.v31i1.1948>
- Abbas, H. A., Bond, W. J., & Midgley, J. J. (2019). The worst drought in 50 years in a South African savannah: Limited impact on vegetation. *African Journal of Ecology*, 57(4), 490–499. <https://doi.org/10.1111/aje.12640>

- Adams, T., Gerber, J.-D., & Amacker, M. (2019). Constraints and opportunities in gender relations: Sugarcane outgrower schemes in Malawi. *World Development*, *122*, 282–294. <https://doi.org/10.1016/j.worlddev.2019.05.029>
- Adetoro, A. A., Abraham, S., Paraskevopoulos, A. L., Owusu-Sekyere, E., Jordaan, H., & Orimoloye, I. R. (2020). Alleviating water shortages by decreasing water footprint in sugarcane production: The impacts of different soil mulching and irrigation systems in South Africa. *Groundwater for Sustainable Development*, *11*, 100464. <https://doi.org/10.1016/j.gsd.2020.100464>
- Adger, W. N., Lorenzoni, I., & O'Brien, K. L. (2009). *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press.
- Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of impact on major crops. *Food and Energy Security*, *4*(2), 110–132. <https://doi.org/10.1002/fes3.61>
- Ahmadi, S. H., Reis Ghorra, M. R., & Sepaskhah, A. R. (2022). Parameterizing the AquaCrop model for potato growth modeling in a semi-arid region. *Field Crops Research*, *288*, 108680. <https://doi.org/10.1016/j.fcr.2022.108680>
- Aleman, J. C., Blarquez, O., & Staver, C. A. (2016). Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Global Change Biology*, *22*(9), 3013–3025. <https://doi.org/10.1111/gcb.13299>
- Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., Yrisarry, J. B., Smith, M., Pereira, L. S., Raes, D., Perrier, A., Alves, I., Walter, I., & Elliott, R. (2006). A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method. *Agricultural Water Management*, *81*(1), 1–22. <https://doi.org/10.1016/j.agwat.2005.03.007>
- Alvar-Beltrán, J., Heureux, A., Soldan, R., Manzanar, R., Khan, B., & Dalla Marta, A. (2021). Assessing the impact of climate change on wheat and sugarcane with the AquaCrop model along the Indus River Basin, Pakistan. *Agricultural Water Management*, *253*, 106909. <https://doi.org/10.1016/j.agwat.2021.106909>
- Archer, E., Landman, W., Malherbe, J., Tadross, M., & Pretorius, S. (2019). South Africa's winter rainfall region drought: A region in transition? *Climate Risk Management*, *25*, 100188. <https://doi.org/10.1016/j.crm.2019.100188>
- Babel, M., Deb, P., & Soni, P. (2018). Performance Evaluation of AquaCrop and DSSAT-CERES for Maize Under Different Irrigation and Manure Application Rates in the Himalayan Region of India. *Agricultural Research*, *8*. <https://doi.org/10.1007/s40003-018-0366-y>
- Babel, M. S., Deb, P., & Soni, P. (2019). Performance Evaluation of AquaCrop and DSSAT-CERES for Maize Under Different Irrigation and Manure Application Rates in the Himalayan Region of India. *Agricultural Research*, *8*(2), 207–217. <https://doi.org/10.1007/s40003-018-0366-y>
- Baez-Gonzalez, A. D., Kiniry, J. R., Meki, M. N., Williams, J., Alvarez-Cilva, M., Ramos-Gonzalez, J. L., Magallanes-Estala, A., & Zapata-Buenfil, G. (2017). Crop Parameters for Modeling Sugarcane under Rainfed Conditions in Mexico. *Sustainability*, *9*(8), Article 8. <https://doi.org/10.3390/su9081337>
- Bahta, Y. T. (2022). Social vulnerability to agricultural drought: Insights from Northern Cape, South Africa. *Scientific African*, *17*, e01324. <https://doi.org/10.1016/j.sciaf.2022.e01324>
- Bakker, H. (2012). *Sugar Cane Cultivation and Management*. Springer Science & Business Media.

- Baskin, C. C. (2022). Chapter 16 - Effects of climate change on annual crops: The case of maize production in Africa. In C. C. Baskin & J. M. Baskin (Eds.), *Plant Regeneration from Seeds* (pp. 213–228). Academic Press. <https://doi.org/10.1016/B978-0-12-823731-1.00020-2>
- Bezuidenhout, C. N., & Singels, A. (2007). Operational forecasting of South African sugarcane production: Part 1 – System description. *Agricultural Systems*, 92(1), 23–38. <https://doi.org/10.1016/j.agsy.2006.02.001>
- Bezuidenhout, C., & Singels, A. (2007). Operational forecasting of South African sugarcane production: Part 1 – System description. *Agricultural Systems*, 92, 23–38. <https://doi.org/10.1016/j.agsy.2006.02.001>
- Biggs, J. S., Thorburn, P. J., Crimp, S., Masters, B., & Attard, S. J. (2013). Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region, Australia. *Agriculture, Ecosystems & Environment*, 180, 79–89. <https://doi.org/10.1016/j.agee.2011.11.005>
- Booyesen, K. C., Foxon, K. M., & Davis, S. B. (2017). The development of a screening tool to identify new products for the South African sugarcane industry. *Proceedings of the Annual Congress - South African Sugar Technologists' Association, No.90*, 431–454. <https://www.cabdirect.org/cabdirect/abstract/20183262257>
- Braidwood, R. J. (1960). The Agricultural Revolution. *Scientific American*, 203(3), 130–152. <https://www.jstor.org/stable/24940620>
- Cairns, J. E., Chamberlin, J., Rutsaert, P., Voss, R. C., Ndhlela, T., & Magorokosho, C. (2021). Challenges for sustainable maize production of smallholder farmers in sub-Saharan Africa. *Journal of Cereal Science*, 101, 103274. <https://doi.org/10.1016/j.jcs.2021.103274>
- Carr, M. K. V., & Knox, J. W. (2011). The Water Relations and Irrigation Requirements Of Sugar Cane (*Saccharum Officinarum*): A Review. *Experimental Agriculture*, 47(1), 1–25. <https://doi.org/10.1017/S0014479710000645>
- Carrer, M. J., Filho, H. M. de S., Vinholis, M. de M. B., & Mozambani, C. I. (2022). Precision agriculture adoption and technical efficiency: An analysis of sugarcane farms in Brazil. *Technological Forecasting and Social Change*, 177, 121510. <https://doi.org/10.1016/j.techfore.2022.121510>
- Change, I. P. on C. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Chinsinga, B. (2017). The Green Belt Initiative, Politics and Sugar Production in Malawi. *Journal of Southern African Studies*, 43(3), 501–515. <https://doi.org/10.1080/03057070.2016.1211401>
- Christina, M., Jones, M.-R., Versini, A., Mézino, M., Le Mézo, L., Auzoux, S., Soulié, J. C., Poser, C., & Gérardaux, E. (2021). Impact of climate variability and extreme rainfall events on sugarcane yield gap in a tropical Island. *Field Crops Research*, 274, 108326. <https://doi.org/10.1016/j.fcr.2021.108326>
- Cockburn, J., Coetzee, H., Van den Berg, J., & Conlong, D. (2014). Large-scale sugarcane farmers' knowledge and perceptions of *Eldana saccharina* Walker (Lepidoptera: Pyralidae), push–pull and integrated pest management. *Crop Protection*, 56, 1–9. <https://doi.org/10.1016/j.cropro.2013.10.014>
- Crutzen, P. J. (2006). The “Anthropocene.” In E. Ehlers & T. Krafft (Eds.), *Earth System Science in the Anthropocene* (pp. 13–18). Springer. https://doi.org/10.1007/3-540-26590-2_3

