



MAVUTO MUHAMMAD BANDA

**IMPACTS OF IRRIGATION HETEROGENEITY ON
SUGARCANE YIELDS, ENERGY AND WATER USE IN
SUB-SAHARAN AFRICA**

SCHOOL OF WATER ENERGY AND ENVIRONMENT (SWEE)
Water Including Design

PhD
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Supervisor: Prof. Jerry W Knox
Associate Supervisor: Prof. Tim M Hess
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ABSTRACT

Sugarcane is an economically strategic crop in Sub-Saharan Africa (SSA), underpinning the rural livelihoods and economies of many SSA countries. Despite its economic importance, yield trends in the region have been declining by an average of 0.03 t/ha per year over the last 60 years. However, total cane production has been increasing by an average of one million tonnes per year over the same period – an indication that the increase in total cane production has largely been due to an overall expansion in cultivated area. However, this situation is not sustainable in the long-term since land availability is limited. Whilst irrigation has the potential to improve yields, production in SSA is typically characterised by poor irrigation management practices as evidenced by high levels of irrigation water use, low irrigated yields and low water productivities.

Understanding the impacts of future climate variability and drought risk on the reliability of irrigation and identifying appropriate technology and management options to improve yields, water and energy use and productivity are key challenges facing the agricultural sector in SSA. Impacts of irrigation non-uniformity on cane yields, water and energy use in SSA were identified as key research gaps in this study.

Thus, the aim of this research was to evaluate the agronomic, environmental and economic impacts of irrigation non-uniformity on sugarcane production in SSA. Initially, a benchmarking study was conducted to identify opportunities to improve cane yields and water productivity and reduce irrigation water and energy use. Biophysical crop, water balance and economic modelling approaches were then integrated to simulate cane yield response to water, the impacts of irrigation non-uniformity and the relative cost and benefits of improving irrigation uniformity. Cane yields were modelled for varying water applications and irrigation uniformity using the DSSAT Canegro model coupled with a water balance model. The relative financial costs and benefits of implementing different interventions to improve irrigation management were then evaluated using a spreadsheet-based economic model.

The results showed that there were opportunities to improve the performance of irrigated cane production in SSA – currently characterised by lower-than-expected yields – ranging between 83.9 and 108.9 t/ha, high irrigation water uses and lower than potential water productivity – ranging between 5.0 and 7.8 kg/m³. It was also established that improving irrigation uniformity leads to improved cane yields, reduced irrigation water and energy use. It was also established that on average a percentage improvement in irrigation uniformity could improve yields by 0.2 – 0.5 t/ha and could reduce irrigation and energy use by 3%. These potential yield improvements (due to improved irrigation uniformity) coupled with a reduction in water and energy use resulted in increased revenues of between 23,300 and 70,900 MK/ha (c£18 – 65/ha) and a reduction in irrigation-related costs by 3,700 MK/ha (c £3/ha).

Overall, the research has provided new valuable insights into the impacts of irrigation heterogeneity on cane yields and addressed existing knowledge gaps relating to how existing irrigation management practices in the sugarcane industry in SSA can be improved, without the need for transformational shifts to precision irrigation technologies. The findings provide the basis for improving cane yields, irrigation water and energy use and productivity in both commercial and smallholder cane production across SSA.

It is, thus, recommended that there is a need for farmers to always operate irrigation with improved level of irrigation uniformity while ensuring proper irrigation scheduling approaches. The implementation of irrigation uniformity improvement interventions and adopting correct irrigation scheduling methods would likely reduce irrigation water use, improve yield average at field level which in turn will improve water productivity and reduce energy requirements for irrigation. The improvement of water productivity and reduction of irrigation water use and energy requirements would maximise crop yield benefits from irrigation and reduce irrigation operation costs, respectively.

Keywords: Benchmarking, crop modelling, DSSAT Canegro, irrigation uniformity

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Dedicated to my dad, Patson Makina Banda

He was so proud to see me start the journey, so heart-breaking that he had to eternally leave me mid-way.

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LIST OF ABBREVIATIONS

ANR	Average net return
APSIM	Agricultural Production Systems Simulator
C	Carbon
cm	Centimetre
CU	Coefficient of uniformity
CV	Coefficient of variation
DSSAT	Decision support system for agrotechnology transfer
DU	Distribution uniformity
E	Evaporation
ET	Evapotranspiration
ET _a	Actual crop evapotranspiration
ET _c	Crop evapotranspiration
ET _o	Reference crop evapotranspiration
EU	European union
GDP	Gross domestic product
GHG	Greenhouse gas
GLAI	Green leaf area index
h	hour
ha	Hectare
Kc	Crop coefficient

kg	kilogram
kPa	kilopascal
KPI	Key performance indicator
kWh	kilowatt hour
LAI	Leaf area index
m	Metre
m ³	Cubic metre
MK	Malawi kwacha
mm	millimetre
NIR	Net irrigation return
PAR	Photosynthetically active radiation
RIS	Relative irrigation supply
RMSE	Root Mean Square Error
RUE	Radiation use efficiency
RWS	Relative water supply
SP	System productivity
SSA	Sub-Saharan Africa
SWC	Soil water content
t	Tonne
WP	Water productivity

Chapter 1. INTRODUCTION

1.1 Background

Sugarcane is an internationally important source of food (sucrose), bio-ethanol and electricity and thus a significant contributor to the economy of many countries around the world (Singels et al., 2021). The crop is grown in more than 100 countries (Singels et al., 2021) and in 2020, global production was estimated to be 1.98 billion tons with Brazil, India and China being the world's top three cane producers (FAOSTAT, 2022). Globally, cane yield has increased from 50.26 t/ha in 1961 to 70.64 t/ha in 2020, representing an average yield increase of 0.4 t/ha per year over that period. The sugarcane production trends in Africa, over the same period, indicate an overall average production increase of over a 1.0 million t/year (FAOSTAT, 2022). However, unlike the global trend, the African yield trend over the same period shows an average reduction of 0.03 t/ha per year (Figure 1-1) - an indication that the increased total production tonnage was due to an expansion in the overall harvested area.

Africa has high potential for agricultural production due to its suitable soils; available water resources for supplementary irrigation; wet and hot summers that are suited for plant growth; cool, sunny and dry winters that provide excellent conditions for conversion to sucrose and low costs of production (cost of labour is relatively low). Africa is also strategically close to European markets (Tyler, 2008), and thus an important region for agricultural expansion (Hess et al., 2016).

In many African countries, irrigation is a requirement for improved sugarcane yields (Hess et al., 2016). However, sugarcane is a high-water demanding crop (Steduto et al., 2012) with average crop water requirements ranging between 18,000 and 20,000 m³/ha (Hess et al., 2014; Shrivastava et al., 2011). Thus, the expansion of the harvested area to increase cane production (tonnage), in the African case, would require more water volumetrically. This would likely intensify competition for water resources among the existing competing sectors including manufacturing industries, hydro-power generation, domestic water supplies, and for protecting environmental flows. Thus, the expansion of irrigated sugarcane to

increase cane production has implications that are more significant for irrigated agriculture compared to the production increase due to improved crop yield.

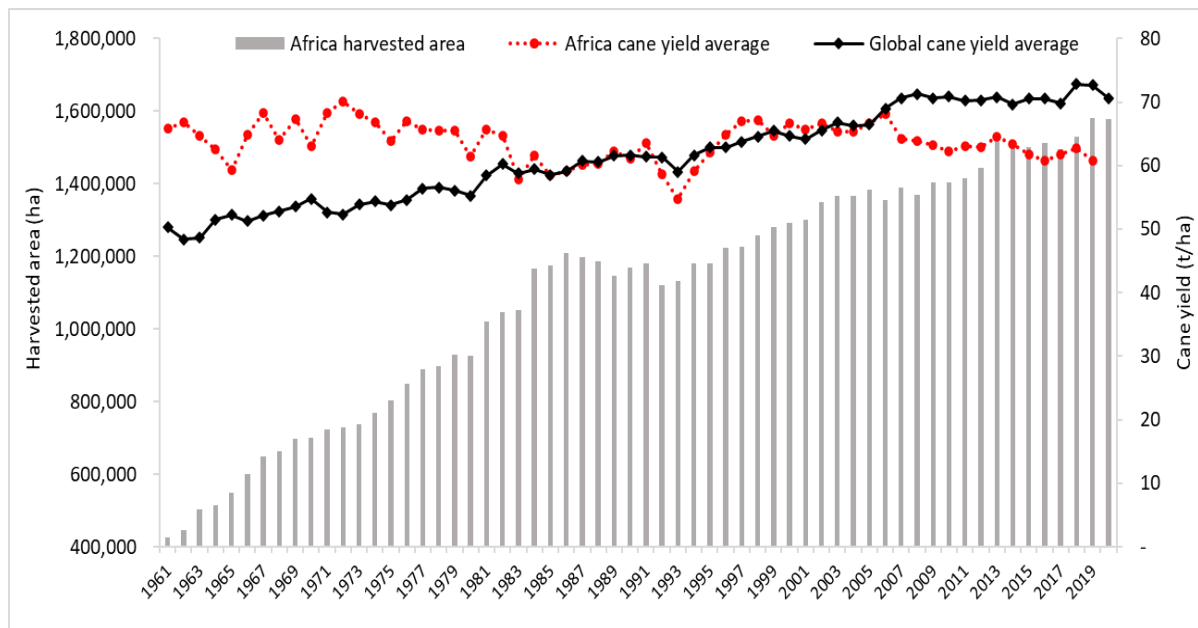


Figure 1-1: Reported cane yields (t/ha) and harvested areas (ha) between 1961 and 2020 (source: FAOSTAT, 2022)

Although sub-Saharan Africa (SSA) is not considered water poor (Lautze & Giordano, 2007) as it contains about 9% of the world's freshwater resources coupled with low per capita rate of water withdrawals (Hess et al., 2016), irrigated sugarcane production has great potential to alter local water balances, thus impacting on the dynamics, quality, and quantity of water supplies for competing uses at the watershed scale and beyond (Hess et al., 2016). Both sugarcane production and sugar processing can have significant impacts on water resources (Hess et al., 2014) with an estimated water consumption of about 209 m³/ton, making sugar production a major consumer of freshwater resources (Gerbens-Leenes & Hoekstra, 2012). In India, the world's second-highest sugarcane producer, irrigated production has led to extreme water shortages (Shrivastava et al., 2011) impacting on the long-term sustainability of the country's sugar industry. Thus, the dependence on expansion of the cane cultivated area to support increased sugarcane production is not a sustainable option.

Understanding the impacts of future climate variability and drought risk on the reliability of water for irrigation and identifying appropriate technology and management options to improve water and energy efficiencies to improve yields are among the key challenges and priorities facing the agricultural sector in SSA. While crop yields are also impacted by local agro-climate variability and other factors including soil variability, irrigation system performance (including uniformity) has also been shown to have a major bearing on crop yields (Pérez-Ortolá et al., 2015; Reinders, 1996; Solomon, 1998) and irrigation water use (Clemmens & Molden, 2007). Although uniform water application on its own is not a guarantee for improved yields since it is also possible to have uniform under- or over-irrigation, improved yields are often associated with uniform application of adequate water.

Current irrigation systems performance gaps and the extent to which irrigation uniformity improvements (if any) might change yields, as well as the relationships between improving irrigation efficiency and energy consumption within sugarcane production in the SSA context are key research gaps in knowledge. Therefore, there is a need to develop a better understanding of the impacts of irrigation heterogeneity on cane yields, water and energy uses and the economic viability of implementing irrigation uniformity improvements to increase sugarcane yields for cane production in SSA. Quantifying the potential agronomic benefits (increased yields), water use efficiency (improved water productivity), environmental benefits (energy use) and economic benefits (increased revenues and reduced costs) as a result of improving irrigation uniformity in sugarcane production in SSA is critically important to support improved irrigation management decision making in the face of increasing water scarcity.

1.1.1 Sugarcane Yield Response to Water Deficit

Water is a critical input for cane production, as it impacts on yields by providing necessary conditions for cane germination and tillering, and making the crop well equipped for extensive water extraction and photosynthesis during the stalk elongation stage which accounts for about 70% of biomass accumulation (Carr &

Knox, 2011; Cock, 2003). Sugarcane requires between 1100 and 1800 mm of water with peak daily requirement of 6 –15 mm (Carr & Knox, 2011; Cock, 2003; Hess et al., 2014; Shrivastava et al., 2011; Steduto et al., 2012). Research into the relationships between water use and cane yields has shown that as more water is applied to the growing crop, more yield is likely to be realised (Steduto et al., 2007, 2012; Waller & Yitayew, 2016) until a point is reached when the law of diminishing returns is triggered (English, 1990a; English & Raja, 1996).

Although sugarcane can tolerate moderate levels of drought stress (Steduto et al., 2012), the timing of stress during the growth cycle of sugarcane determines the significance of the impact on cane yields. The elongation stage of sugarcane growth and development is the most sensitive to water stress (Banda, 2019; Cock, 2003; Singels et al., 2005). Thus, cane crop that experience water stress (due to inadequate water supply) which coincides with the elongation stage would have its yields more significantly reduced than cane that experiences water stress during any other growth stage.

While high yields are associated with adequate water supplies, adequate water supplies on its own is of no use without proper irrigation scheduling. The timing and frequency of irrigation applications determines the level of consistency in output as adequate irrigation scheduling prevents excessive water use, helps to reduce the costs of excess water pumping, and improves crop yield and quality. Proper irrigation scheduling involves correct timing and administering irrigation water applications in a manner that meets the water demands of the growing crop with minimal water, soil, plant nutrients, or energy wastage (Klausmeyer, 2005). In principle, proper irrigation scheduling demands that an irrigation system should be able to correctly apply irrigation at the right time, in the right quantity and with correct placement. While the timing and quantity of water are management decision as regards to when to irrigate (in non-automated systems), the application of irrigation water in-field is more to do with system design and configuration. The appropriate placement of adequate water where and when (uniformity) it is required helps to ensure maximum yields are attained across the field.

1.1.2 Irrigation water use, uniformity and yield relationships

Solomon (1998) defined "irrigation uniformity" as the differences in water application depths from one location (spatial) to another within an irrigation system's defined area of command. In essence, irrigation uniformity is among the indicators of how good a given system is in placing water within its area of command. The higher the variation of water application (depths applied) from one point to another, the poorer the irrigation uniformity and vice-versa. Heermann et al., (1990) determined that irrigation uniformities for overhead irrigation systems (including sprinkler and pivot systems) could be evaluated by measuring the spatial distribution of water depths caught in grid of catch cans.