- Dai, A., Zhao, T., & Chen, J. (2018). Climate Change and Drought: A Precipitation and Evaporation Perspective. *Current Climate Change Reports*, 4(3), 301–312. <https://doi.org/10.1007/s40641-018-0101-6>
- Dal Belo Leite, J. G., Langa, F. M., von Maltitz, G., Lima Verde Leal, M. R., & Barbosa Cortez, L. A. (2020). Sugarcane outgrower schemes model: Friend or foe? A question for smallholder farmers in Mozambique. *World Development Perspectives*, 19, 100232. <https://doi.org/10.1016/j.wdp.2020.100232>
- Daroub, S. H., Van Horn, S., Lang, T. A., & Diaz, O. A. (2011). Best Management Practices and Long-Term Water Quality Trends in the Everglades Agricultural Area. *Critical Reviews in Environmental Science and Technology*, 41(sup1), 608–632. <https://doi.org/10.1080/10643389.2010.530905>
- de Fátima Rodrigues de Souza, R., Dutra, E. D., Leite, F. C. B., Cadete, R. M., Rosa, C. A., Stambuk, B. U., Stamford, T. L. M., & de Moraes, M. A. (2018). Production of ethanol fuel from enzyme-treated sugarcane bagasse hydrolysate using d-xylose-fermenting wild yeast isolated from Brazilian biomes. *3 Biotech*, 8(7), 312. <https://doi.org/10.1007/s13205-018-1340-x>
- Deressa, T., Hassan, R., & Poonyth, D. (2005). Measuring The Impact of Climate Change On South African Agriculture: The Case Of Sugarcane Growing Regions. *Agrekon*, 44(4), 524–542. <https://doi.org/10.1080/03031853.2005.9523726>
- Devnarain, N., Snyman, S. J., Hunter, C., McFarlane, S. A., & Rutherford, R. S. (2010). The establishment of in vitro screening methods for evaluating sugarcane (*Saccharum* spp. Hybrids) susceptibility to *Ustilago scitaminea* H. & P. Sydow and *Eldana saccharina* Walker. *South African Journal of Botany*, 76(2), 409. <https://doi.org/10.1016/j.sajb.2010.02.062>
- Dias, H. B., & Sentelhas, P. C. (2018a). Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. *Science of The Total Environment*, 637–638, 1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
- Dias, H. B., & Sentelhas, P. C. (2018b). Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. *Science of The Total Environment*, 637–638, 1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
- Dias, H. B., & Sentelhas, P. C. (2021). Assessing the performance of two gridded weather data for sugarcane crop simulations with a process-based model in Center-South Brazil. *International Journal of Biometeorology*, 65(11), 1881–1893. <https://doi.org/10.1007/s00484-021-02145-6>
- Dlamini, P. J. (2021). Drought stress tolerance mechanisms and breeding effort in sugarcane: A review of progress and constraints in South Africa. *Plant Stress*, 2, 100027. <https://doi.org/10.1016/j.stress.2021.100027>
- Dubb, A. (2015). Dynamics of decline in small-scale sugarcane production in South Africa: Evidence from two ‘rural’ wards in the Umfolozi region. *Land Use Policy*, 48, 362–376. <https://doi.org/10.1016/j.landusepol.2015.06.029>
- Dubb, A., Scoones, I., & Woodhouse, P. (2017). The Political Economy of Sugar in Southern Africa – Introduction. *Journal of Southern African Studies*, 43(3), 447–470. <https://doi.org/10.1080/03057070.2016.1214020>
- Dunkelberg, E., Finkbeiner, M., & Hirschl, B. (2014). Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions. *Biomass and Bioenergy*, 71, 37–45. <https://doi.org/10.1016/j.biombioe.2013.10.006>
- Eksteen, A., Singels, A., & Ngxaliwe, S. (2014). Water relations of two contrasting sugarcane genotypes. *Field Crops Research*, 168, 86–100. <https://doi.org/10.1016/j.fcr.2014.08.008>

- Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: The scale of the potential resource. *Trends in Ecology & Evolution*, 23(2), 65–72. <https://doi.org/10.1016/j.tree.2007.12.001>
- Fischer, K., & Hajdu, F. (2015). Does raising maize yields lead to poverty reduction? A case study of the Massive Food Production Programme in South Africa. *Land Use Policy*, 46, 304–313. <https://doi.org/10.1016/j.landusepol.2015.03.015>
- Fischer, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research*, 182, 9–18. <https://doi.org/10.1016/j.fcr.2014.12.006>
- Forsell, N., Turkovska, O., Gusti, M., Obersteiner, M., Elzen, M. den, & Havlik, P. (2016). Assessing the INDCs' land use, land use change, and forest emission projections. *Carbon Balance and Management*, 11(1), 26. <https://doi.org/10.1186/s13021-016-0068-3>
- Fundira, T., & Henley, G. (2017). *Biofuels in Southern Africa: Political economy, trade, and policy environment* (WIDER Working Paper Series wp-2017-48). World Institute for Development Economic Research (UNU-WIDER). <https://econpapers.repec.org/paper/unuwpaper/wp-2017-48.htm>
- Gasparatos, A., Maltitz, G. von, Roland, N., Ahmed, A., Mudombi, S., & Jarzebski, M. P. (2021). Institutional and socioeconomic transformation from sugarcane expansion in northern Eswatini. In *Political Ecology of Industrial Crops*. Routledge.
- Gasparotto, L. G., Rosa, J. M., Grassini, P., & Marin, F. R. (2022). Developing an operational framework to diagnose yield gaps in commercial sugarcane mills. *Field Crops Research*, 278, 108433. <https://doi.org/10.1016/j.fcr.2022.108433>
- German, L. A., Hepinstall-Cymerman, J., Biggs, T., Parker, L., & Salinas, M. (2020). The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. *Applied Geography*, 121, 102240. <https://doi.org/10.1016/j.apgeog.2020.102240>
- Gleick, P. (2000). The Changing Water Paradigm—A Look at Twenty-First Century Water Resources Development. *Water International - WATER INT*, 25, 127–138. <https://doi.org/10.1080/02508060008686804>
- Hadebe, S. T., Mabhaudhi, T., & Modi, A. T. (2020). Sorghum best practice management recommendations based on AquaCrop modeling scenario analysis in various agro-ecologies of KwaZulu Natal, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 117, 102866. <https://doi.org/10.1016/j.pce.2020.102866>
- Hennessy, K., Lawrence, J., & Mackey, B. (2022). *IPCC Sixth Assessment Report (AR6): Climate Change 2022 - Impacts, Adaptation and Vulnerability: Regional Factsheet Australasia*. https://policycommons.net/artifacts/2264302/ipcc_ar6_wgii_factsheet_australasia/3023355/
- Hess, T. M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Montegudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A., Marin, F., & Knox, J. W. (2016). A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change*, 39, 181–194. <https://doi.org/10.1016/j.gloenvcha.2016.05.003>
- Hiloidhari, M., Banerjee, R., & Rao, A. B. (2021). Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. *Journal of Cleaner Production*, 290, 125170. <https://doi.org/10.1016/j.jclepro.2020.125170>
- Houghton, J. (2005). Global warming. *Reports on Progress in Physics*, 68(6), 1343. <https://doi.org/10.1088/0034-4885/68/6/R02>

- Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). Climate change: The IPCC scientific assessment. *American Scientist; (United States)*, 80:6. <https://www.osti.gov/biblio/6819363>
- Inman-Bamber, N., Bonnett, G., Thorburn, P., Garside, A., Berding, N., & Attard, S. (2008). Inman-Bamber NG et al. Pointers for Better Farming and Research from Sugarcane Physiology. *Proceedings Australian Society of Sugar Cane Technologists*, 30, 231–240.
- Inman-Bamber, N. G. (2004). Sugarcane water stress criteria for irrigation and drying off. *Field Crops Research*, 89(1), 107–122. <https://doi.org/10.1016/j.fcr.2004.01.018>
- Inman-Bamber, N. G., Jackson, P. A., Stokes, C. J., Verrall, S., Lakshmanan, P., & Basnayake, J. (2016). Sugarcane for water-limited environments: Enhanced capability of the APSIM sugarcane model for assessing traits for transpiration efficiency and root water supply. *Field Crops Research*, 196, 112–123. <https://doi.org/10.1016/j.fcr.2016.06.013>
- Inman-Bamber, N. G., Muchow, R. C., & Robertson, M. J. (2002). Dry matter partitioning of sugarcane in Australia and South Africa. *Field Crops Research*, 76(1), 71–84. [https://doi.org/10.1016/S0378-4290\(02\)00044-8](https://doi.org/10.1016/S0378-4290(02)00044-8)
- Inman-Bamber, N. G., & Smith, D. M. (2005). Water relations in sugarcane and response to water deficits. *Field Crops Research*, 92(2), 185–202. <https://doi.org/10.1016/j.fcr.2005.01.023>
- Iqbal, M. A., Shen, Y., Stricevic, R., Pei, H., Sun, H., Amiri, E., Penas, A., & del Rio, S. (2014). Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation. *Agricultural Water Management*, 135, 61–72. <https://doi.org/10.1016/j.agwat.2013.12.012>
- Ishtiaque, A., Estoque, R. C., Eakin, H., Parajuli, J., & Rabby, Y. W. (2022). IPCC’s current conceptualization of ‘vulnerability’ needs more clarification for climate change vulnerability assessments. *Journal of Environmental Management*, 303, 114246. <https://doi.org/10.1016/j.jenvman.2021.114246>
- James, P., & Woodhouse, P. (2017). Crisis and Differentiation among Small-Scale Sugar Cane Growers in Nkomazi, South Africa. *Journal of Southern African Studies*, 43(3), 535–549. <https://doi.org/10.1080/03057070.2016.1197694>
- Jewitt, G., & Kunz, R. (2011). The impact of biofuel feedstock production on water resources: A developing country perspective. *Biofuels, Bioproducts and Biorefining*, 5(4), 387–398. <https://doi.org/10.1002/bbb.314>
- Jones, M. R., & Singels, A. (2018). Refining the Canegro model for improved simulation of climate change impacts on sugarcane. *European Journal of Agronomy*, 100, 76–86. <https://doi.org/10.1016/j.eja.2017.12.009>
- Jones, M. R., Singels, A., Chinorumba, S., Patton, A., Poser, C., Singh, M., Martiné, J. F., Christina, M., Shine, J., Annandale, J., & Hammer, G. (2019). Exploring process-level genotypic and environmental effects on sugarcane yield using an international experimental dataset. *Field Crops Research*, 244, 107622. <https://doi.org/10.1016/j.fcr.2019.107622>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015a). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015b). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>

- Jones, M. R., Singels, A., & Ruane, A. C. (2015c). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, *139*, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Kalantari, Z., Ferreira, C. S. S., Keesstra, S., & Destouni, G. (2018). Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. *Current Opinion in Environmental Science & Health*, *5*, 73–78. <https://doi.org/10.1016/j.coesh.2018.06.003>
- Kasambala Donga, T., & Eklo, O. M. (2018). Environmental load of pesticides used in conventional sugarcane production in Malawi. *Crop Protection*, *108*, 71–77. <https://doi.org/10.1016/j.cropro.2018.02.012>
- Kaufmann, R. K., Kauppi, H., Mann, M. L., & Stock, J. H. (2011). Reconciling anthropogenic climate change with observed temperature 1998–2008. *Proceedings of the National Academy of Sciences*, *108*(29), 11790–11793. <https://doi.org/10.1073/pnas.1102467108>
- Kayiwa, R., Kasedde, H., Lubwama, M., & Kirabira, J. B. (2021). The potential for commercial scale production and application of activated carbon from cassava peels in Africa: A review. *Bioresource Technology Reports*, *15*, 100772. <https://doi.org/10.1016/j.biteb.2021.100772>
- Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., ... Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, *18*(3), 267–288. [https://doi.org/10.1016/S1161-0301\(02\)00108-9](https://doi.org/10.1016/S1161-0301(02)00108-9)
- Kelly, T. D., & Foster, T. (2021). AquaCrop-OSPy: Bridging the gap between research and practice in crop-water modeling. *Agricultural Water Management*, *254*, 106976. <https://doi.org/10.1016/j.agwat.2021.106976>
- Kerridge, E. (2013). *The Agricultural Revolution*. Routledge.
- Knapp, A. K., Ciais, P., & Smith, M. D. (2017). Reconciling inconsistencies in precipitation–productivity relationships: Implications for climate change. *New Phytologist*, *214*(1), 41–47. <https://doi.org/10.1111/nph.14381>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010a). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, *103*(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010b). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, *103*(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Koo, J., Pardey, P. G., & Kubik, Z. (2020). *HarvestChoice: Supporting strategic investment choices in agricultural technology development and adoption* (0 ed.). International Food Policy Research Institute. <https://doi.org/10.2499/p15738coll2.133807>
- Laing, A. G., Carbone, R. E., & Levizzani, V. (2011). Cycles and Propagation of Deep Convection over Equatorial Africa. *Monthly Weather Review*, *139*(9), 2832–2853. <https://doi.org/10.1175/2011MWR3500.1>
- Laurie, S., Faber, M., Adebola, P., & Belete, A. (2015). Biofortification of sweet potato for food and nutrition security in South Africa. *Food Research International*, *76*, 962–970. <https://doi.org/10.1016/j.foodres.2015.06.001>
- Linnenluecke, M. K., Nucifora, N., & Thompson, N. (2018). Implications of climate change for the sugarcane industry. *WIREs Climate Change*, *9*(1), e498. <https://doi.org/10.1002/wcc.498>

- Lumsden, T. G., Schulze, R. E., Lecler, N. L., & Schmidt, E. J. (2000). Assessing the potential for improved sugarcane yield forecasting using seasonal rainfall forecasts and crop yield models. *Proceedings of the Annual Congress - South African Sugar Technologists' Association*, No.74, 131–139. <https://www.cabdirect.org/cabdirect/abstract/20023018386>
- Mabhaudhi, T., Modi, A. T., & Beletse, Y. G. (2014). Parameterisation and evaluation of the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. *Agricultural and Forest Meteorology*, 192–193, 132–139. <https://doi.org/10.1016/j.agrformet.2014.03.013>
- Marin, F. R., Rattalino Edreira, J. I., Andrade, J., & Grassini, P. (2019). On-farm sugarcane yield and yield components as influenced by number of harvests. *Field Crops Research*, 240, 134–142. <https://doi.org/10.1016/j.fcr.2019.06.011>
- Mason, S. J., Waylen, P. R., Mimmack, G. M., Rajaratnam, B., & Harrison, J. M. (1999). Changes in Extreme Rainfall Events in South Africa. *Climatic Change*, 41(2), 249–257. <https://doi.org/10.1023/A:1005450924499>
- Matsa, M., & Muyemeki, L. (2010). Matsa Mark and Muyemeki Luckson (2010) The Relationship Between Satellite Derived and Ground Measurement Sugar-cane Water Use: The Case of Hippo Valley Estates in Zimbabwe. *Journal of Sustainable Development in Africa*, Vol. 12, No.8 2010 Pages 191-216. *Journal of Sustainable Development in Africa*, 12, 191–216.
- McKay, B., Sauer, S., Richardson, B., & Herre, R. (2016). The political economy of sugarcane flexing: Initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies*, 43(1), 195–223. <https://doi.org/10.1080/03066150.2014.992016>
- Mekonnen, M. M., & Hoekstra, A. Y. (2010). *The green, blue and grey water footprint of crops and derived crops products*. <https://research.utwente.nl/en/publications/the-green-blue-and-grey-water-footprint-of-crops-and-derived-crop-3>
- Meyer, J., & Antwerpen, R. (2021). *Soil Degradation As A Factor In Yield Decline In The South African Sugar Industry*.
- Meyfroidt, P., Lambin, E. F., Erb, K.-H., & Hertel, T. W. (2013). Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability*, 5(5), 438–444. <https://doi.org/10.1016/j.cosust.2013.04.003>
- Mhlanga, B., Ercoli, L., Thierfelder, C., & Pellegrino, E. (2022). Conservation agriculture practices lead to diverse weed communities and higher maize grain yield in Southern Africa. *Field Crops Research*, 289, 108724. <https://doi.org/10.1016/j.fcr.2022.108724>
- Mhlanga, B. F. N., Ndlovu, L. S., & Senzanje, A. (2006). Impacts of irrigation return flows on the quality of the receiving waters: A case of sugarcane irrigated fields at the Royal Swaziland Sugar Corporation (RSSC) in the Mbuluzi River Basin (Swaziland). *Physics and Chemistry of the Earth, Parts A/B/C*, 31(15), 804–813. <https://doi.org/10.1016/j.pce.2006.08.028>
- Mirza, M. M. Q. (2003). Climate change and extreme weather events: Can developing countries adapt? *Climate Policy*, 3(3), 233–248. <https://doi.org/10.3763/cpol.2003.0330>
- Morita. (2021). Chapter 9—Constraints of improving crop water productivity in rainfed and irrigated systems in South Asia and Sub-Saharan Africa. In M. D. Kumar (Ed.), *Current Directions in Water Scarcity Research* (Vol. 3, pp. 197–218). Elsevier. <https://doi.org/10.1016/B978-0-323-91277-8.00004-6>

- Mubvuma, Michael. T., Ogola, J. B. O., & Mhizha, T. (2021). AquaCrop model calibration and validation for chickpea (*Cicer arietinum*) in Southern Africa. *Cogent Food & Agriculture*, 7(1), 1898135. <https://doi.org/10.1080/23311932.2021.1898135>
- Mudombi, S., Ochieng, C., Johnson, F. X., von Maltitz, G., Luhanga, D., Dompreeh, E. B., Romeu-Dalmau, C., & Gasparatos, A. (2021). Fuelling rural development? The impact of biofuel feedstock production in southern Africa on household income and expenditures. *Energy Research & Social Science*, 76, 102053. <https://doi.org/10.1016/j.erss.2021.102053>
- Musakwa, W., & Niekerk, A. V. (2013). Implications of land use change for the sustainability of urban areas: A case study of Stellenbosch, South Africa. *Cities*, 32, 143–156. <https://doi.org/10.1016/j.cities.2013.01.004>
- Näschen, K., Diekkrüger, B., Leemhuis, C., Steinbach, S., Seregina, L. S., Thonfeld, F., & Van der Linden, R. (2018). Hydrological Modeling in Data-Scarce Catchments: The Kilombero Floodplain in Tanzania. *Water*, 10(5), Article 5. <https://doi.org/10.3390/w10050599>
- Ngcobo, S., & Jewitt, G. (2017). Multiscale drivers of sugarcane expansion and impacts on water resources in Southern Africa. *Environmental Development*, 24, 63–76. <https://doi.org/10.1016/j.envdev.2017.07.004>
- Ngcobo, S., Jewitt, G., Stuart-Hill, S., & Warburton, M. (2013). Impacts of global change on southern African water resources systems. *Current Opinion in Environmental Sustainability*, 5(6), 655–666. <https://doi.org/10.1016/j.cosust.2013.10.002>
- Ofori, S. A., Cobbina, S. J., & Obiri, S. (2021). Climate Change, Land, Water, and Food Security: Perspectives From Sub-Saharan Africa. *Frontiers in Sustainable Food Systems*, 5. <https://www.frontiersin.org/articles/10.3389/fsufs.2021.680924>
- O’Gorman, P. A. (2015). Precipitation Extremes Under Climate Change. *Current Climate Change Reports*, 1(2), 49–59. <https://doi.org/10.1007/s40641-015-0009-3>
- Oliveira, K. D., Tomasella, J., Caram, R. de O., Falck, A. S., & Sanches, I. D. (2022). Impacts of sugarcane expansion on water availability in a river basin in southeastern Brazil. *CATENA*, 216, 106437. <https://doi.org/10.1016/j.catena.2022.106437>
- Olivier, F. C., & Singels, A. (2015). Increasing water use efficiency of irrigated sugarcane production in South Africa through better agronomic practices. *Field Crops Research*, 176, 87–98. <https://doi.org/10.1016/j.fcr.2015.02.010>
- Oosterveer, P., & Mol, A. P. J. (2010). Biofuels, trade and sustainability: A review of perspectives for developing countries. *Biofuels, Bioproducts and Biorefining*, 4(1), 66–76. <https://doi.org/10.1002/bbb.194>
- Potgieter, L., van Vuuren, J. H., & Conlong, D. E. (2013). A reaction–diffusion model for the control of Eldana saccharina Walker in sugarcane using the sterile insect technique. *Ecological Modelling*, 250, 319–328. <https://doi.org/10.1016/j.ecolmodel.2012.11.019>
- Pryor, S. W., Smithers, J., Lyne, P., & van Antwerpen, R. (2017). Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. *Journal of Cleaner Production*, 141, 137–145. <https://doi.org/10.1016/j.jclepro.2016.09.069>
- Rahimi Jamnani, M., Mirzaei, F., & Liaghat, A. (2022). Evaluation of sugarcane irrigation using AquaCrop model and remote sensing. *Irrigation and Drainage*, 71(4), 1034–1047. <https://doi.org/10.1002/ird.2718>
- Raut, S. U., & Bhagat, P. R. (2021). Sugarcane bio-refinery products: An efficient one umbrella approach for synthesis of biofuel and value-added compounds using metal-free photo-catalyst. *Fuel*, 303, 121154. <https://doi.org/10.1016/j.fuel.2021.121154>