Uniform application of adequate water across the field would ensure that each point in the field provides maximum yields (assuming nutrient availability and other factors of crop production are not limiting). Non-uniform water application results in water wastage (in over-irrigated spots) and water stress (in under-irrigated spots) – all of which result in yield losses and reduced profit margin. The uniformity of water application influences crop yields through the agronomic effects of under-irrigation and over-irrigation. Inadequate water leads to water stress and reduced crop yields while excess water reduce crop yields as a result of nutrient leaching, increased disease risks and/or growth stimulation failure of harvestable parts of the plants (Solomon, 1998). Thus, irrigation uniformity is an important system performance indicator for yield, water and energy use optimisation.

1.1.3 Crop Water Requirements – Irrigation Water Use – Energy Nexus

In irrigated agriculture, an irrigation system and its distribution network provide a means of pumping and delivering water from the source to the field. Since it is only in rare circumstances that field conditions coincide with water sources that facilitate gravity fed application in-field, pumping becomes necessary in irrigated agriculture. Water pumping requires energy and crop water requirements and the anticipated system inefficiencies determine the energy requirements for an

irrigation system operation that meets irrigation water requirement of the growing crop. Clemmens & Molden, (2007) indicated that where irrigation heterogeneity exists, the farmer can choose to either (i) reduce the irrigation heterogeneity or (ii) apply more water than required to compensate for the deficiencies in irrigation uniformity. The latter entails that the level of irrigation uniformity at which the system operates determines water use which in turn influences energy use. This highlights the interdependencies between crop water requirements, water and energy use with irrigation performance being the main determining factor. Coupled with correct irrigation scheduling, improvements in irrigation uniformity can help reduce irrigation water use and energy requirements for pumping, whilst increased water application to compensate for poor irrigation uniformity would lead to higher irrigation and energy uses.

The relationships between crop yield and water usually takes a quadratic form (English, 1990b; English & Raja, 1996). This entails that beyond some defined point, additional applications of water do not produce additional yields. This makes high irrigation water uses undesirable and uneconomical, especially when such increases are a result of poor irrigation uniformity. Furthermore, increasing water use in the face of water scarcity with competing water uses among industries is also an unsustainable option.

1.1.4 Water-Energy-Food Nexus and Need for Change in the Management of Irrigation Water

The need to produce adequate food crops, including sugarcane, to meet the demands and food requirements for a growing global population, requires irrigation which requires energy. The need for more food would require more water and more energy (Tomlinson, 2013), all of which are interdependent variables. Water is a requirement for the production of both food and electricity, while energy is required for irrigation pumping. The complex nexus between water, energy and food (WEF) and understanding of their linkages and trade-offs is key to sustainable agricultural production (Naranjo et al., 2023).

Scientific evidence indicates that on average Africa will experience an increase in temperature and reduced precipitation due to climate change (Calvin et al., 2023; IPCC, 2014). The rising temperatures and dwindling precipitation further entail that irrigation water needs are likely to increase (Fortes et al., 2022). The combination of a growing population (Paice, 2022), climate change (Calvin et al., 2023; IPCC, 2014), increasing water scarcity (Cai & Rosegrant, 2003), and unreliable and expensive energy supplies (KfW Development Bank, 2020) are signals for the need to find more sustainable ways of crop production.

The quest to improve and maintain sustainable crop productivity means it is increasingly necessary to improve the efficiency of irrigation systems (Malano, Burton, et al., 2004), because efficient irrigation systems enhance crop and water productivity. Thus, understanding and addressing the water, energy, and food related complexities is therefore a priority action area for sustainable irrigated agriculture.

1.2 Aim and Objectives

Despite significant potential for agricultural expansion, SSA's agricultural productivity remains low (Zamanillo et al., 2017; Mukasa et al., 2017; Ritchie, 2022; Sadras et al., 2015). Implementation of interventions that improve irrigation uniformity have potential yields benefits (Baillie, 2004; A. J. Clemmens & Molden, 2007; Holzapfel et al., 1985; N. Inman-Bamber et al., 1998; Pérez-Ortolá et al., 2015; Reinders, 1996; Solomon, 1998). However, the extent to which the implementation of such irrigation uniformity improvements impacts on cane yields, irrigation water and energy use as well as economics of irrigated cane production remains unknown. Thus, the overall aim of this PhD research was to evaluate the agronomic, environmental and economic impacts of improving irrigation uniformity in sugarcane production in sub-Saharan Africa (SSA).

The research set out to address the following key questions:

- i. Are there irrigation related opportunities for improving cane yields, water and energy use and productivity in SSA?

- ii. How does irrigation non-uniformity impact on cane yields, water and energy use and water productivity?
- iii. How does implementation of interventions to improve irrigation uniformity in the sugarcane industry in sub-Saharan Africa impact on the agronomic and economic benefits?

The following research hypotheses were defined and tested in the course of the research:

- i. There are opportunities for further improvement in cane yields, and reductions in water and energy use in SSA sugarcane production.
- ii. Irrigation non-uniformity has an impact on cane yield, water and energy use and productivity.
- iii. Implementation of irrigation uniformity improvement interventions has agronomic, environmental and economic benefits.

1.3 Thesis Structure

The thesis sets out by initially benchmarking irrigation performance and water management practices in selected SSA countries to identify opportunities for improving cane yields, water use and productivity (Chapter 2). A biophysical model is then selected and used to simulate cane yield response to water using field data from a representative cane estate in Malawi (Chapter 3). This is followed by the development of a conceptual modelling framework that aids in the simulation of the impacts of irrigation heterogeneity on field-scale cane yields, water and energy use and productivity (Chapter 4). The conceptual modelling framework is then applied to a selected case study in Chapter 5. The key findings, methodological limitations and future research prospects are discussed in Chapter 6 with conclusions and contributions to knowledge and research drawn in Chapter 7.

Chapter 2. BENCHMARKING IRRIGATION MANAGEMENT PRACTICES FOR THE SUGARCANE INDUSTRY IN SUB-SAHARAN AFRICA

2.1 Introduction

In irrigated production, the irrigation system (comprising infield equipment, water pumping and conveyance and control structures) provides a means for supplying irrigation water to the growing crop. While the system is designed to apply water via a defined method of application (e.g. surface, subsurface or overhead), it is important that it should consider crop water needs and the soil characteristics (including texture and depth) in which the crop is growing, in order to minimise water wastage or crop stress due to inadequate water supply. Thus, the choice and performance of a particular irrigation system has an important bearing on the final crop yield.

Therefore, where crop yields are deemed lower than what might be achieved by best management practices or through comparison with industry benchmark performance (what is considered attainable), the irrigation system offers options for possible yield improvement. Improvements in irrigation system performance (with irrigation uniformity as a performance indicator) have been shown to improve yields (Baillie, 2004; Holzapfel et al., 1985; Inman-Bamber et al., 1998; Pérez-Ortolá et al., 2015; Reinders, 1996). Achieving sustainable and increased cane yields would similarly require a commitment towards driving continuous improvements in irrigation systems performance. The need to enhance sustainable irrigated agricultural production in the face of dwindling water resources (Cai & Rosegrant, 2003; Neupane & Guo, 2019), means it is becoming increasingly necessary to improve the performance of irrigation systems (Malano, et al., 2004) which in turn would improve water use efficiency since inefficient irrigation systems negatively impact on crop, energy and water productivity.

The need for more intensified agricultural production to meet demands for the growing population in the face of limiting and finite resources, including water for irrigation, demands more sustainable exploitation of these scarce resources. The

concept of sustainable exploitation of resources does not only ensure continued benefits into the future, but it also ensures that resources are exploited maximally. Thus, a sustainably managed farm unit maximizes financial outputs, preserves and protects the environment in the pursuit to meet society needs (Dillon et al., 2009). Quantifying and understanding where and why gaps in performance exist is important to make improvements in any operation. The need to establish the performance 'gaps' to inform the processes required for continuous improvement and to ensure sustainable agricultural production has led to the development of various methods for assessing and/or evaluating on-farm performance. Among the commonly used performance assessment/evaluation methods includes baselining and benchmarking.

A baseline is a point of reference from which performance progress can be measured (Satpathy, 2023). Thus, baselining is a process of self-assessment of performance from a known point of reference (baseline). It involves comparison of performance before and after an intervention or over time (Regoniell, 2013). Baselining is essential for performance assessment and measurement and also helps providing improvements in the accuracy of future target projections (Satpathy, 2023).

On the other hand, a benchmark is a point of reference (known standard) from which a comparison is made (Malano & Burton, 2001). While Malano & Burton (2001, p. 1) defined benchmarking as *“a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards”*, in essence benchmarking involves comparing or assessing attributes or criteria (key performance indicators - KPIs) of interest against known standard or point of reference – benchmark (Malano & Burton, 2001). It can also involve a self-comparison of performance over time or between entities. Such comparison seeks to establish the extent and direction of deviation from the point of reference (performance gap). In a way, it is a method of gauging one's performance (Knox et al., 2013).

Both baselining and benchmarking are tools that can be applied to gauge the performance of business entities; however, the contrast between them is that baselining compares an entity's performance against its own historical performance whilst benchmarking gauges performance in relation to a given standard (regarded to be best practice or result) which can be either internal or external. In this research, the identification of opportunities for improvement in irrigation management across a number of sugar estates in SSA will be carried out. Thus, benchmarking would be an appropriate tool for the assessment as it accommodates the comparison of indicators from different entities.

The application of the benchmarking concept in agriculture, as a way of ensuring long-term sustainability of agribusiness and agri-food systems, has gained worldwide attention (Knox et al., 2013; Malano, et al., 2004). Benchmarking is a well-established technique and has been applied in different sectors including healthcare (Dewan et al., 2000), power generation (Andersson et al., 2018; Maldonado, 2015), education (Herman et al., 2010; Jaap & Hendriks, 2004), and water supply (Suchacek et al., 2018). In recent research, benchmarking has been used to assess the productivity and performance of rice irrigation schemes in Mauritania (Borgia et al., 2013). Mua et al., (2017) employed the benchmarking concept to identify a set of benchmarking indicators to evaluate the environmental performance of 55 dairy farms in selected western European countries. Muema et al. (2018) applied the concept of benchmarking to quantify and rank the irrigation performance of three rice schemes in Kenya. In Asia, Devkota et al., (2019) applied the benchmarking approach to identify gaps in rice yield, nitrogen use efficiency, profit, water productivity, and labour productivity in six countries. While working on a Life Cycle Analysis for the production of milk, pork, poultry, potato and wheat, Grinsven et al., (2019) used benchmarking concept to compare greenhouse gas (GHG) emissions per unit product among selected EU countries. In Poland, Lewandowska-Czarnecka et al., (2019) applied the benchmarking concept to establish the performance of farms in relation to sustainable development in the transformation period before the accession to the EU.

Inman-Bamber et al. (1998), Baillie (2004), Greaves (2007) and Karimi et al. (2019) applied the technique of benchmarking specifically to irrigated sugarcane production. Those studies focused on benchmarking agricultural performance using a crop modelling approach (Inman-Bamber et al., 1998), benchmarking irrigation management practices (Baillie, 2004), and benchmarking water inflows and outflows (to determine efficiency of water storage and conveyance structures) using a water accounting approach (Greaves, 2007) and identifying high and low performing sugarcane growers using remotely sensed irrigation performance indicators (Karimi et al., 2019). All the studies, except for Karimi et al., (2019), focused on how the performance of a given farm unit (estate) varied over time. While such comparisons would be essential for continuous improvement on a specific estate, they are of less importance to someone who would like to consider how benchmarking can be used to assess variations in performance across different estates. The work of Karimi et al., (2019) focused on establishing the utility of satellite-based ET products for improving irrigation management and how to establish irrigation performance indicators that were sensitive to different land holding sizes, management regimes, locations and types of irrigation systems in Eswatini. For example, it was determined that estate managed sugarcane farms were more water productive compared to farms managed by communities and individuals.

2.1.1 Aim and Objectives

The aim of this study was to apply the concept of benchmarking across selected Illovo Africa sugarcane estates in southern Africa to evaluate current practices, the extent to which irrigation performance varied across the sample and to identify opportunities for irrigation management improvement.

Specifically, the research set out to answer the following questions:

- i. What irrigation systems are used across selected sugarcane estates and how does their relative performance impact on water use and crop yields?
- ii. How does cane water productivity vary between different irrigation systems and what factors might be responsible?

- iii. To what extent do water supplies across the estates meet the sugarcane crop water requirements and how does the relative water availability impact on cane yields?
- iv. To what extent do irrigation water supplies meet irrigation water demands and how does the relative irrigation water supplies affect cane yields?

2.2 Methodology

A questionnaire was developed to determine data availability and then administered to five Illovo Africa estates. The available and appropriate datasets were collected and prepared for the determination of a set of benchmarking KPIs. A set of KPIs were then defined from the available datasets established from the preliminary questionnaire administration to enable the comparison of irrigation performance of irrigated sugarcane across the selected estates. Finally, a comparison of irrigation performance among the estates was completed. Figure 2-1 provides an overview of the methodological approach.