- Revathy, R., & Balamurali, S. (2022). *Developing an efficient irrigation scheduling system using hybrid machine learning algorithm to enhance the sugarcane crop productivity* [Preprint]. In Review. <https://doi.org/10.21203/rs.3.rs-1504824/v1>
- Rice, R. W., Izuno, F. T., & Garcia, R. M. (2002). Phosphorus load reductions under best management practices for sugarcane cropping systems in the Everglades Agricultural Area. *Agricultural Water Management*, 56(1), 17–39. [https://doi.org/10.1016/S0378-3774\(01\)00196-2](https://doi.org/10.1016/S0378-3774(01)00196-2)
- Richardson, A. E. (2009). Regulating the phosphorus nutrition of plants: Molecular biology meeting agronomic needs. *Plant and Soil*, 322(1–2), 17–24. <https://doi.org/10.1007/s11104-009-0071-5>
- Rosa, S. L. K., Souza, J. L. M. de, & Tsukahara, R. Y. (2019). Performance of the AquaCrop model for the wheat crop in the subtropical zone in Southern Brazil. *Pesquisa Agropecuária Brasileira*, 55. <https://doi.org/10.1590/S1678-3921.pab2020.v55.01238>
- Roudier, P., Muller, B., d'Aquino, P., Roncoli, C., Soumaré, M. A., Batté, L., & Sultan, B. (2014). The role of climate forecasts in smallholder agriculture: Lessons from participatory research in two communities in Senegal. *Climate Risk Management*, 2, 42–55. <https://doi.org/10.1016/j.crm.2014.02.001>
- Ruddiman, W. F. (2013). The Anthropocene. *Annual Review of Earth and Planetary Sciences*, 41(1), 45–68. <https://doi.org/10.1146/annurev-earth-050212-123944>
- Sandhu, S. S., Mahal, S. S., & Kaur, P. (2015). Calibration, validation and application of AquaCrop model in irrigation scheduling for rice under northwest India. *Journal of Applied and Natural Science*, 7(2), Article 2. <https://doi.org/10.31018/jans.v7i2.668>
- Schulze, R. E. (2000). Modelling Hydrological Responses to Land Use and Climate Change: A Southern African Perspective. *Ambio*, 29(1), 12–22. <https://www.jstor.org/stable/4314988>
- Sexton, J., Everingham, Y. L., & Inman-Bamber, G. (2017). A global sensitivity analysis of cultivar trait parameters in a sugarcane growth model for contrasting production environments in Queensland, Australia. *European Journal of Agronomy*, 88, 96–105. <https://doi.org/10.1016/j.eja.2015.11.009>
- Sezen, S. M., Yazar, A., Daşgan, Y., Yucel, S., Akyıldız, A., Tekin, S., & Akhoundnejad, Y. (2014). Evaluation of crop water stress index (CWSI) for red pepper with drip and furrow irrigation under varying irrigation regimes. *Agricultural Water Management*, 143, 59–70. <https://doi.org/10.1016/j.agwat.2014.06.008>
- Shavazipour, B., Stray, J., & Stewart, T. J. (2020). Sustainable planning in sugar-bioethanol supply chain under deep uncertainty: A case study of South African sugarcane industry. *Computers & Chemical Engineering*, 143, 107091. <https://doi.org/10.1016/j.compchemeng.2020.107091>
- Silva, V. de P. R. da, Silva, R. A. e, Maciel, G. F., Braga, C. C., Silva, J. L. C. da, Souza, E. P. de, Almeida, R. S. R., Silva, M. T., & Holanda, R. M. de. (2017a). Calibration and validation of the AquaCrop model for the soybean crop grown under different levels of irrigation in the Motopiba region, Brazil. *Ciência Rural*, 48. <https://doi.org/10.1590/0103-8478cr20161118>
- Silva, V. de P. R. da, Silva, R. A. e, Maciel, G. F., Braga, C. C., Silva, J. L. C. da, Souza, E. P. de, Almeida, R. S. R., Silva, M. T., & Holanda, R. M. de. (2017b). Calibration and validation of the AquaCrop model for the soybean crop grown under different levels of irrigation in the Motopiba region, Brazil. *Ciência Rural*, 48. <https://doi.org/10.1590/0103-8478cr20161118>

- Singels, A., Donaldson, R. A., & Smit, M. A. (2005). Improving biomass production and partitioning in sugarcane: Theory and practice. *Field Crops Research*, 92(2), 291–303. <https://doi.org/10.1016/j.fcr.2005.01.022>
- Singels, A., Jackson, P., & Inman-Bamber, G. (2021). Sugarcane. In *Crop Physiology Case Histories for Major Crops* (pp. 674–713). Elsevier. <https://doi.org/10.1016/B978-0-12-819194-1.00021-9>
- Singels, A., Jones, M., Marin, F., Ruane, A., & Thorburn, P. (2014). Predicting Climate Change Impacts on Sugarcane Production at Sites in Australia, Brazil and South Africa Using the Canegro Model. *Sugar Tech*, 16(4), 347–355. <https://doi.org/10.1007/s12355-013-0274-1>
- Singels, A., Paraskevopoulos, A. L., & Mashabela, M. L. (2019). Farm level decision support for sugarcane irrigation management during drought. *Agricultural Water Management*, 222, 274–285. <https://doi.org/10.1016/j.agwat.2019.05.048>
- Singels, A., Smit, M. A., Redshaw, K. A., & Donaldson, R. A. (2005). The effect of crop start date, crop class and cultivar on sugarcane canopy development and radiation interception. *Field Crops Research*, 92(2), 249–260. <https://doi.org/10.1016/j.fcr.2005.01.028>
- Singels, A., van den Berg, M., Smit, M. A., Jones, M. R., & van Antwerpen, R. (2010). Modelling water uptake, growth and sucrose accumulation of sugarcane subjected to water stress. *Field Crops Research*, 117(1), 59–69. <https://doi.org/10.1016/j.fcr.2010.02.003>
- Smithers, J. C., Rowe, T. J., Horan, M. J. C., & Schulze, R. E. (2018). Development and assessment of rules to parameterise the ACRU model for design flood estimation. *Water SA*, 44(1), Article 1. <https://doi.org/10.4314/wsa.v44i1.11>
- Srivastava, A. K., & Rai, M. K. (2012). Review: Sugarcane production: Impact of climate change and its mitigation. *Biodiversitas Journal of Biological Diversity*, 13(4), Article 4. <https://doi.org/10.13057/biodiv/d130407>
- Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal*, 101(3), 426–437. <https://doi.org/10.2134/agronj2008.0139s>
- Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. (2011). The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1938), 842–867. <https://doi.org/10.1098/rsta.2010.0327>
- Stokes, C. J., Inman-Bamber, N. G., Everingham, Y. L., & Sexton, J. (2016). Measuring and modelling CO2 effects on sugarcane. *Environmental Modelling & Software*, 78, 68–78. <https://doi.org/10.1016/j.envsoft.2015.11.022>
- Styles, D., Schoenberger, H., & Galvez-Martos, J.-L. (2012). Environmental improvement of product supply chains: A review of European retailers' performance. *Resources, Conservation and Recycling*, 65, 57–78. <https://doi.org/10.1016/j.resconrec.2012.05.002>
- Sulle, E. (2017). Social Differentiation and the Politics of Land: Sugar Cane Outgrowing in Kilombero, Tanzania. *Journal of Southern African Studies*, 43(3), 517–533. <https://doi.org/10.1080/03057070.2016.1215171>
- Sulle, E., & Dancer, H. (2020). Gender, politics and sugarcane commercialisation in Tanzania. *The Journal of Peasant Studies*, 47(5), 973–992. <https://doi.org/10.1080/03066150.2019.1632294>
- Suresh, K. R., & Nagesh, M. A. (2015). Experimental Studies on Effect of Water and Soil quality on Crop Yield. *Aquatic Procedia*, 4, 1235–1242. <https://doi.org/10.1016/j.aqpro.2015.02.161>

- Tesfay, T., Berhane, A., & Gebremariam, M. (2019). Optimizing Irrigation Water and Nitrogen Fertilizer Levels for Tomato Production. *The Open Agriculture Journal*, 13(1). <https://doi.org/10.2174/1874331501913010198>
- The Anthropocene: Conceptual and historical perspectives | Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.* (n.d.). Retrieved January 5, 2023, from <https://royalsocietypublishing.org/doi/full/10.1098/rsta.2010.0327>
- Thornton, P. K., Ericksen, P. J., Herrero, M., & Challinor, A. J. (2014). Climate variability and vulnerability to climate change: A review. *Global Change Biology*, 20(11), 3313–3328. <https://doi.org/10.1111/gcb.12581>
- Tongwane, M. I., & Moeletsi, M. E. (2018). A review of greenhouse gas emissions from the agriculture sector in Africa. *Agricultural Systems*, 166, 124–134. <https://doi.org/10.1016/j.agry.2018.08.011>
- Trambauer, P., Dutra, E., Maskey, S., Werner, M., Pappenberger, F., van Beek, L. P. H., & Uhlenbrook, S. (2014). Comparison of different evaporation estimates over the African continent. *Hydrology and Earth System Sciences*, 18(1), 193–212. <https://doi.org/10.5194/hess-18-193-2014>
- Tweddle, P. B., Lyne, P. W. L., van Antwerpen, R., & Lagerwall, G. L. (2021). Chapter Three—A review and synthesis of sugarcane losses attributed to infield traffic. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 166, pp. 197–250). Academic Press. <https://doi.org/10.1016/bs.agron.2020.10.002>
- Valim, W. C., Panachuki, E., Pavei, D. S., Alves Sobrinho, T., & Almeida, W. S. (2016). Effect of sugarcane waste in the control of interrill erosion. *Semina: Ciências Agrárias (Londrina)*, 37(3), 1155–1164. <https://www.cabdirect.org/cabdirect/abstract/20163226955>
- van den Berg, M., & Singels, A. (2013). Modelling and monitoring for strategic yield gap diagnosis in the South African sugar belt. *Field Crops Research*, 143, 143–150. <https://doi.org/10.1016/j.fcr.2012.10.009>
- van Eekelen, M. W., Bastiaanssen, W. G. M., Jarmain, C., Jackson, B., Ferreira, F., van der Zaag, P., Saraiva Okello, A., Bosch, J., Dye, P., Bastidas-Obando, E., Dost, R. J. J., & Luxemburg, W. M. J. (2015). A novel approach to estimate direct and indirect water withdrawals from satellite measurements: A case study from the Incomati basin. *Agriculture, Ecosystems & Environment*, 200, 126–142. <https://doi.org/10.1016/j.agee.2014.10.023>
- Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T. C., Fereres, E., Heng, L. K., Garcia Vila, M., & Mejias Moreno, P. (2014). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling & Software*, 62, 351–360. <https://doi.org/10.1016/j.envsoft.2014.08.005>
- Veldkamp, A., & Lambin, E. F. (2001). Predicting land-use change. *Agriculture, Ecosystems & Environment*, 85(1), 1–6. [https://doi.org/10.1016/S0167-8809\(01\)00199-2](https://doi.org/10.1016/S0167-8809(01)00199-2)
- von Maltitz, G. P., Henley, G., Ogg, M., Samboko, P. C., Gasparatos, A., Read, M., Engelbrecht, F., & Ahmed, A. (2019). Institutional arrangements of outgrower sugarcane production in Southern Africa. *Development Southern Africa*, 36(2), 175–197. <https://doi.org/10.1080/0376835X.2018.1527215>
- Warburton Toucher, M., Schulze, R., & Jewitt, G. (2010). Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences*, 7. <https://doi.org/10.5194/hess-14-2399-2010>
- Watson, H. K. (2011). Potential to expand sustainable bioenergy from sugarcane in southern Africa. *Energy Policy*, 39(10), 5746–5750. <https://doi.org/10.1016/j.enpol.2010.07.035>

- Wellens, J., Raes, D., Fereres, E., Diels, J., Copppe, C., Adiele, J. G., Ezui, K. S. G., Becerra, L.-A., Selvaraj, M. G., Dercon, G., & Heng, L. K. (2022). Calibration and validation of the FAO AquaCrop water productivity model for cassava (*Manihot esculenta* Crantz). *Agricultural Water Management*, 263, 107491. <https://doi.org/10.1016/j.agwat.2022.107491>
- Wendimu, M. A., Henningsen, A., & Gibbon, P. (2016). Sugarcane Outgrowers in Ethiopia: “Forced” to Remain Poor? *World Development*, 83, 84–97. <https://doi.org/10.1016/j.worlddev.2016.03.002>
- World Bank. (2019). *The World Bank Annual Report 2019: Ending Poverty, Investing in Opportunity*. Washington, DC: World Bank. <https://doi.org/10.1596/978-1-4648-1470-9>
- Yang, L., Zhou, Y., Meng, B., Li, H., Zhan, J., Xiong, H., Zhao, H., Cong, W., Wang, X., Zhang, W., Lakshmanan, P., Deng, Y., Shi, X., Chen, X., & Zhang, F. (2022). Reconciling productivity, profitability and sustainability of small-holder sugarcane farms: A combined life cycle and data envelopment analysis. *Agricultural Systems*, 199, 103392. <https://doi.org/10.1016/j.agsy.2022.103392>
- Zhou, M. (2013). *Conventional Sugarcane Breeding in South Africa: Progress and Future Prospects. 2013*. <https://doi.org/10.4236/ajps.2013.42025>
- Zu, Q., Mi, C., Liu, D. L., He, L., Kuang, Z., Fang, Q., Ramp, D., Li, L., Wang, B., Chen, Y., Li, J., Jin, N., & Yu, Q. (2018). Spatio-temporal distribution of sugarcane potential yields and yield gaps in Southern China. *European Journal of Agronomy*, 92, 72–83. <https://doi.org/10.1016/j.eja.2017.10.005>
- Zulu, N. S., Sibanda, M., & Tlali, B. S. (2019). Factors Affecting Sugarcane Production by Small-Scale Growers in Ndwedwe Local Municipality, South Africa. *Agriculture*, 9(8), 170. <https://doi.org/10.3390/agriculture9080170>

CHAPTER SIX

SYNTHESIS

The importance of sugarcane production in southern Africa cannot be overstated. This crop has been demonstrated to be a vital high-value commodity crop that supports millions of livelihoods and has the immense potential of lifting millions more out of crippling poverty and unemployed across the region (Deressa et al., 2005; Hess et al., 2016; German et al., 2020). While the environmental impact footprint of sugarcane production surpasses that of other staple crops such as maize, sorghum, cassava, and sweet potatoes (Laurie et al., 2015; Cairns et al., 2021; Kayiwa et al., 2021), it remains inextricably tied to the socio-economic development trajectories on numerous countries in southern Africa. The works of numerous scholars (*e.g.*, Knox et al., 2010a; Singels et al., 2014; Jones and Singels, 2018; Hess *et al.*, 2016) have provided clear evidence of the economic and social value of sugarcane production, but also of the significant challenges that cultivating sugarcane faces particularly with regard to the regional hydroclimatic environment, the magnitude of resources required to produce adequate yields and the favourability of the sugarcane production landscape with respect to policies governing the production of the crop (Dubb, 2015; Dias & Sentelhas, 2018b; Jones et al., 2015a; van den Berg & Singels, 2013; Zu et al., 2018). The findings of this study corroborated the findings of current research which analyses the factors undermining the sustainability of sugarcane production in southern Africa. This was demonstrated on multiple occasions throughout this study wherein factors such as land degradation (**Chapter Two**), competition for limited resources including water and land (**Chapter Three**), climate variability (**Chapter 4**), labour and adaptation policy (**Chapter 5**) were shown to be the primary determinants of the successful cultivation of sugarcane.