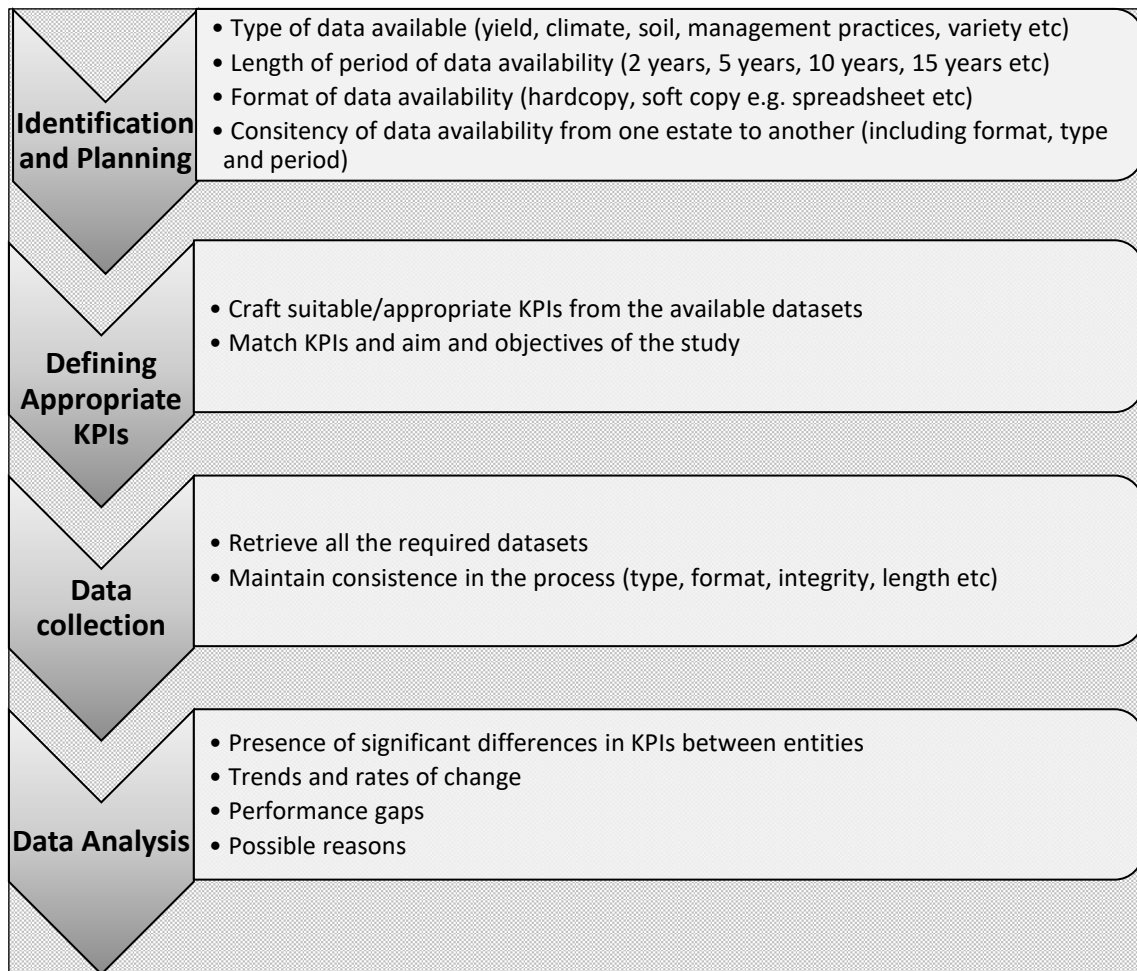


Figure 2-1: Summarised methodological approach for the irrigation benchmarking used in the study

2.2.1 Study Areas

The benchmarking approach was applied across five sugarcane estates who were all part of the Illovo Sugar (Africa) group and located in Eswatini, Malawi, Tanzania and Zambia (Figure 2-2). The four countries are significant cane producers that collectively contributed on average >15% of the global cane production between 2000 and 2020 (FAOSTAT, 2022). The estates included in the study were Nchalo and Dwangwa in Malawi, Kilombero estate in Tanzania, Ubombo estate in Eswatini and Nakambala estate in Zambia.

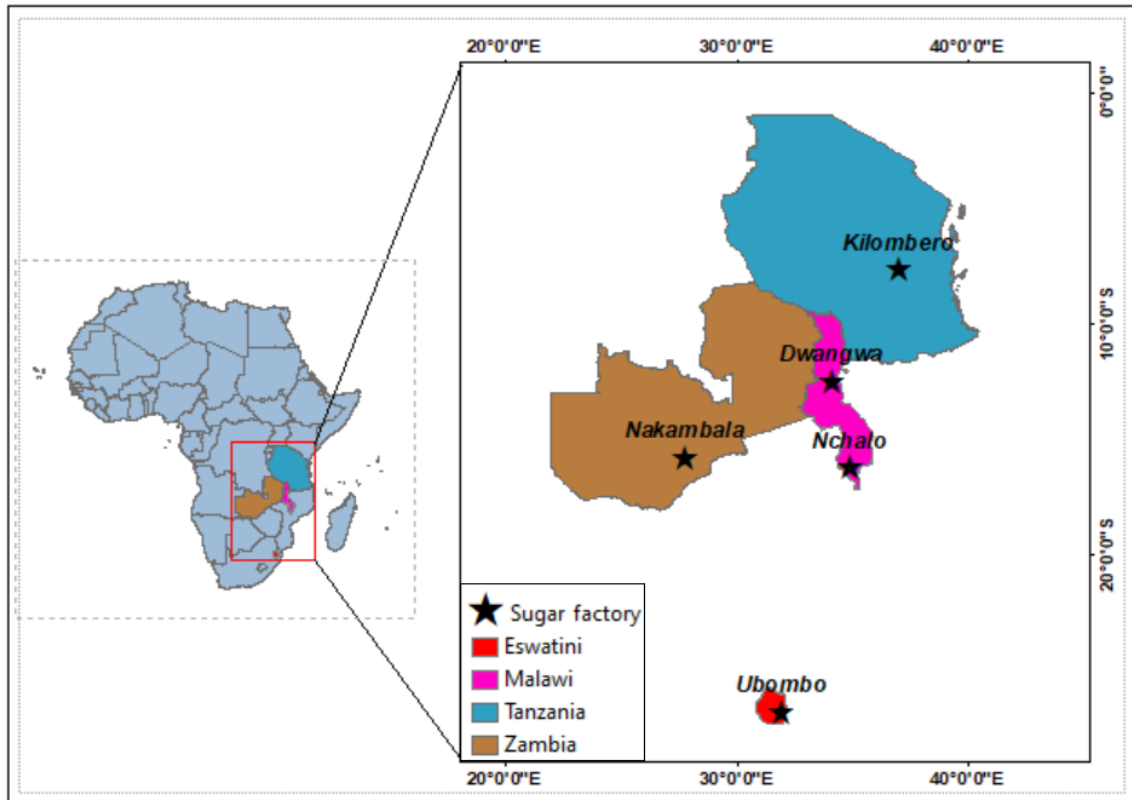


Figure 2-2: Location of the five estates involved in the irrigation benchmarking study

2.2.2 Data Collection

A preliminary questionnaire was developed and administered to the five estates. The managers responsible for irrigation were requested to complete the questionnaire with information that initially aimed to establish data availability for the benchmarking exercise including data types, sources and length of period over which data recording had been undertaken.

The preliminary questionnaire established that each of the estates record and keep seasonal data on annual crop yields, cane varieties, seasonal net irrigation application depths, crop water requirements, local climate (rainfall, minimum and maximum temperature, wind speed, relative humidity, and solar radiation) and data on the different areas of cane under each type of irrigation system. Following the administration of the questionnaire, a series of online meetings were then held with the estate managers to clarify the data requirements and the

recommended format. Through these meetings, it was established that all the estates had an information management system that handles all the production records called Canepro (SQR Software, 2023). However, each estate had datasets spanning different time periods, for example, Dwangwa estate had records for 1979 to 2019, Kilombero estate was for 2001 to 2019, Nakambala estate was for 2000 to 2019, Nchalo estate was for 1992 to 2019, while Ubombo estate was from 2000 to 2019. However, application of data quality checks (including accuracy, completeness and consistency) showed that the quality of the data across the estates improved between 2009 and 2019. Thus, datasets spanning the period from 2009 to 2019, were retrieved from each estates' CanePro database and used for the calculation of the defined KPIs.

It was also established that the estates adopted the reference cane evapotranspiration (ET_{cane}) approach in the determination of crop water requirements for the sugarcane crop. This approach follows the technique outlined in the work of Inman-Bamber & McGlinchey (2003). The estates calculate ET_{cane} from daily weather data collected from their automatic weather stations located on each estate. Thus, all the estates employed a similar method for determining their irrigation water requirements.

In general, it was observed that all estates followed similar practices including record keeping, their determination of crop water requirements, and irrigation management scheduling. The similarity of these practices across the estates was particularly important as it provided a useful common platform for conducting the benchmarking exercise.

2.2.3 Defining Key Performance Indicators

Having established the data availability from each estate, a set of KPIs were defined. Agricultural productivity and irrigation and water supply KPIs were used in this study. Table 2-1 summarises the KPIs and datasets that were required for their calculation.

Table 2-1: Key performance indicators (KPIs) and corresponding data requirements

Domain	Key performance indicator (KPI)	Data requirement
Agricultural productivity	Irrigation system productivity (t/ha)	• Cane yield (t) under given system • Harvested area (ha) under each system
	Water productivity (kg/m ³)	• Total cane yield (t) • Total harvested area (ha) • Seasonal irrigation water use (mm) • Total effective rainfall (mm)
Irrigation system operation	Relative water supply	• Seasonal crop water requirement ($ET_c - \text{mm}$) • Seasonal irrigation water use (mm) • Seasonal effective rainfall (mm)
	Relative irrigation supply	• Seasonal crop water requirement ($ET_c - \text{mm}$) • Seasonal irrigation water use (mm) • Seasonal effective rainfall (mm)

2.2.3.1 Irrigation systems productivity

Irrigation system productivity in this study was defined as the cane yield (t/ha) under a given irrigation system. In an ideal situation, no significant differences in performance are expected from a given irrigation system from place to place. Differences in performance would likely be an indicator of poor irrigation management practices in the low performing estate. Thus, irrigation system productivity (yield tonnage per unit area of a given irrigation system) was used as a benchmarking indicator to gauge the performance of given irrigation systems from one estate to another. The common irrigation systems across the five estates were identified to determine their respective crop productivities. Crop yields (sugarcane yield tonnage per unit area) under each irrigation system common to the five estates were compared to gauge the performance of each system across the estates.

The irrigation system productivity (SP) in t/ha for each estate was determined by equation (1)

$$SP = \frac{y_{irr\ sys}}{a_{irr\ sys}} \quad (1)$$

Where $y_{irr\ sys}$ is the cane production under the given irrigation system (t) and $a_{irr\ sys}$ is the corresponding harvested area under the irrigation system (ha).

2.2.3.2 Water productivity

Ali & Talukder (2008) defined water productivity as the amount of yield produced per unit volume of water consumption. Cai & Rosegrant (2003) argued that water consumption includes both beneficial and non-beneficial water consumption and such water volumes could be 'green' water (effective rainfall) for rain-fed crops and/or 'blue' water (net irrigation) for irrigated crops. In this research the definition of water consumption as proposed by Cai & Rosegrant (2003) was extended to represent the total volume of water made available to the growing crop (both effective rainfall and net irrigation). With the extended definition, the net water volume includes both the beneficially consumed water (which has a direct

contribution to crop growth and yield) and non-beneficially consumed water (which has no direct contribution to crop growth and yield including evaporation losses, surface run-off and deep percolation losses). High water productivity is likely a result of proper irrigation water management practices including correct irrigation scheduling (amount and timing of water application), efficient irrigation systems (less non-beneficial water consumption), and higher crop yield as a result of improved beneficial water consumption and reduced crop stress.

The water productivity (WP) in kg/m³ were determined by equation (2)

$$WP = 10,000 \left(\frac{y_{total}}{(i_{net} + r_{eff}) * a_{total}} \right) \quad (2)$$

Where y_{total} is the total cane yield (t), i_{net} is the net irrigation application depth (mm), r_{eff} is effective rainfall (mm) and a_{total} is the total harvested area (ha).

2.2.3.3 Relative water supply (RWS)

Sakthivadivel et al. (1993) and Kloezen & Garcés-Restrepo (1998) defined relative water supply (RWS) as the total amount of water made available to the crop from all sources including rainfall, groundwater and irrigation in relation to the theoretical crop water demand (ET_{crop}). It indicates relative water abundance or shortage during the season and overall water availability. The total crop water demand includes consumptive use, non-beneficial ET, losses to drains, and net flow to groundwater (Kloezen & Garcés-Restrepo, 1998). It includes water supplies from sources that are almost impossible to schedule and control like rainfall and groundwater, hence not necessarily a good measure of irrigation performance. However, it indicates the extent of water availability to the growing crop which is the basis for proper water resources management – one needs to know the total available water resources to plan efficient water allocations. RWS value greater than 1 indicates an over-supply and RWS less than 1 indicates insufficient water supply.

The RWS values were determined by equation (3)

$$RWS = \frac{i_{net} + r_{eff}}{ET_c} \quad (3)$$

Where i_{net} is the net irrigation application (mm), r_{eff} is effective rainfall (mm) and ET_c is the crop water demands (mm).

2.2.3.4 Relative irrigation supply (RIS)

Relative Irrigation Supply (RIS) is the water supplied via irrigation in relation to irrigation water demand (Kloezen & Garcés-Restrepo, 1998). It indicates how well an irrigation system meets irrigation water demands. While RWS takes into consideration of the total crop water requirements, RIS is only concerned with the irrigation water demand – the difference between total crop water demand and the water supplied from other sources like rainfall and groundwater (Kloezen & Garcés-Restrepo, 1998). It is a better measure of irrigation performance as it considers only water supplied to the crop via irrigation, which can be scheduled, controlled, and managed. While an ideal RIS is equal to 1, a RIS value higher than 1 signals over-irrigation and RIS less than 1 suggests under irrigation.

The RIS values were calculated by equation (4)

$$RIS = \frac{i_{net}}{(ET_c - r_{eff})} \quad (4)$$

Where the parameters i_{net} , r_{eff} and ET_c are as defined in equation 3.

2.2.4 Data Analysis

For each estate dataset and variable, the KPI values were estimated and statistically compared between each estate to establish the performance trends for each KPI. Analysis of variance (ANOVA) was also performed on each of the calculated KPI values to establish statistical significance of the levels of variation across the estates.

2.3 Results

2.3.1 Crop Water Requirements, Rainfall and Irrigation Water Use

The seasonal and mean crop water requirements for each estate between 2009 and 2019 are presented in Figure 2-3. While insignificant differences in seasonal crop water demands ($p>0.05$) were observed between Nchalo, Kilombero and Nakambala estates, there were significant differences in mean crop water requirements between Dwangwa and Ubombo estates. However, the average crop water requirements for both Dwangwa and Ubombo estates were significantly lower than those for Nchalo, Kilombero and Nakambala estates.

Reported rainfall figures across the five estates were also compared. A comparison of the seasonal variation in rainfall and mean rainfall among the estates over the study period is presented in Figure 2-4. As can be observed, significant differences ($p<0.05$) in rainfall were observed between the five estates. Kilombero estate had the highest mean rainfall (1236 mm) while Ubombo estate had the lowest (585 mm).

Figure 2-5 shows the average and variation in irrigation application depths at each estate between 2009 and 2019. Significant differences ($p<0.05$) in average irrigation depth were observed across all estates. Overall, the average irrigation applications for Nchalo were significantly higher than those of the other estates and Kilombero had the lowest irrigation applications.