The study established the basis for various aspects of global change which influence the regional dynamics of, among others, land use change (**Chapter Two**). While this discussion did not explicitly address sugarcane production *per se*, it outlined the causes that lead to the extensive alteration of land to cultivate high-value agricultural commodity crops such as sugarcane. This assessment used the Environmental Kuznets Curve Theory (Rockström et al., 2009) to outline the drivers and impacts of land use change and the realistic responses that can be adopted to simultaneously secure the sustainability of resource-based socio-economic growth and safeguard the long-term integrity of natural resources. This theory suggests that extensive environmental degradation and pollution are often a ubiquitous hallmark for developing nations and one which only potentially reverses once high per capita

income and high human development indices are achieved. This remains true in southern Africa considering the fact that this is one of the most rapidly developing regions in the world (Dubb, 2015; World Bank, 2019). The catchments of focus in this study, *i.e.*, Mngeni and uMlaas (both in South Africa), Big Bend (eSwatini), Nchalo (Malawi) and Kilombero (Tanzania), share a similar narrative when the factors driving land use change, particularly in support of the expansion and intensification of sugarcane production, are considered. However, the distribution of studies that assess the impacts of sugarcane production on land degradation and water resources is vastly uneven, with the majority of these studies mainly originating from South Africa and eSwatini where growers have the support of well-resourced governments and private research institutions. Per the Environmental Kuznets Curve Theory, this raises some risks for the chronically under-resourced commercial and outgrowers in Malawi and Tanzania by enhancing the exposure and vulnerability of their sugarcane production schemes to external shocks such as increased climate variability and climate change. Current studies (e.g., Jones et al., 2019; Sulle & Dancer, 2020; Hiloidhari et al., 2021; Mudombi et al., 2021; Dias & Sentelhas, 2021; Carrer et al., 2022) support this narrative by pointing out that securing successful sugarcane cultivation requires increased research efforts and investments in agronomic monitoring systems at different spatial and temporal scales. This is to ensure that a healthy and low-risk rate of sugarcane production expansion is achieved without undermining the sustainability of resources. Further, increasing knowledge transfer between commercial and outgrowers in all the countries considered in this study, was shown to be a key turning point that can ensure that the regional sugarcane production landscape is equitable and insulated from external disturbances.

To take advantage of the opportunities for an improved sugarcane production value chain, this study highlighted the importance of a multifaceted and detailed analysis of the proximate and ultimate drivers of sugarcane production, and the potential impacts of climatic extremes on this important commodity crop (**Chapter 3**). Whilst there is clear evidence of the opportunities for improving the philosophies of sugarcane production in the region (Olivier & Singels, 2015; Adetoro et al., 2020; Dlamini, 2021), the issue of scale remains a critical and inescapable challenge that requires continuous attention. Conducting this study at a regional scale in six different mill areas located in six catchments across four countries generated useful lessons but also unearthed significant challenges that were deeply acknowledged and recognised. In particular, the issue of acquiring observed hydrological

and agronomic data at appropriate scales for use in the modelling exercises was a significant challenge that required extensive effort to overcome.

It has been recognised by various authors (e.g., Näschen et. al., 2018; Harvest-Choice, 2019; Jones et. al., 2019; Yang et. al., 2022) that accessing reliable data that can be independently verified is a significant challenge in southern Africa. Despite this, however, this study managed to generate long-term records that could be reliably used as input through a series of exercises which included data infilling, creating synthetic records and using default parameters based on verified and published records (**Chapter 3, Section 3.5.1** and **Chapter 4, Section 4.3.7**) Despite the challenge of obtaining high quality observed data, this study managed to generate useful and hitherto little-known lessons regarding the proximate and ultimate drivers of sugarcane production unique to southern Africa across different spatial scales (**Chapter Two, Fig. 2.1**). While ultimate drivers, owing to their intrinsic human dimension, assume a far greater role in influencing the expansion and intensification of sugarcane production in the region, proximate drivers such as land use change, which are often closely related to ultimate drivers, are more relevant with regard to impacts to land and water resources. This is because proximate drivers involve the direct alteration of the landscape which, by extension, changes hydrological processes and fluxes thus changing water resource responses. At mill area levels, or local catchment scales, these proximate drivers, despite not being the most dominant, are the ones that reflect the cost of expansion of sugarcane production, particularly on water resources.

While contemporary sugarcane production research remains largely concentrated in catchments from South Africa and eSwatini, it is extremely important that both proximate and ultimate drivers are assessed at larger scales. This is particularly crucial since sugarcane production is demonstrably expanding and intensifying but the empirical evidence into its impacts remains relative unknown especially in the catchments from Malawi and Tanzania. This study effectively showed that technological advancements and the definitive economic benefits of sugarcane production are the key drivers of sugarcane expansion across all mill areas and, indeed, across all countries under study. The consequential influx of investments in sugarcane production have seen a steady increase in research concerned with impacts on water resources (Ngcobo and Jewitt, 2017; Singels et al., 2021), land (German et. al., 2020) and even societies (Dubb, 2015; Dubb et al., 2017).

This study confirmed the prognosis that sugarcane production will expand and intensify in the mill areas considered because of the substantial socio-economic benefits of cultivating this crop. It was further demonstrated that agronomic management, and not necessarily climate variability, assumes a far greater role as the key determinant of the viability and sustainability of sugarcane production. These findings were considered valuable in dispelling misconceptions regarding the drivers and impacts of sugarcane production in southern Africa and the impacts of climate variability and change. The commonly held assumption that climate change is the overriding ‘stressor’ that has been suppressing yields in the region was proven to be misleading if not entirely incorrect. While climate change still exerts an important influence on hydroclimatic variability, it is not at present the most dominant factor affecting sugarcane yields in the mill areas studied. Instead, day-to-day water resources management in conjunction with agronomic management are the most critical factors that exert the most important influence over the success of sugarcane production.

The panarchy or ‘kite’ concept describing rapid and small changes at local scales cascading to large and slow changes at larger scales, showed that while sugarcane production is largely local (i.e., mill area) in scale, its impacts can accumulate and cascade upwards and have significant impacts on water resources at larger (i.e., national and regional) scales. This is because the southern African sugarcane production value chain is tightly connected and, in many instances, shares multiple common threads related to agronomic management paradigms. The importance of this connectivity is reflected in the fact that novel approaches related to water resources management and other research-based innovations are often shared among the sugar producing community and, by inference, play a significant role in the expansion and success of sugar production in the region. While the more technologically advanced mill areas in South Africa and eSwatini tend to adopt new innovations at a much faster rate compared to their counterparts in Malawi and Tanzania, sugar production in the latter two nations tends to be strongly supported and heavily subsidised by their governments and this can affect the macro-economics of sugar production particularly sugar prices and import-export dynamics in the entire region. That is to say, the decisions made by growers in one country can affect the competitiveness of growers in another country and can exert pressure on natural resources when growers are attempting to maintain pace with respect to yields and production costs. In keeping with the ‘kite’ concept, initiatives such as the SADC Regional Infrastructure Development Master Plan, conceived at regional scales can have real

impacts for local growers by potentially changing their fundamental approaches to cultivating sugarcane if they wish to maintain profitability.

The projected expansion of sugarcane production will evidently result in, or at the very least, necessitate increases in water use (**Chapter Three, Figure 3.8b, c**). Despite this observation, there is no guarantee that sugarcane yields will correspondingly increase (**Chapter Four, Figure 4.12**). Modelling results showed that this is because yields are declining for the mill areas in South Africa, Malawi and Tanzania, resulting in increased yield gaps, and that yields are stagnant in eSwatini, resulting in relatively fixed yield gaps. Yield gaps remained high across all mill areas consequent to reductions in water resources due to increased climatic variability and competition, and approaches to crop management over the past 25 years. Further, since the hydroclimatic environment for most of southern Africa does not necessarily support the industrial-scale production of sugarcane, and climate change is anticipated to increase hydroclimatic variability, improving yields will become increasingly challenging (**Chapter Four**). The observation that sugarcane water use will increase is not surprising; however, this research showed that the agronomic approaches that will need to be adopted under a changing climate will have to be novel, incisive, and forward-thinking and there cannot be ‘one-size fits-all’ solutions (**Chapter Five**) for all mill areas regardless of the connectivity of the regional sugarcane production value chain.

Recent studies (e.g., Hennessy et al., 2022) have shown that climate variability will increase across southern Africa and will be characterised by increases in the frequency of floods and droughts (Kalantari et al., 2018; Smithers et al., 2018). This means that, similar to every other anthropogenic activity, sugarcane production will be vulnerable to a certain degree to the effects of increased climate variability. This is well-recognised by both commercial and outgrowers. Depending on the prevailing hydroclimatic and economic conditions, growers from individual mill areas can be expected to adopt a range of adaptation strategies to reduce their vulnerability to climate change. While this research offered informed suggestions for adaptation strategies (**Chapter Five, Section 5.7**), these were in no means considered to be generic for all mill areas. They were, however, tailored to the southern African sugar industry and particularly to the mill areas under study. The conditions of sugarcane production are constantly changing and the selection of a particular set of adaptation strategies must be informed by these prevailing conditions. For instance, growers in relatively technologically advanced countries such as South Africa and eSwatini may consider adopting strategies such

as improving in-field technologies and developing drought-resistant high-yielding sugarcane varieties, while those in Malawi and Tanzania mill areas may consider growing multiple sugarcane varieties within a single mill area to negate the effects of water stress during droughts. The key messages related to adaptation include the recognition that climate change is already increasing the frequency of extreme events, that the sugar industry will inevitably have to adapt, and that agronomic management will continue to play a critical role in the sustainability of sugarcane production.