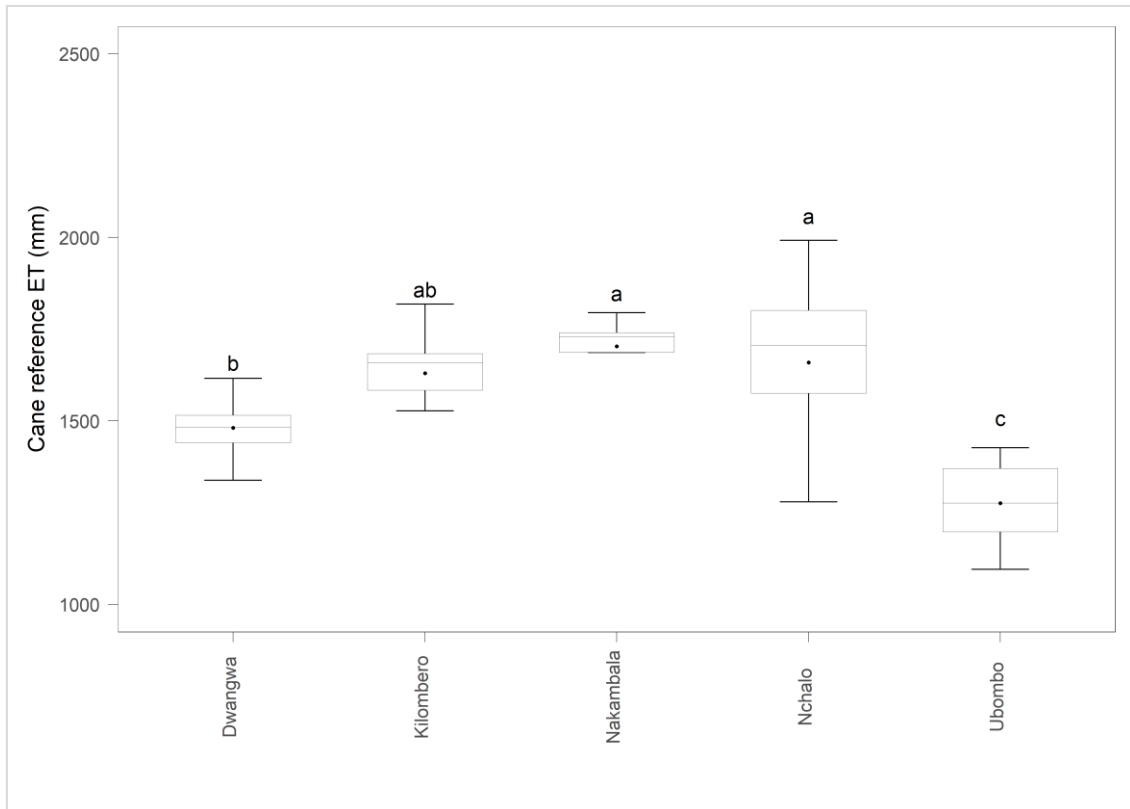


Figure 2-3: Variation in crop water requirements (mm) between the 5 individual estates based on data from 2009 to 2019. The point inside the box denotes the average crop water requirements, the upper and lower whiskers represents the maximum and minimum crop water requirements, respectively within the period and the letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

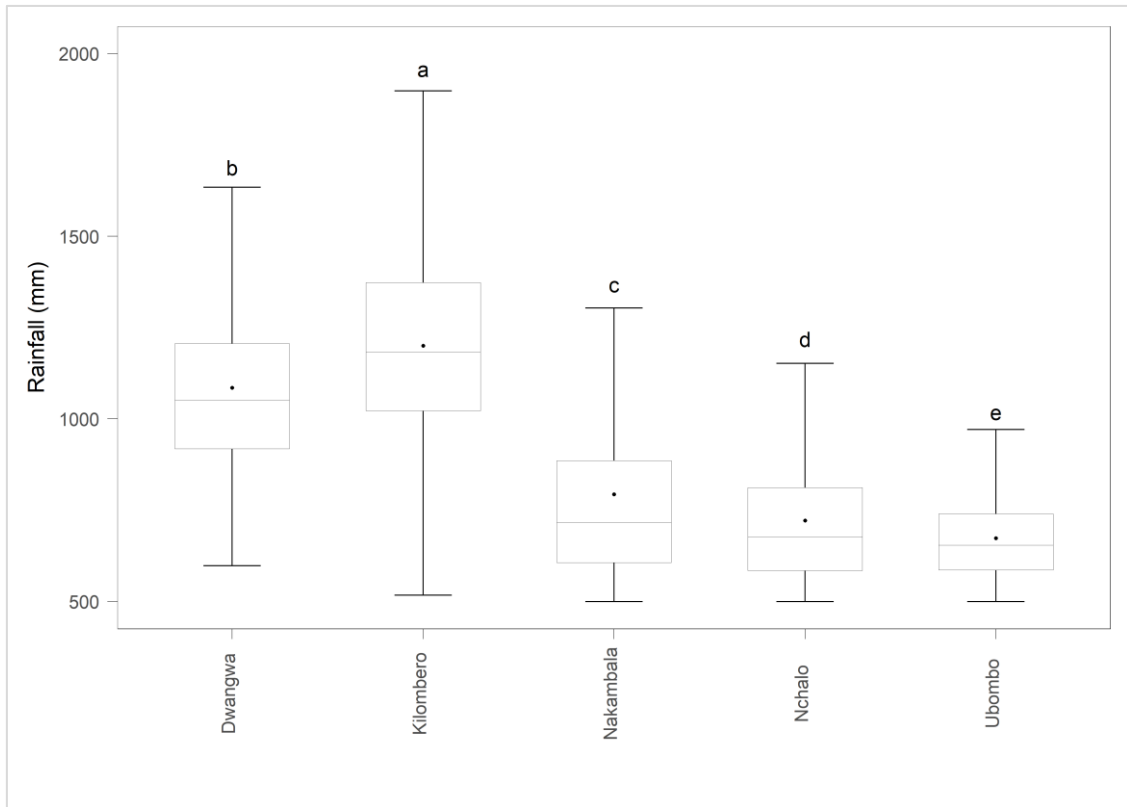


Figure 2-4: Comparison of annual rainfall averages between the 5 individual estates based on met data from 2009 and 2019. The letters on each boxplot denote significant differences between estates.

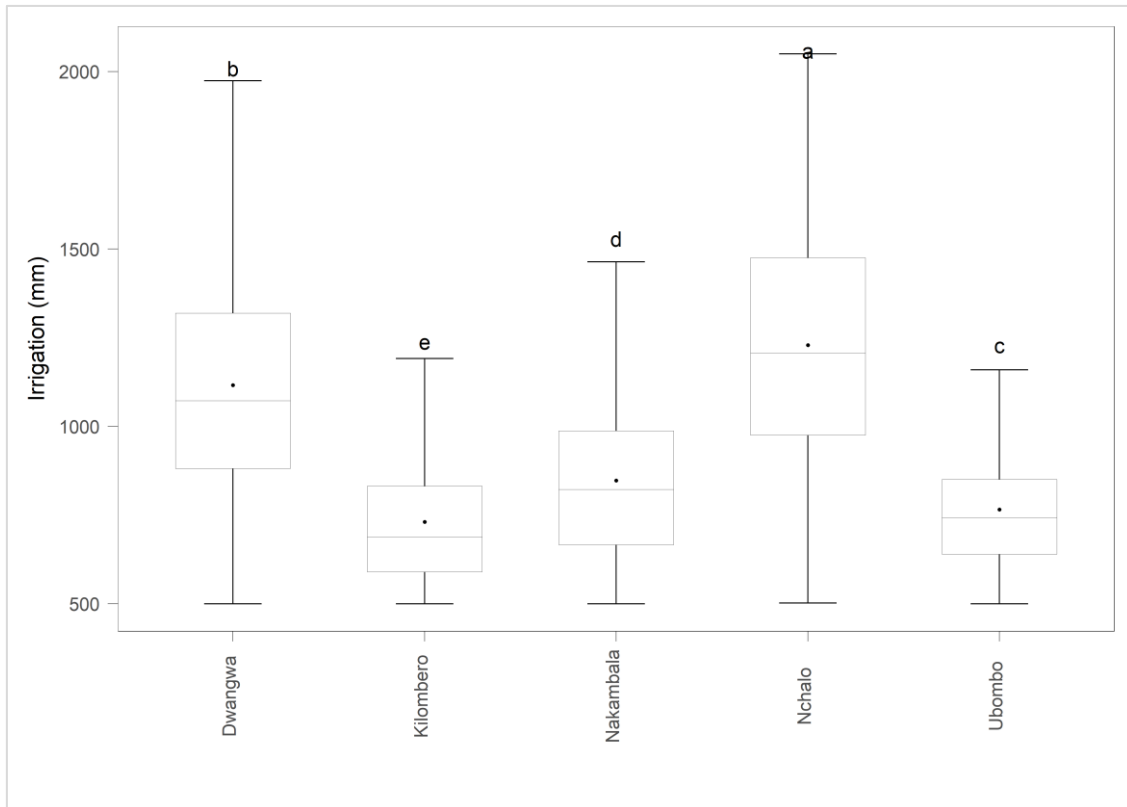


Figure 2-5: Comparison of irrigation application depths (mm) between the 5 individual estates based on data from 2009 to 2019. The letters a, b and c denote significant differences between estates.

The irrigation applications for each system used on each estate over the study period is presented in Figure 2-6. The comparison between the centre pivot and furrow systems at Dwangwa estate showed that centre pivot applied significantly more water ($p < 0.05$) than the furrow systems. No significant differences ($p > 0.05$) in irrigation applications were observed between the centre pivot, furrow and sprinkler systems at Kilombero estate. At Nakambala estate, all the three systems (centre pivot, furrow and sprinkler) applied significantly different ($p < 0.05$) amounts of water with the centre pivot and sprinkler systems reporting the highest and lowest water applications, respectively. Insignificant differences ($p > 0.05$) in water applications were observed between the centre pivot and furrow systems at Nchalo estate, but the water applications for each of them was significantly lower than that of the sprinkler system. The amounts of water applied under the furrow and sprinkler irrigation systems at Ubombo estate were significantly

different, however their respective applications were not significantly different to that of the centre pivot.

The KPI analysis of irrigation applications by system (Figure 2-7) revealed significant differences ($p < 0.05$) in centre pivot applications from one estate to another. Comparisons of water applications under the furrow system at each estate was significantly different ($p < 0.05$) except for at Nakambala and Ubombo. Also, there were significant differences in water applications under the sprinkler system between estates, except for Kilombero and Nakambala.

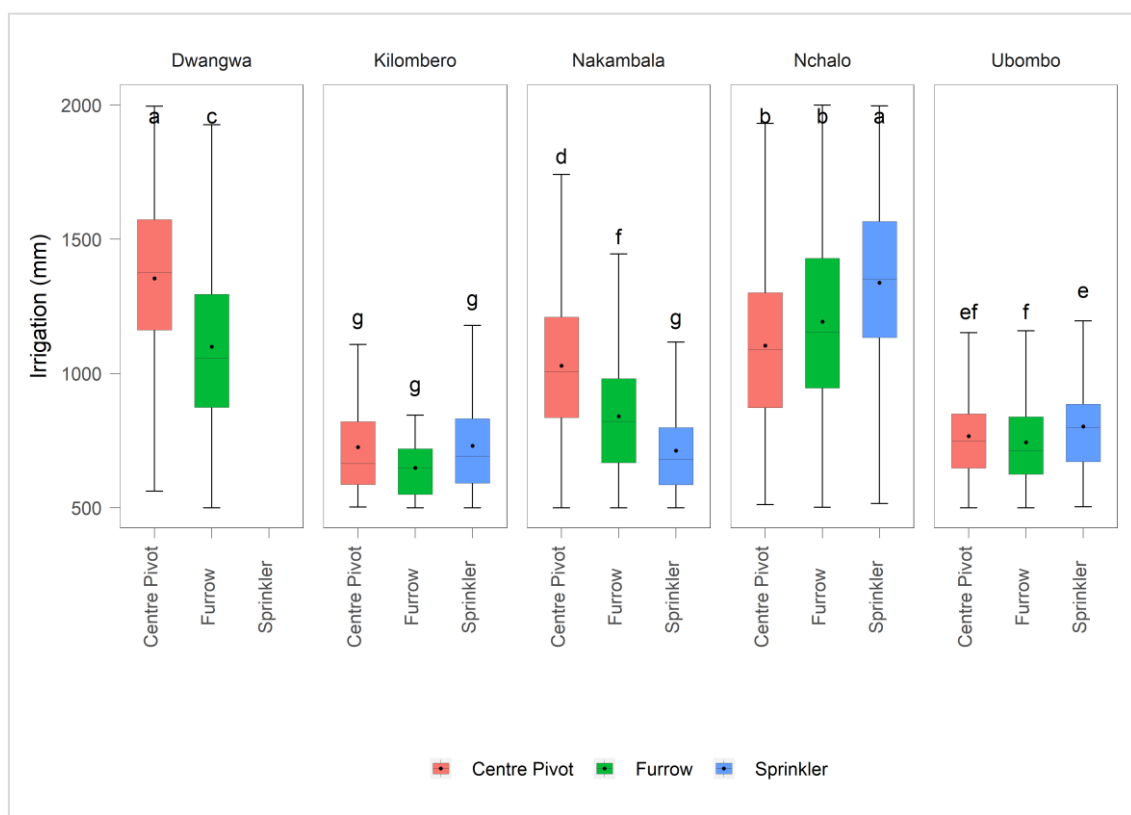


Figure 2-6: Comparison of irrigation application depths (mm) by irrigation system across all estates. The letters on each boxplot denote significant differences between irrigation systems. Systems with same letters are not significantly different from each other