The mill areas in this research were deliberately selected owing to both their similarities and differences. Mill areas in South Africa, Malawi and Tanzania follow a combination of rainfed and irrigation growing regimes, while the mill area in eSwatini is exclusively irrigated. Other factors considered included differences in the length of growing cycles (18-months vs 24-months), rainfall seasonality, and sugarcane production policies at each mill area. While this approach yielded useful lessons, it also presented some challenges, and these are described in the following section.

6.1 Research Challenges

One of the most profound challenges in this study was related to accessing high-quality datasets that are crucial in crop modelling. The AquaCrop model, being the main model employed in this study, was beneficial in simulating sugarcane crop yields and in performing yield gap analyses particularly in data scarce areas. As is often the case in southern Africa, observed long term records are difficult to obtain as these are either missing, poorly curated or proprietary and thus challenging to access. It was fortunate that mill areas such as Eston, UCL and Noodsberg in South Africa and, to an extent, Ubombo in eSwatini had reliable and long-term observed climate, historical yield data and agronomic datasets which were critical inputs in the AquaCrop model. The same, however, could not be said for the Nchalo and Kilombero mill areas. It was necessary and unavoidable to access climate records from online sources and estimate yields from the total annual output and area under sugarcane as there were either no known or reliable records prior to the year 2000 for these two mill areas. A limitation with datasets from Nchalo and Kilombero was the lack of independent verification, and this necessitated the back-calculation of observed yields from available area and mill crush/production data to create synthetic yield records from secondary sources. Despite this challenge, the simulations for these two mill areas were considered to be a close

reflection of the actual dynamics of sugarcane production. As such, the conclusions drawn from the results were appropriate.

As noted in Chapter Four, the AquaCrop model was run with the assumption that a full set of crop development and production parameters was available. Certain of these parameters had to be estimated from observed records as obtained from agronomy annual reports published annually by individual mills, and from previously published records. This was because the model was run at *mill area level* and not at individual estate level. It would have been impractical and beyond the scope of this research to try and estimate crop parameters for each sugar estate for six mill areas over 25 years. To ensure the verisimilitude of model results, the model was validated and verified over a 15-year period ranging from 2004 to 2019 against observed sugarcane yield data for the three South African mill areas and the Ubombo mill area.

Another challenge identified was the scale at which the crop productivity ratio (CPR) was calculated. The CPR was calculated at mill area level, and while the CPR offered a useful indicator of mill areas that are vulnerable to water stress, this scale may be too coarse to allow for a detailed description of the vulnerability of individual growers to water stress. To account for important determinants of water stress such as irrigation and sugarcane agronomic management, it would be useful to calculate the CPR at the scale of sugar producing estates. Lastly, the inclusion of additional sugar producing countries in southern Africa would have provided more insights and added further value to this research.

6.2 The Way Forward

Similar to any other agricultural activity that involves land use change, the drivers of sugarcane production in southern Africa are continuously evolving. Further, the impacts of climate change are going to become increasingly important as sugarcane production continues to expand. Therefore, the approaches adopted in the pursuit of understanding the relationship between climate change and sugarcane production must evolve. The drivers of sugarcane production (**Chapters Two and Three**) are complex and unique to each country and mill area and with how climate change is expected to increase rainfall variability, these would need to be updated. While this research presented a detailed assessment of these

drivers, it would be useful to conduct surveys with growers to understand some of the more obscure factors that influence the expansion of sugarcane production.

This research used a single model to assess the impacts of climate extremes on sugarcane yields, and to assess yield gaps at mill area level. The use of an ensemble of crop models at finer scales would be useful in providing a clearer picture of yield trends in the region. While access to data at small scales remains a significant challenge, it is still important to explore the use of different models and include more mill areas in understanding current and, potentially, future yield trends.

Finally exploring the impacts of climate change on the entire sugarcane production value chain is critical in obtaining a more complete understanding of the vulnerability of sugarcane production and developing more robust and holistic adaptation strategies.

6.3 Contributions of Research to New Knowledge

The main contributions of this research to new knowledge may be summarised as follows:

- Enhancement of the understanding of the drivers of global change which include climate change, land-use change, and economic development which are coupled and interrelated anthropic-forms of change and the recognition that they need to be treated as such. The study made clear that the management of the impacts of global and local change requires a holistic approach which recognizes the interrelationships and adopts an integrated and adaptive management framework.
- Effectively demonstrating that the interactions between the various drivers of sugarcane production display different strengths of causal relationships at local and regional scales. That is, as spatial scales change, the degree to which various drivers interact changes. This is a consequence of the evolution of connectivity patterns and cross-scale interactions which further demonstrates the importance of ‘ultimate’ drivers in determining the dynamics of sugarcane production in the region.
- Confirmation of decreasing yield trends and increasing yield gaps across most mill areas. This research confirmed that yield gaps are increasing and this remains a cause for concern. Growers 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 research and these were considered 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 research can potentially increase yields and reduce yield gaps while minimizing resource inputs.

- Confirmation that despite the current successful cultivation of sugarcane production in the selected mill areas, they are all still vulnerable to water stress as demonstrated by the CPR calculations. Certain mill areas such as the Big Bend and Nchalo are under perpetual threat of collapse due to their over-reliance on irrigation and consequently, have a strong need for adaptation.
- Contribution to and enhancement of the understanding of the vulnerability of sugarcane to water stress and recommending viable adaptation strategies.
- Illustration that 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 were shown to be invaluable in reducing the present and future vulnerability of sugarcane to water stress.
- Analysis of crop productivity ratios was a unique study in this region, and it provided useful insights into the current and, potentially, future vulnerability of sugarcane to water stress. It was observed that the adaptation potential of individual mill areas is a function of current agronomic practices and of the present and projected changes to regional climatic extremes.
- Contribution to the understanding of the importance of irrigation as a buffer for water deficits. While it is true that nearly all 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 and pest resistant varieties will be central in the sustainable cultivation of sugarcane in the region.

This research has highlighted the importance of understanding the drivers of sugarcane expansion and intensification particularly under a changing climate. Further, this study showed the importance of understanding the evolution of proximate and ultimate drivers of

sugarcane production and the impacts of both climate change and agronomic management on this important commodity crop, particularly in a rapidly developing region such as southern Africa. It is important to continuously develop forward-thinking and innovative adaptation strategies and policies that will not only safeguard the already-pressured water resources but also secure the viability and sustainability of sugarcane production as an important economic enterprise in the region.

References

- Adetoro, A. A., Abraham, S., Paraskevopoulos, A. L., Owusu-Sekyere, E., Jordaan, H., & Orimoloye, I. R. (2020). Alleviating water shortages by decreasing water footprint in sugarcane production: The impacts of different soil mulching and irrigation systems in South Africa. *Groundwater for Sustainable Development*, 11, 100464. <https://doi.org/10.1016/j.gsd.2020.100464>
- Cairns, J. E., Chamberlin, J., Rutsaert, P., Voss, R. C., Ndhlela, T., & Magorokosho, C. (2021). Challenges for sustainable maize production of smallholder farmers in sub-Saharan Africa. *Journal of Cereal Science*, 101, 103274. <https://doi.org/10.1016/j.jcs.2021.103274>
- Carrer, M. J., Filho, H. M. de S., Vinholis, M. de M. B., & Mozambani, C. I. (2022). Precision agriculture adoption and technical efficiency: An analysis of sugarcane farms in Brazil. *Technological Forecasting and Social Change*, 177, 121510. <https://doi.org/10.1016/j.techfore.2022.121510>
- Deressa, T., Hassan, R., & Poonyth, D. (2005). Measuring The Impact Of Climate Change On South African Agriculture: The Case Of Sugarcane Growing Regions. *Agrekon*, 44(4), 524–542. <https://doi.org/10.1080/03031853.2005.9523726>
- Dias, H. B., & Sentelhas, P. C. (2018a). Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. *Science of The Total Environment*, 637–638, 1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
- Dlamini, P. J. (2021). Drought stress tolerance mechanisms and breeding effort in sugarcane: A review of progress and constraints in South Africa. *Plant Stress*, 2, 100027. <https://doi.org/10.1016/j.stress.2021.100027>
- Dubb, A. (2015). Dynamics of decline in small-scale sugarcane production in South Africa: Evidence from two ‘rural’ wards in the Umfolozi region. *Land Use Policy*, 48, 362–376. <https://doi.org/10.1016/j.landusepol.2015.06.029>
- Dubb, A., Scoones, I., & Woodhouse, P. (2017). The Political Economy of Sugar in Southern Africa – Introduction. *Journal of Southern African Studies*, 43(3), 447–470. <https://doi.org/10.1080/03057070.2016.1214020>
- German, L. A., Hepinstall-Cymerman, J., Biggs, T., Parker, L., & Salinas, M. (2020). The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. *Applied Geography*, 121, 102240. <https://doi.org/10.1016/j.apgeog.2020.102240>
- HarvestChoice. 2019. <http://www.harvestchoice.org/maps/sugar-cane-area-harvested-ha-2000.html>
- Hennessy, K., Lawrence, J., & Mackey, B. (2022). IPCC Sixth Assessment Report (AR6): Climate Change 2022 - Impacts, Adaptation and Vulnerability: Regional Factsheet