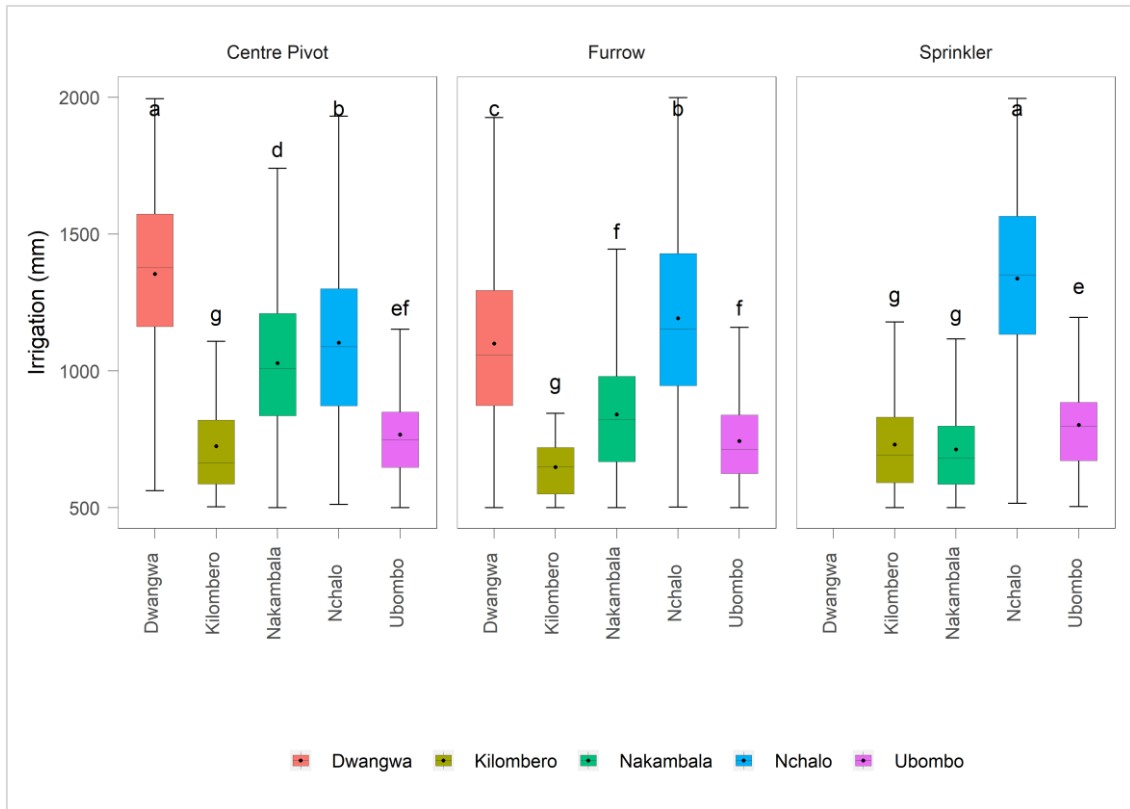


Figure 2-7: Irrigation application depths comparison by irrigation systems from one estate to another (2009 - 2019). The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

2.3.2 Irrigation Systems and Cane Productivity

It was established that centre pivot, furrow and sprinkler systems were the dominant methods of water application (80%) used on the estates (Table 2-2). The other 20% of estates (Dwangwa) did not have sprinkler or drip irrigation systems. While the analysis included sprinkler systems it excluded drip irrigation systems even it was used on some estates because the period of use was not sufficient to conduct a statistically meaningful comparison. Some estates had only used drip system for one or two seasons, for example.

Cane yield average for each estate between 2009 and 2019 are shown in Figure 2-8. As can be observed, the yields had been highly variable within estates over the period under consideration. The average crop yields for each estate showed

significant variation ($P < 0.05$) from one place to another. On average, the cane yields ranged between 83.90 t/ha and 108.89 t/ha with Dwangwa estate being the highest performer and Kilombero being the lowest.

Table 2-2: Summary of irrigation systems in use at each estate between 2009 and 2019.

Irrigation type	Irrigation System	Nchalo	Dwangwa	Kilombero	Ubombo	Nakambala
Surface	Furrow	✓	✓	✓	✓	✓
Overhead	Sprinkler	✓		✓	✓	✓
	Centre pivot	✓	✓	✓	✓	✓
Micro	Drip	✓		✓	✓	✓

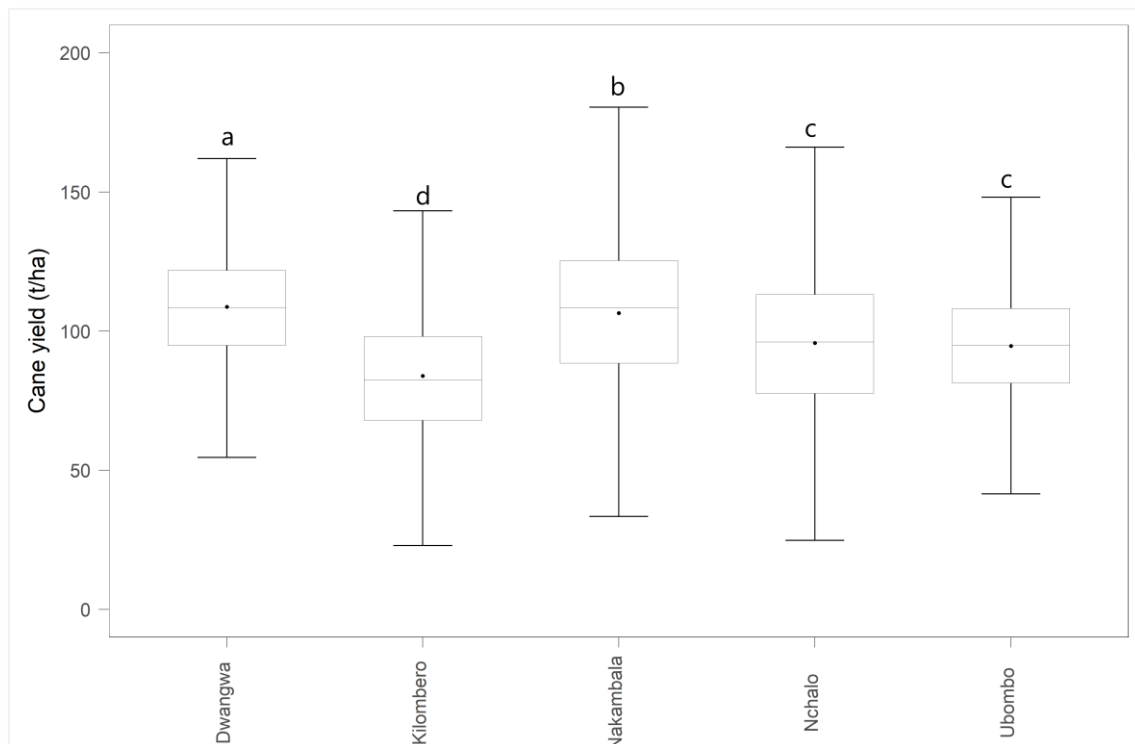


Figure 2-8: Variations in annual cane yields (t/ha) by estate (2009 – 2019). The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

The different irrigation systems used on each estate produced significantly different cane yield averages (Figure 2-9). No significant differences ($p>0.05$) in cane yields between irrigation systems were observed at Dwangwa (for furrow and centre pivot) and at Kilombero estate (for centre pivot, furrow and sprinkler). However, at Nakambala, Nchalo and Ubombo cane yields under each respective irrigation system (centre pivot, furrow and sprinkler) were significantly different ($p<0.05$) from each other. The centre pivot systems produced significantly higher yields at Kilombero, Nakambala, Nchalo and Ubombo while the sprinkler systems produced significantly lower yields at the same estates over the period of study.

Significant yield differences ($p<0.05$) were also observed for the irrigation systems between each estate (Figure 2-10). Fields irrigated using the centre pivots at Dwangwa, Nakambala and Nchalo showed no significant differences in cane yields. However, the centre pivot fields at Kilombero and Ubombo showed significant yield differences although yields were significantly lower than those of Dwangwa, Nakambala and Nchalo estates. Cane yields for the centre pivot system across all estates ranged between 92.92 and 110.6 t/ha. A comparison of furrow irrigated fields at each estate showed significant yield differences ($p<0.05$). The average yields from furrow irrigated fields ranged between 85.47 t/ha and 111.77 t/ha. There were no significant differences in average cane yields for sprinkler irrigated fields across all five estates (Dwangwa, Kilombero, Nakambala, Nchalo and Ubombo).

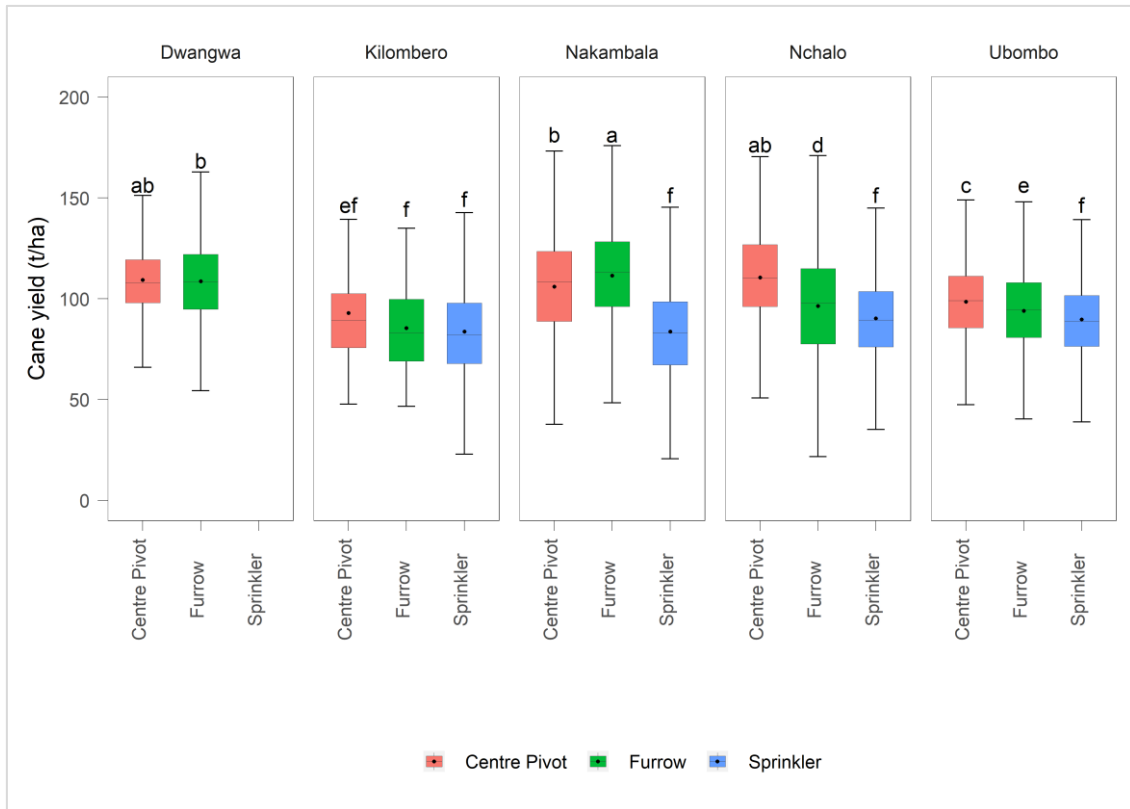


Figure 2-9: Cane yield variations by irrigation system within estates. The letters on each boxplot denote significant differences between irrigation systems. Systems with same letters are not significantly different from each other

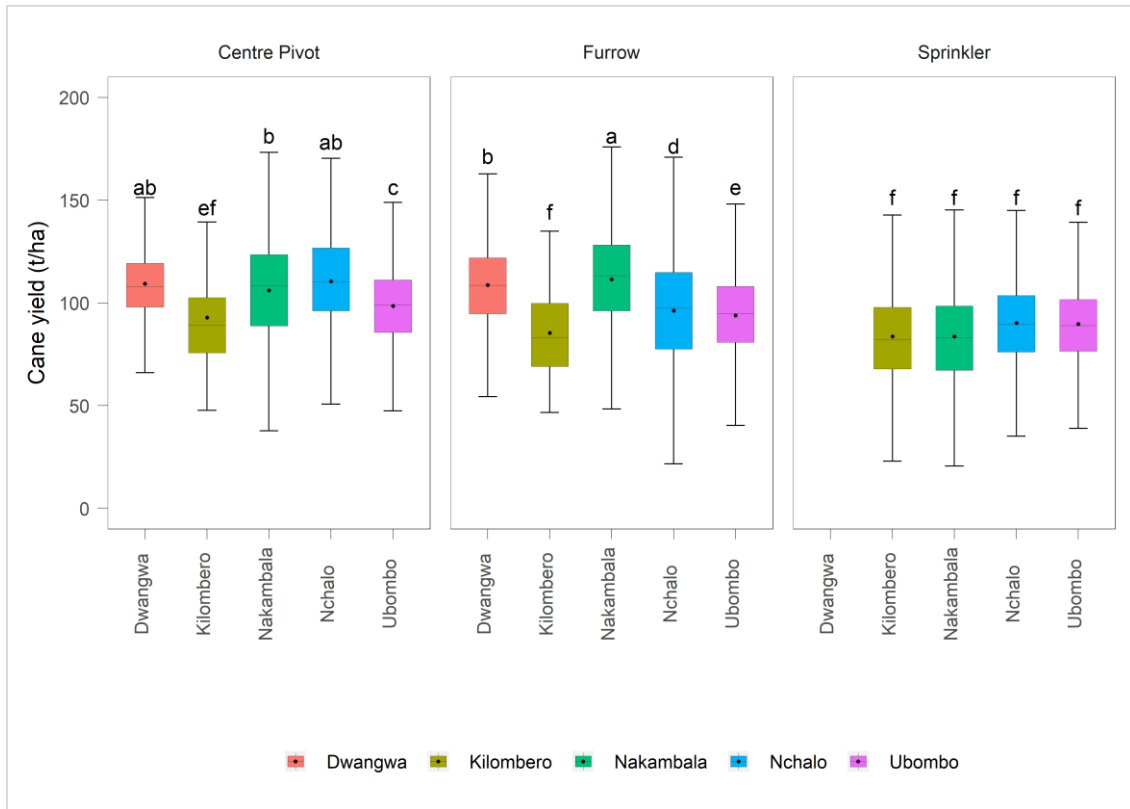


Figure 2-10: Cane yield variation (t/ha) by estate within irrigation systems (2009-2019). The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

2.3.3 Water Productivity

Figure 2-11 shows the variations in water productivity at each estate between 2009 and 2019. In general, the water productivities at Dwangwa, Kilombero and Nchalo estates were not significantly different ($p > 0.05$). On the other, the water productivities at Nakambala and Ubombo were significantly different from the other estates with Nakambala having the highest average water productivity (7.8 kg/m^3).

A comparison of water productivity between irrigation systems at each estate is presented in Figure 2-12. At Dwangwa, no significant differences ($p > 0.05$) were observed between furrow and centre pivot systems. Similarly, at Kilombero there were no significant differences ($p > 0.05$) across the three systems (centre pivot, furrow and sprinkler). Nakambala, Nchalo and Ubombo estates showed

significant differences across their respective irrigation systems. The centre pivot system had the highest water productivity at both Nchalo and Ubombo whilst furrow system was the most productive system at Nakambala. At three estates (Nakambala, Nchalo and Ubombo) the sprinkler system had the lowest water productivity.