- Australasia. https://policycommons.net/artifacts/2264302/ipcc_ar6_wgii_factsheet_australasia/3023355/
- Hess, TM, Sumberg, J, Biggs, T, Georgescu, M, Haro-Monteagudo, D, Jewitt, G, Odzogan, M, Marshall, M, Thenkabail, P, Daccache, A, Marin, F and Knox, JW. 2016. A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change*. 39:181-194. doi:10.1016/j.gloenvcha.2016.05.003
- Hiloidhari, M., Banerjee, R., & Rao, A. B. (2021). Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. *Journal of Cleaner Production*, 290, 125170. <https://doi.org/10.1016/j.jclepro.2020.125170>
- Jones, M. R., & Singels, A. (2018). Refining the Canegro model for improved simulation of climate change impacts on sugarcane. *European Journal of Agronomy*, 100, 76–86. <https://doi.org/10.1016/j.eja.2017.12.009>
- Jones, M. R., Singels, A., & Ruane, A. C. (2015a). Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agricultural Systems*, 139, 260–270. <https://doi.org/10.1016/j.agsy.2015.07.007>
- Jones, M. R., Singels, A., Chinorumba, S., Patton, A., Poser, C., Singh, M., Martiné, J. F., Christina, M., Shine, J., Annandale, J., & Hammer, G. (2019). Exploring process-level genotypic and environmental effects on sugarcane yield using an international experimental dataset. *Field Crops Research*, 244, 107622. <https://doi.org/10.1016/j.fcr.2019.107622>
- Kalantari, Z., Ferreira, C. S. S., Keesstra, S., & Destouni, G. (2018). Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. *Current Opinion in Environmental Science & Health*, 5, 73–78. <https://doi.org/10.1016/j.coesh.2018.06.003>
- Kayiwa, R., Kasedde, H., Lubwama, M., & Kirabira, J. B. (2021). The potential for commercial scale production and application of activated carbon from cassava peels in Africa: A review. *Bioresource Technology Reports*, 15, 100772. <https://doi.org/10.1016/j.biteb.2021.100772>
- Knox, J. W., Rodríguez Díaz, J. A., Nixon, D. J., & Mkhwanazi, M. (2010b). A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems*, 103(2), 63–72. <https://doi.org/10.1016/j.agsy.2009.09.002>
- Laurie, S., Faber, M., Adebola, P., & Belete, A. (2015). Biofortification of sweet potato for food and nutrition security in South Africa. *Food Research International*, 76, 962–970. <https://doi.org/10.1016/j.foodres.2015.06.001>
- Mudombi, S., Ochieng, C., Johnson, F. X., von Maltitz, G., Luhanga, D., Dompheh, E. B., Romeu-Dalmau, C., & Gasparatos, A. (2021). Fuelling rural development? The impact of biofuel feedstock production in southern Africa on household income and expenditures. *Energy Research & Social Science*, 76, 102053. <https://doi.org/10.1016/j.erss.2021.102053>
- Näschen, K., Diekkrüger, B., Leemhuis, C., Steinbach, S., Seregina, L. S., Thonfeld, F., & Van der Linden, R. (2018). Hydrological Modeling in Data-Scarce Catchments: The Kilombero Floodplain in Tanzania. *Water*, 10(5), Article 5. <https://doi.org/10.3390/w10050599>
- Ngcobo, S., Jewitt, G., Stuart-Hill, S., & Warburton, M. (2013). Impacts of global change on southern African water resources systems. *Current Opinion in Environmental Sustainability*, 5(6), 655–666. <https://doi.org/10.1016/j.cosust.2013.10.002>
- Olivier, F. C., & Singels, A. (2015). Increasing water use efficiency of irrigated sugarcane production in South Africa through better agronomic practices. *Field Crops Research*, 176, 87–98. <https://doi.org/10.1016/j.fcr.2015.02.010>

- Rockström, J, Steffen, W, Noone, K, Persson, A, Chapin, FS, Lambin, T, Lenton, TM, Scheffer, M, Folke, C, Schellnhuber, H, Nykvist, B, De Wit, CA, Hughes, T van der Leeuw, S, Rodhe, H, Sörlin, S, Snyder, PK, Costanza, R, Svedin, U, Falkenmark, M, Karlberg, L, Corell, RW, Fabry, VJ, Hansen, J Walker, B, Liverman, D, Richardson, K, Crutzen, P and Foley, J. 2009. Planetary Boundaries: A Safe Operating Space For Humanity. *Nature* 461: 472-475.
- Singels, A., Jackson, P., & Inman-Bamber, G. (2021). Sugarcane. In *Crop Physiology Case Histories for Major Crops* (pp. 674–713). Elsevier. <https://doi.org/10.1016/B978-0-12-819194-1.00021-9>
- Singels, A., Jones, M., Marin, F., Ruane, A., & Thorburn, P. (2014). Predicting Climate Change Impacts on Sugarcane Production at Sites in Australia, Brazil and South Africa Using the Canegro Model. *Sugar Tech*, 16(4), 347–355. <https://doi.org/10.1007/s12355-013-0274-1>
- Smithers, J. C., Rowe, T. J., Horan, M. J. C., & Schulze, R. E. (2018). Development and assessment of rules to parameterise the ACRU model for design flood estimation. *Water SA*, 44(1), Article 1. <https://doi.org/10.4314/wsa.v44i1.11>.
- Sulle, E., & Dancer, H. (2020). Gender, politics and sugarcane commercialisation in Tanzania. *The Journal of Peasant Studies*, 47(5), 973–992. <https://doi.org/10.1080/03066150.2019.1632294>
- van den Berg, M., & Singels, A. (2013). Modelling and monitoring for strategic yield gap diagnosis in the South African sugar belt. *Field Crops Research*, 143, 143–150. <https://doi.org/10.1016/j.fcr.2012.10.009>
- World Bank. (2019). *The World Bank Annual Report 2019: Ending Poverty, Investing in Opportunity*. Washington, DC: World Bank. <https://doi.org/10.1596/978-1-4648-1470-9>
- Yang, L., Zhou, Y., Meng, B., Li, H., Zhan, J., Xiong, H., Zhao, H., Cong, W., Wang, X., Zhang, W., Lakshmanan, P., Deng, Y., Shi, X., Chen, X., & Zhang, F. (2022). Reconciling productivity, profitability and sustainability of small-holder sugarcane farms: A combined life cycle and data envelopment analysis. *Agricultural Systems*, 199, 103392. <https://doi.org/10.1016/j.agsy.2022.103392>
- Zu, Q., Mi, C., Liu, D. L., He, L., Kuang, Z., Fang, Q., Ramp, D., Li, L., Wang, B., Chen, Y., Li, J., Jin, N., & Yu, Q. (2018). Spatio-temporal distribution of sugarcane potential yields and yield gaps in Southern China. *European Journal of Agronomy*, 92, 72–83. <https://doi.org/10.1016/j.eja.2017.10.005>

CHAPTER SEVEN

CONCLUSIONS

The southern African sugarcane production industry is a highly complex and tightly coupled system involving multiple actors and hydroclimatic components that interact at various spatial and temporal scales. This study demonstrated that the current increases in climate variability and, consequently, change will enhance the complexity of this system and will potentially undermine the successful cultivation of this crop for both commercial and outgrowers at different spatiotemporal scales. Developing a clear and comprehensive understanding of the drivers of sugarcane production and the impacts of this vital agricultural activity on land and water resources requires continuous study and understanding in order to secure its progress without jeopardizing the sustainability of finite natural resources. These resources, which include land, water, and people, have to be managed judiciously such that their exposure and vulnerability to climate variability and change is minimized. While it is understood that the ultimate aim is to maximize yields, reduce production costs and operate within established legal frameworks, the sugarcane production industry has to adapt to the reality of an increasingly difficult agricultural production environment that includes increases in extreme climatic events and competition from other land uses.

The hydroclimatic and production diversity of the mill areas in the study provided useful outlooks and lessons that illustrated the importance of understanding every aspect of the sugarcane value chain to limit the exposure and vulnerability of sugarcane production to external stressors. While this study was primarily concerned with sugarcane yields, yield gaps, water use and the drivers and impacts of sugarcane production, it did not address other important aspect such as in-field technological advancements and biotechnical advancements, both of which can improve the resilience of sugarcane to climatic variability. Therefore, further studies are required that will include the entire complement of the sugarcane production value chain for individual mill areas in order to dispel misconceptions about the actual factors (i.e., agronomic management *vs.* climate change) that affect the sustainability of sugarcane production. In conclusion, understanding the potential impacts of climate variability and change on the entire sugarcane production value chain is critical in obtaining a more complete understanding of the vulnerability of sugarcane production and developing more robust, holistic, and realistic adaptation strategies, particularly in a rapidly developing region such as southern Africa.