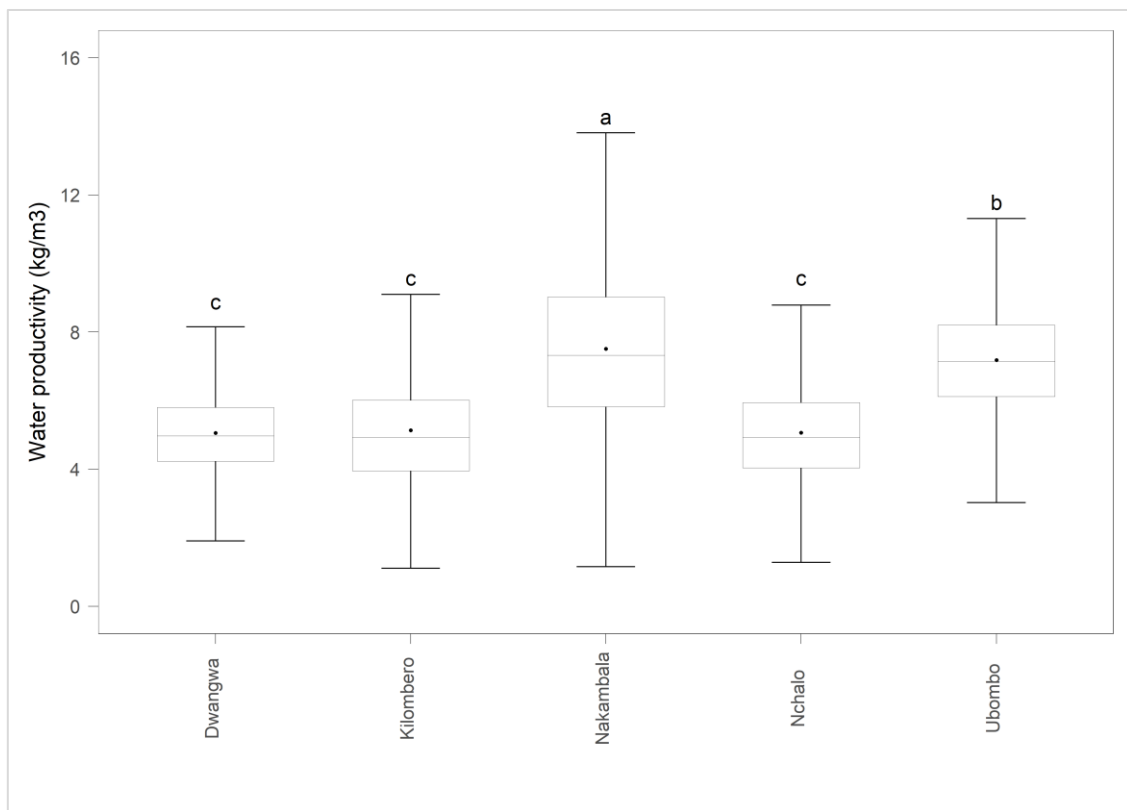


Figure 2-11: Water productivity variation between estates (2009 - 2019). The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

Figure 2-13 shows the variation in water productivities by irrigation system between 2009 and 2019. Ubombo estate's centre pivot system was the most water productive (7.5 kg/m^3) and Dwangwa and Kilombero estates' centre pivots were jointly least productive (4.3 and 5.1 kg/m^3 , respectively). Nakambala's furrow fields were the most productive (7.5 kg/m^3) whilst water productivities at Dwangwa, Kilombero and Nchalo were the lowest (5.1 , 5.6 and 5.2 kg/m^3 , respectively). Ubombo estate had the highest sprinkler water productivity (6.7

kg/m³) while Kilombero and Nchalo estates' sprinkler fields were the least water productive (5.1 and 4.6 kg/m³, respectively).

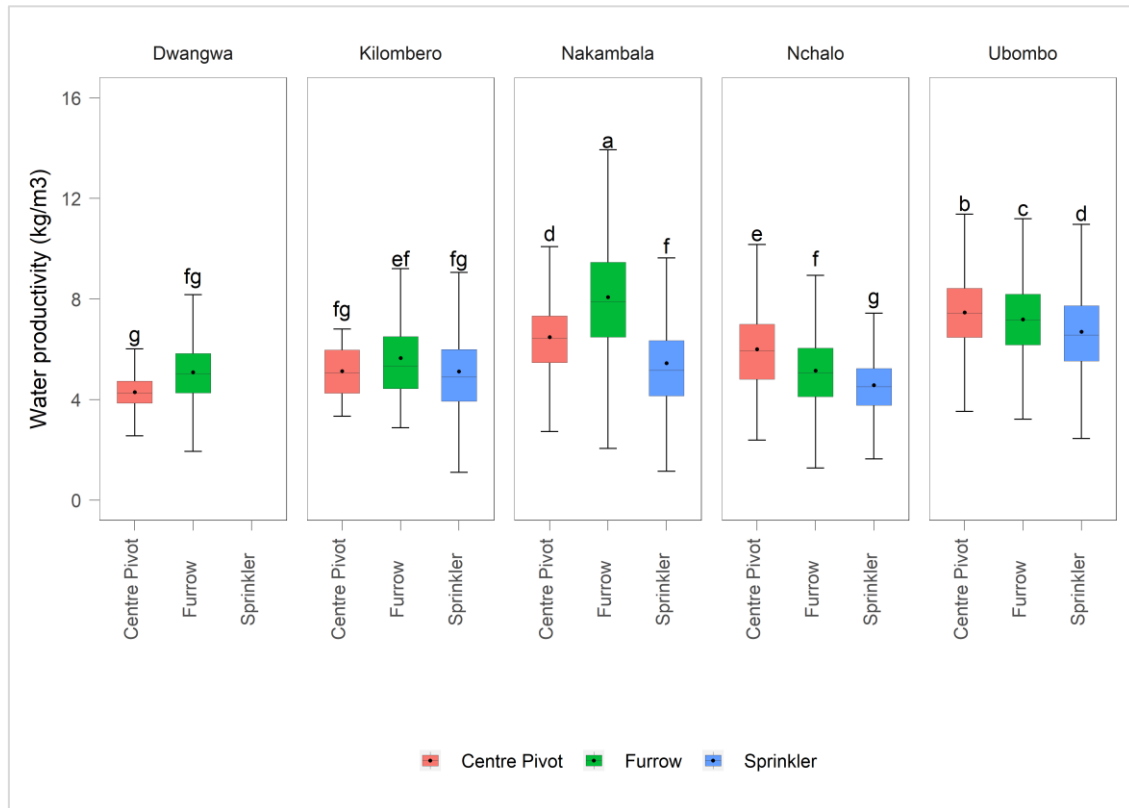


Figure 2-12: Variation in water productivity between irrigation systems within estates (2009 – 2019). The letters on each boxplot denote significant differences between irrigation systems. Systems with same letters are not significantly different from each other

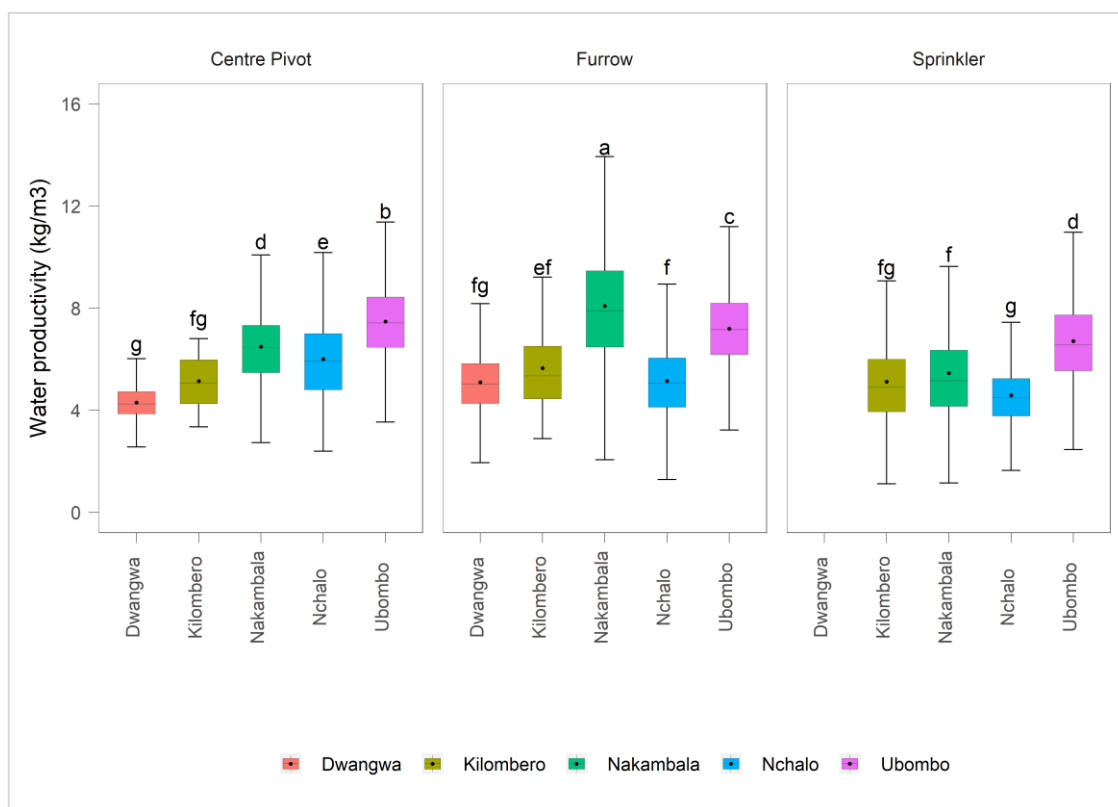


Figure 2-13: Water productivity variation at each estate between 2009 and 2019. The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

2.3.4 Relative Water Supply (RWS)

The calculated RWS across the five estates between 2009 and 2019 are presented in Figure 2-14. There were significant variations in the RWS across the estates (Figure 2-15). At Dwangwa there was a consistent over-supply of water (34%, on average, each year) while at Nchalo and Ubombo there was a more variable situation with the total water supply above crop water requirements in some years but inadequate in other years. Nakambala and Kilombero also showed consistently inadequate water supplies to meet crop water requirements. On average, Nchalo had 13% over-supply each year while Kilombero, Nakambala and Ubombo had average water supply deficits of 13%, 25% and 1% each, respectively.

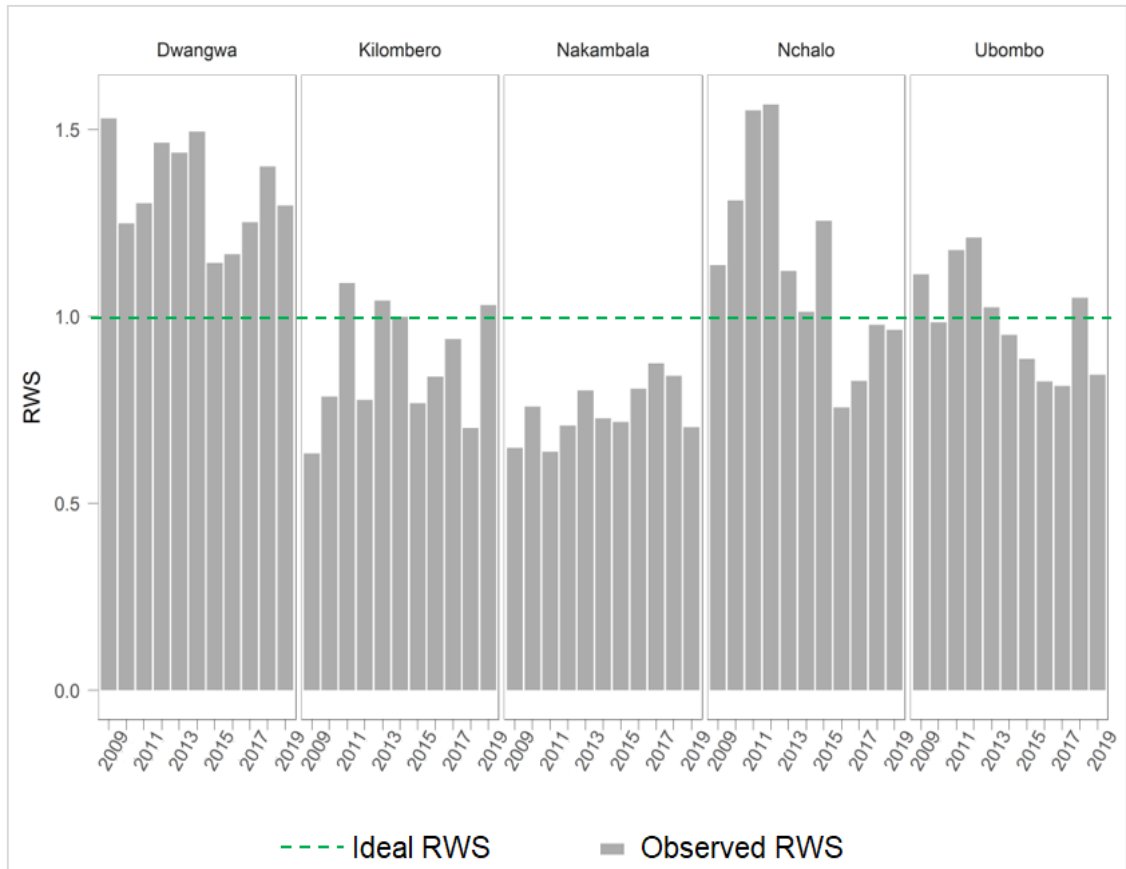


Figure 2-14: Relative water supply (RWS) for each estate between 2009 and 2019

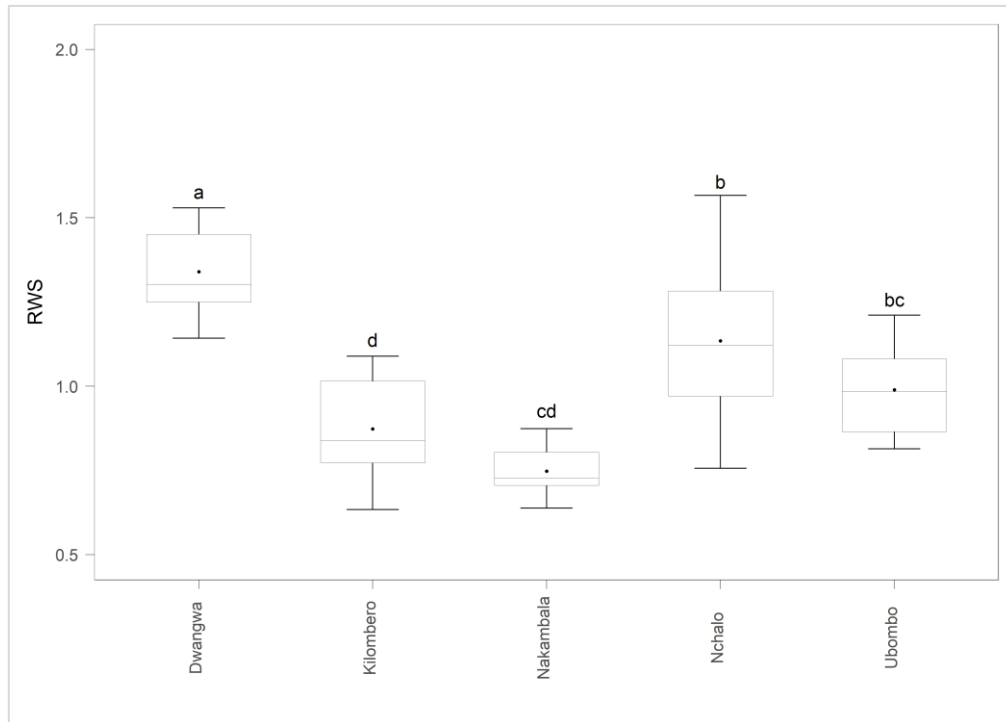


Figure 2-15: RWS variations within estates between 2009 and 2019. The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

2.3.5 Relative Irrigation Supply (RIS)

The estimated RIS for each estate is summarised in Figure 2-16 and shows statistically significant ($p < 0.05$) variations between each estate (Figure 2-17). At Dwangwa there was consistent over-irrigation (on average 105% over-irrigation per year). At Nchalo there was on average 23% over-irrigation but with consistent under-irrigation between 2016 and 2019 while at Ubombo, Kilombero and Nakambala there was an average of 2%, 26% and 40% under-irrigation per year, respectively.

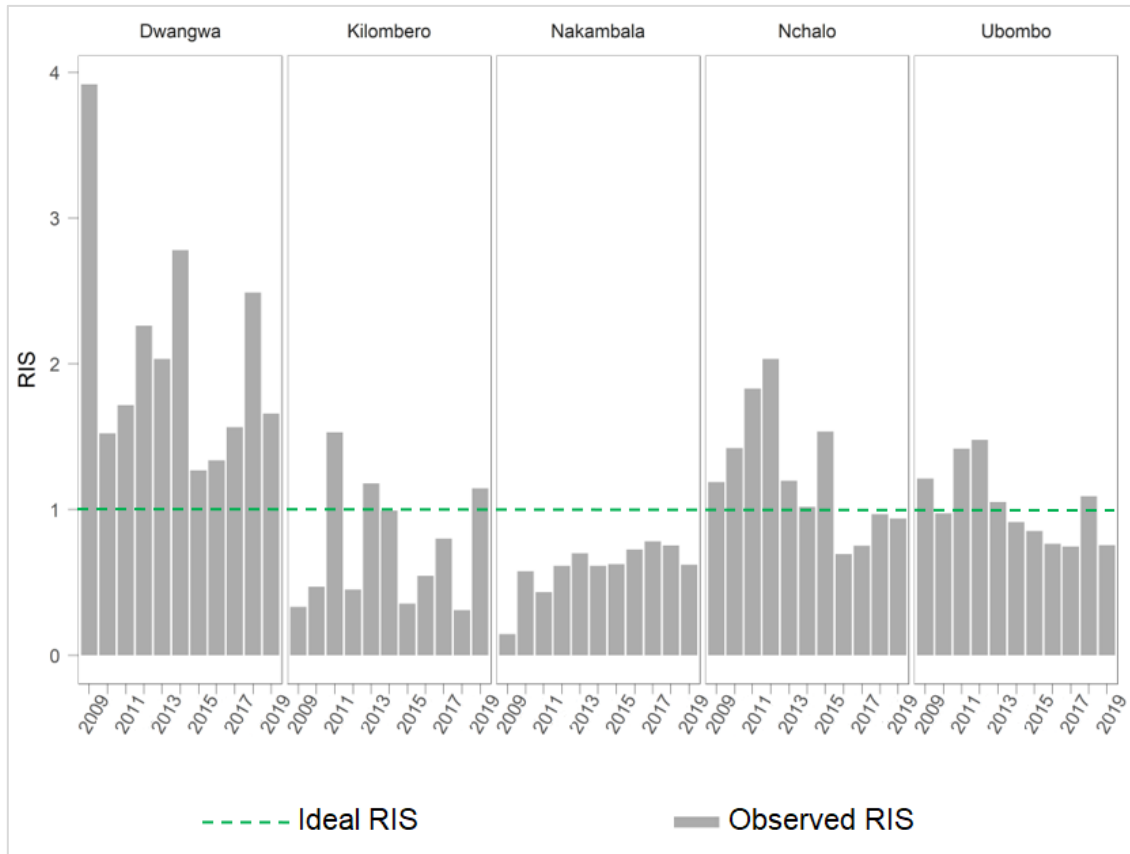


Figure 2-16: Relative irrigation supply (RIS) for each estate between 2009 and 2019

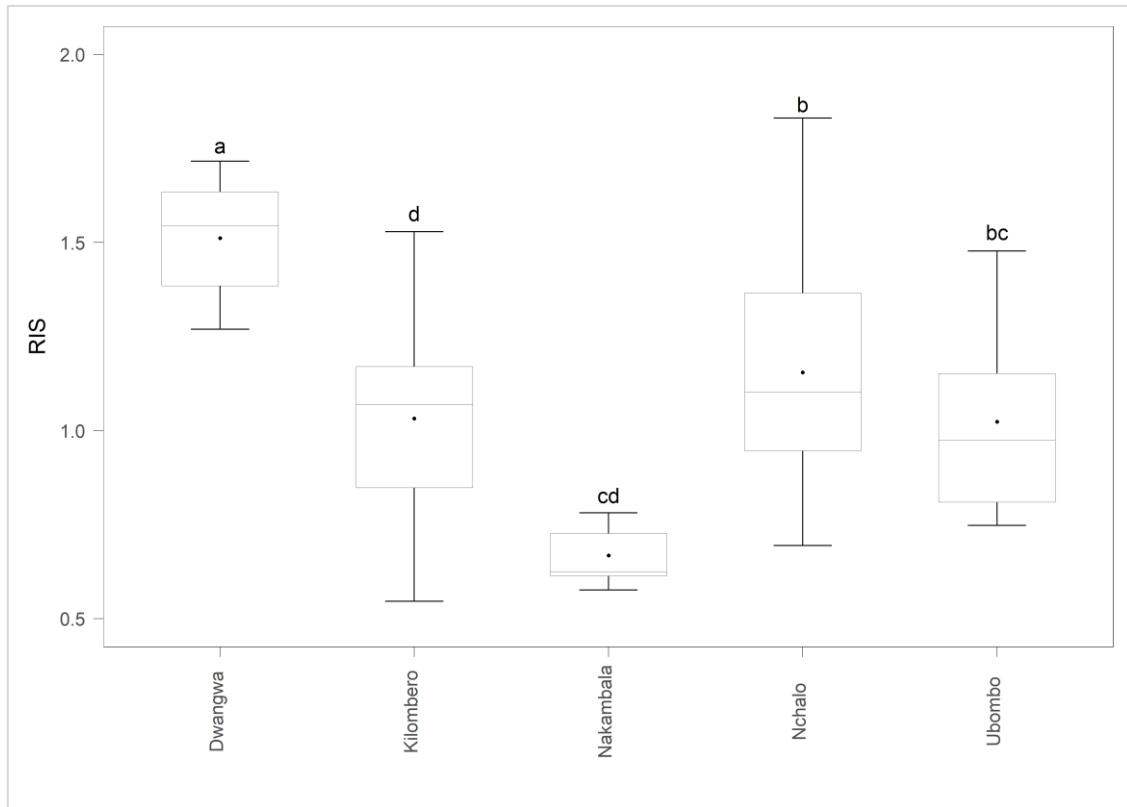


Figure 2-17: Variation in RIS within estates between 2009 and 2019. The letters on each boxplot denote significant differences between estates. Estates with same letters are not significantly different from each other

2.4 Discussion

Significant variations were observed in reported crop yields, water productivity, RWS and RIS both within individual estates and between estates. Such differences are likely due to the impacts of water supply availability and irrigation management (scheduling) practices at each estate. Crop yield variations are expected between different locations due to the spatial differences in crop yield potential as a result of differences in factors influencing crop production including local agro-climate, soils and water availability. However, significant variations in water productivity in irrigated production are a sign of poor irrigation management practices, resulting in lower water productivities and irrigated yield benefits not being fully maximised. Thus, there were opportunities to improve the irrigated

yield benefits at Dwangwa, Kilombero and Nchalo estates as they were characterised as having the lowest water productivities.

While it is acknowledged that the genetic characteristics for specific cane varieties determines levels of pest and disease resistance, drought tolerance, ratooning suitability, harvesting characteristics (Dumont et al., 2019), and hence yielding capabilities; this research did not consider the extent to which these traits impacted on yields and water productivity. Thus, only the water supply and irrigation water management components of the environment in which the cane is grown were considered as likely causes of yield variability. The assumption that cane yields in the selected estates were impacted by irrigation water management practices was made considering that the estates under consideration were part of the same company (Illovo Africa group) and thus the rest of crop husbandry practices (including land preparation, weed control, and crop nutrition) were assumed to be uniform across the estates. This assumption, however, might not always hold and might have affected the results, especially the crop yields differences between estates.

Due to unavailability of appropriate data, the RWS and RIS were estimated at estate level rather than field level. Such spatial resolution had a potential to overshadow the possible differences in total water and irrigation water supplies across the estates. For example, it was observed that irrigation water uses significantly varied across systems with centre pivot system applying the most water and sprinkler system applying the least, on average. However, the average RIS might signal overirrigation at estate level due to the high-water application in centre pivots while obscuring the underirrigation in the sprinkler systems.

2.4.1 Irrigation System and Cane Productivity

In general, all estates reported yields below 120 t/ha which is considered globally to be “good” for irrigated sugarcane (Steduto et al., 2012). However, Wacławovsky et al. (2010) reported that actual commercial yields for irrigated sugarcane typically range between 80 and 150 t/ha while Hess et al. (2016)

estimated average productivity of 98 t/ha for irrigated cane. The commercial yield criterion makes Kilombero estate the only estate to fall outside the lower range.

The performance (in terms of crop yield) of the different irrigation systems varied from one estate to the other. While the differences in irrigation system yield productivity between estates could be due differences in crop yield potential of the localities in which the cane was grown, it could also be an indication of differences in irrigation management practices. For example, it was observed that Dwangwa estate cane yields under the centre pivot and furrow systems were not significantly different from each other despite the irrigation applications being significantly different. Similarly, at the other estates (Kilombero, Nakambala, Nchalo and Ubombo) the systems that applied the highest irrigation applications did not deliver the highest yields. This could be an indication of poor irrigation management practices (including scheduling) and means that the potential yield benefits from irrigation were not being maximised.

2.4.2 Water Productivity

Svendsen et al. (2009) reported that average sugarcane water productivities for Eswatini, Malawi, Tanzania and Zambia were 14.20, 11.56, 10.24 and 12.55 kg/m³ respectively. The estimated water productivities for all five estates were below these reported potential productivity figures for each corresponding country. Hess et al. (2016) reported that irrigated sugarcane productivity is almost threefold higher than that for rain-fed cane production. However, the impact of irrigation can only be maximized if it is applied at the right time and in the right amount. The need for precise triggering of irrigation requires appropriate irrigation scheduling. The water productivity trends across the five estates showed that there is scope for improvement in scheduling practices that should be exploited.

2.4.3 RWS and RIS

It was observed that for all estates in many instances, the RIS values were rarely close to the ideal value (1.0). While RIS values of <1.0 indicate an inadequate amount of irrigation, any divergency (positive or negative) could also imply poor

irrigation management (including scheduling). Irrigation is meant to supplement rainfall to support cane production and applied when rainfall is insufficient to meet crop water requirements. The gap between actual and ideal RIS values highlights the need for improved scheduling including accurate in-situ monitoring of soil moisture fluctuations.

While high yields are associated with adequate water supplies, adequate water supply on its own is of no use in the absence of appropriate water management. The management of irrigation determines the level of consistency in output of operations as adequate water management limits excessive non-beneficial water losses, reduces the costs of pumping, and can improve crop yield and quality. While rainfall and irrigation were both considered as the major water supplies for production in this study, much emphasis was directed to the impact of irrigation on yields as irrigation offers the flexibility to be managed and controlled for maximum benefit.

2.5 Conclusions

Various irrigation methods are used in SSA cane production including overhead (centre pivot and sprinklers), localised or micro (drip), and surface (furrow). The irrigation water use across the systems showed that centre pivot system uses the most water while the sprinkler system uses the least with furrow system falling in between. Further, the crop yields and water productivities under each system (from one estate to another) were not only variable, but also showed significant spatial differences.

On the other hand, significant spatial and temporal differences were observed in both total water and irrigation water supplies across SSA. Despite the significant differences in irrigation water uses between irrigation systems, estate level averages showed that most of the estates met the irrigation water requirements of their cane. This finding, however, needs further exploring as the water supplies were considered at estate levels and not field level (due to lack of appropriate data). Such level of spatial resolution obscured potential impacts of irrigation systems on water use. This implies that there are opportunities for maximizing

the benefits from irrigated cane production in SSA. Such benefits may include increased cane yields, improved water productivity, reduced cost of irrigation operations and increased returns.

Chapter 3. CROP MODEL SELECTION AND PERFORMANCE ASSESSMENT

3.1 Introduction

An over-simplified adage of crop yield maximization is that, *“in order to achieve high crop yields it is fundamental to maximize the extent and duration of radiation interception, use the captured energy in an efficient photosynthesis process; partition the new assimilates in ways that provide optimal proportions of leaf, stem, root and reproductive structures and maintain the process at a minimum cost”* (Cock, 2003, p. 6). However, the process of how crops produce and partition assimilates is not as straightforward as it sounds; it involves extremely complex and dynamic processes and some mechanisms underlying such processes are yet to be established (Ainsworth and Rogers, 2007). The lack of comprehensive understanding of all the mechanisms underlying the physiological processes responsible for crop growth and development makes it hard for crop scientists to pinpoint a single process that needs to be controlled for maximum water productivity (Banda, 2019). Observing and assessing yield response to varying water application levels via fieldwork and/or controlled experimental setup is not only laborious and time consuming; it is also an expensive process (Andarzian et al., 2011).

The past fifty years have seen crop modelling develop into a valuable scientific discipline, more so due to the advancement in crop and environmental sciences as well as in computing technologies (Singels, 2014). Thus, the development and readily availability of crop models have simplified methods of understanding the impacts of different scenarios on crop growth and development and ultimately on crop yields.

While Bouman et al. (1996) defined a model as a basic illustration of a system with the system being finite part of reality that contains interconnected components, Singels, (2014, p. 542) defined crop modelling as *“the construction of mathematical analogues of the cropping system and their use in dynamic simulation of constituent processes by numerical integration with the use of computers”*. Thus, a crop model could be defined as a simplified representation of the crop system that contains interrelated elements that mimics the processes for crop growth and development in response to corresponding requirements (for example water, nutrients, sunlight and temperature) by means of algorithms run on computers. Crop models have been used to understand the impacts of different production scenarios in sugarcane farming. As such various models have been developed and used specifically for sugarcane including DSSAT Canegro(Inman-Bamber, 1991; Singels and Bezuidenhout, 2002), APSIM-Sugarcane (Keating et al., 1999), CANESIM (Singels and Paraskevopoulos, 2017) and AquaCrop (Raes et al., 2009). Models have an ability to assess the impacts of different factors affecting yields and derive optimal input – output conditions for different scenarios (Andarzian et al., 2011). Models assist in the understanding of new knowledge, analysis of scientific hypotheses and situation analyses, strategic and tactical decisions (Singels, 2014).

3.1.1 Approaches to Crop Modelling

There are two main approaches to crop modelling and these are the functional (empirical) modelling approach and the mechanistic (process-based) modelling approach (Singels et al., 2010). The empirical approach to modelling simplifies intricate crop growth processes and emphasises on macro-growth processes. Empirical models are suitable for large scale simulations (Vanuytrecht et al., 2012) and are often employed to support management decisions (Singels 2014). On the other hand, mechanistic approach to modelling aims to develop an in-depth understanding of the cropping systems and how plant growth and development processes relate to each other. Mechanistic models are mainly used in research (Singels, et al., 2010; Singels, 2014; Vanuytrecht et al., 2012).

Empirical models have advantages over mechanistic models in that they are less intricate and are easier to use and understand. They also require less input parameters that are mostly easier to obtain. However, empirical models employ generic algorithms which could result in less accuracy.

3.1.2 Crop Growth Engines in Crop Modelling

At the centre of any crop growth and development model, is a mechanism that controls biomass accumulation processes. There are three main approaches to biomass accumulation employed in crop modelling and these are (i) carbon - biomass conversion, (ii) conversion of intercepted solar radiation into biomass and (ii) transpiration – biomass conversion (Singels, 2014). As a result, models fall into three main categories based on the growth engine employed in the accumulation of biomass.

3.1.2.1 Carbon-Driven Models

The carbon – biomass conversion approach to biomass accumulation is based on the assumption that biomass is mainly composed of cellulose, hemicellulose, lignin, extractives/volatiles and ash, of which carbon (C) is a major component (Williams et al., 2017). Plants get C from the atmosphere via their stomata in the process of photosynthesis. Use of plant photosynthetic rate, in turn, helps to estimate how much C the plant receives in a day that could contribute to biomass accumulation (Figure 3-1). Thus, knowledge of carbon assimilated over a given period would lead to the estimation of the amount of biomass generated over the period.

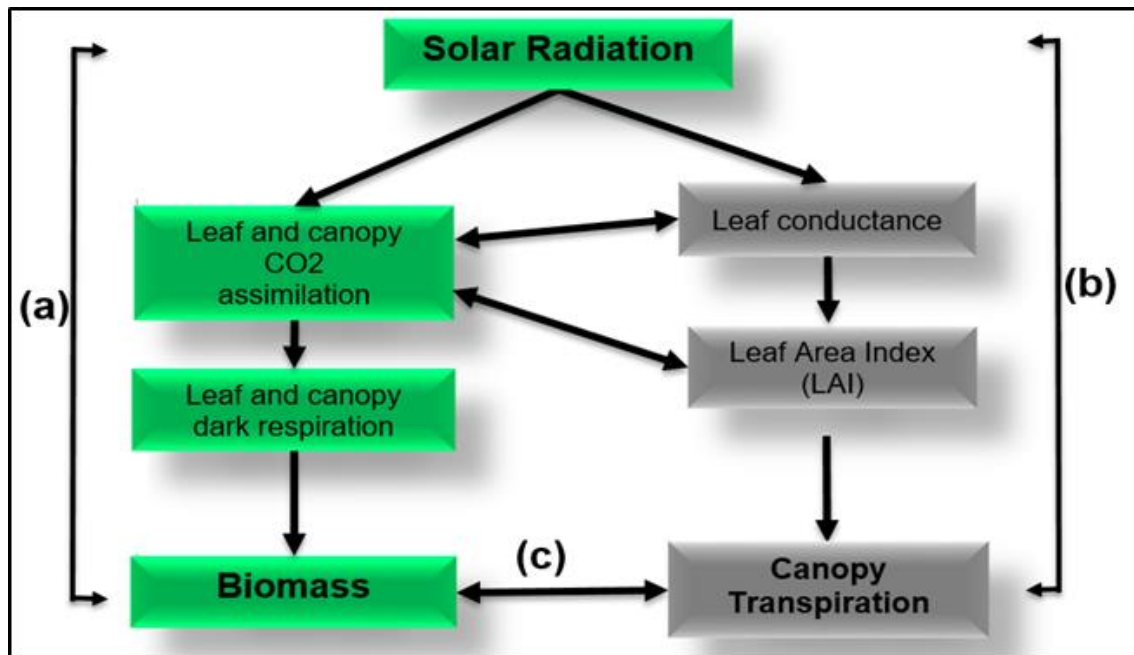


Figure 3-1: Biomass estimation pathway in carbon-driven crop models (adapted from Mokono (2018)). The processes not required in the modelling process have been greyed out.

3.1.2.2 Radiation-Driven Models

There is a direct relationship between radiation and biomass (Monteith, 1977) and studies on different crops have shown that radiation use efficiency (RUE) of well-watered crops (RUE_0) is stable over different growing conditions for a given species (Singels, 2014). This is the understanding on which the radiation use conversion to biomass approach is based. The knowledge of the radiation interception of the crop and associated RUE help in the estimation of biomass in this approach. In the use of radiation use conversion approach to estimate crop productivity, data on radiation intercepted by the crop is a requirement. The method is less intricate and has fewer data requirements than the carbon conversion approach since lower-level processes and parameters (such as leaf photosynthetic efficiency) are taken care of in the reference radiation use efficiency (RUE_0) parameter (Singels, 2014). The estimation of biomass in radiation-driven models follow route (b) as shown in Figure 3-2.

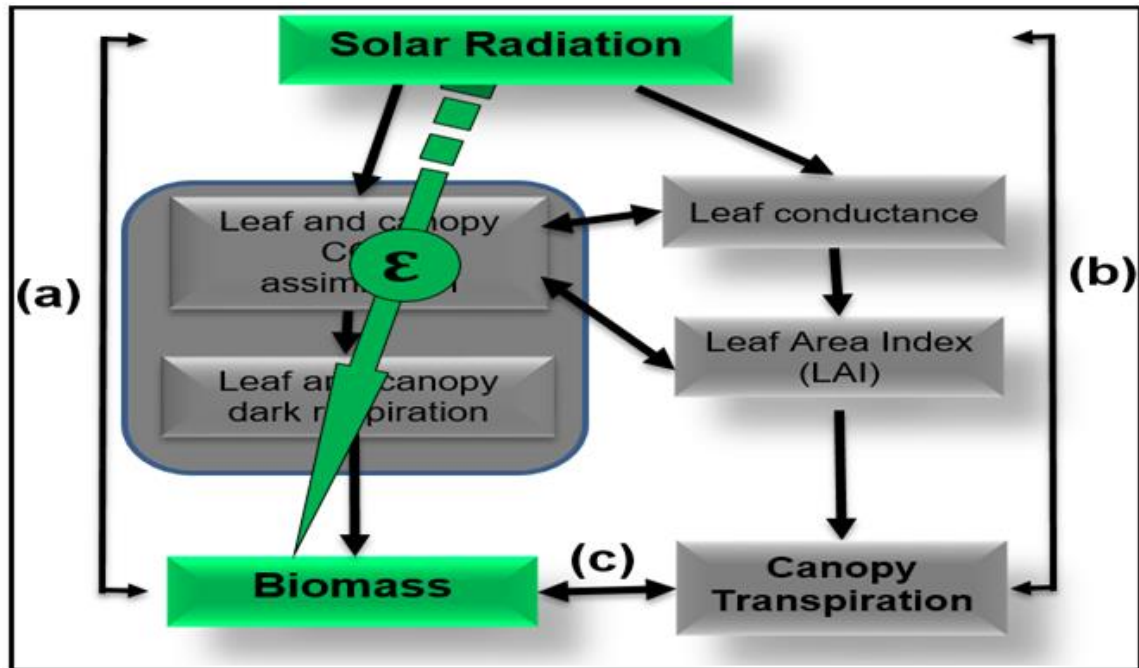


Figure 3-2: Biomass estimation pathway in radiation-driven crop models (adapted from Mokonoto (2018)). The processes not required in the modelling process have been greyed out.

3.1.2.3 Water-Driven Models

Water-driven models exploit the direct relationship between transpiration (T) and biomass. de Wit (1958) established a linear relationship between seasonal transpiration and biomass production, whose slope represents crop water productivity (WP). Steduto et al. (2007) showed the conservative nature of WP when normalised with reference evapotranspiration (ET_0). Knowledge of the amount of water transpired by a crop and WP makes the estimation of biomass production possible. The conservative nature of normalised WP makes water driven models robust (Steduto, 2006) as reported by Mokonoto (2018). Biomass estimation in water-driven models follow route (c) as shown in Figure 3-3.

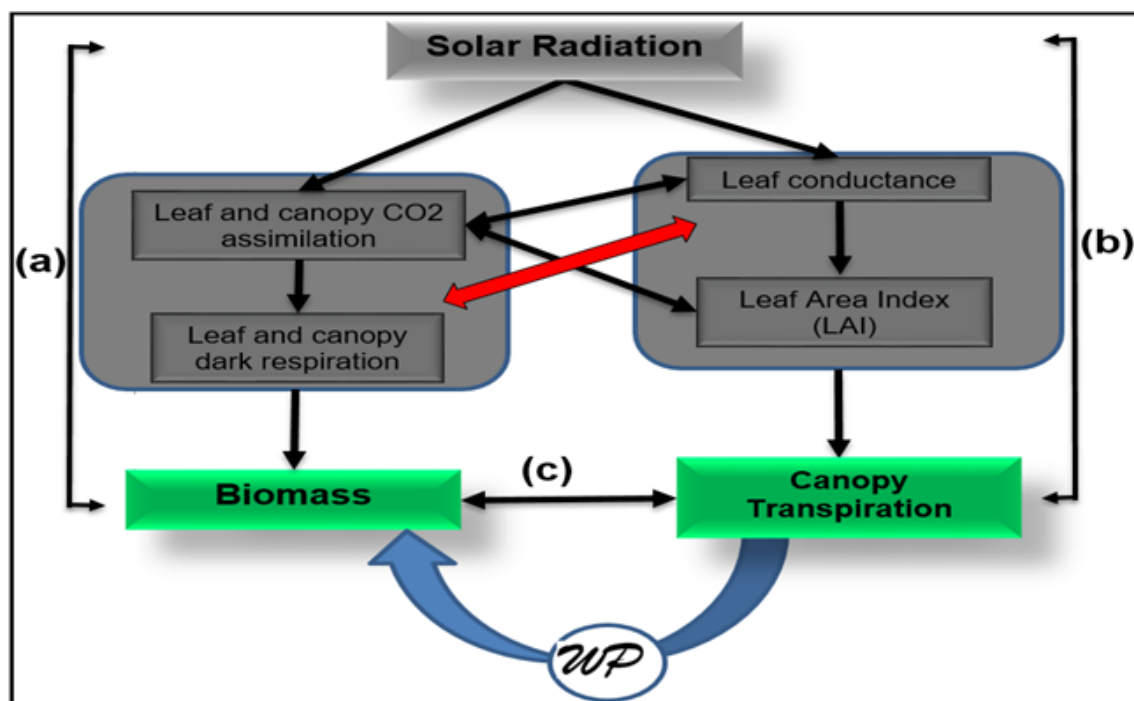


Figure 3-3: Biomass estimation pathway in water-driven crop models (adapted from Mokono (2018)). The processes not required in the modelling process have been greyed out.

3.1.3 Sugarcane Crop Models

Several crop models were reviewed to identify those commonly used models for cane modelling. The models reviewed were then compared for their suitability on the basis of purpose, applicability, accuracy and data requirements. The model suitability criteria included the ability to simulate cane yield on daily time step, determination of the soil water balance, the ability to define irrigation scheduling criteria, biomass simulation, and soil and crop characteristics handling.

3.1.3.1 Agricultural Production Systems Simulator (APSIM)

APSIM – Sugarcane model (Keating et al., 1999) is one of the widely used models for sugarcane crop growth and development simulation (O’Leary, 2000). It is embedded within the Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003). APSIM – Sugarcane is a radiation-based model that considers radiation use efficiency (RUE) of the crop to determine biomass accumulation (Jiang et al., 2017). The RUE approach to the determination of

biomass accumulation, as applied in APSIM, assumes that the radiation use efficiency does not vary across crops.

APSIM – Sugarcane has been employed in numerous applications around the world, including assessment of potential and attainable sugarcane yield in Mauritius (Cheeroo-Nayamuth et al., 2000), the development of a decision support system for the design of optimal water storage for sugarcane irrigation (Lisson et al., 2003) and examining the effects of different crop planting times and harvest age on productivity (McDonald & Lisson, 2001). APSIM – Sugarcane was also used in the benchmarking of sugarcane yields in Australia (Muchow et al., 1997) and for the estimation of nitrogen losses from irrigated and rain-fed sugarcane cropping systems used in Australia (Stewart et al., 2006; Thorburn et al., 2010; Webster et al., 2009). In a quest to evaluate the merits of breeding for drought resistance and improved water-use efficiency, Inman-Bamber (2007) used APSIM-Sugarcane model to assess the economic effects of water stress on sugar production as well as investigating the optimum timing of limited irrigation water in Australia (Inman-Bamber et al. 1999) as reported by Singels (2014).

Singels (2014) reported that O’Leary (2000) established that APSIM simulated green biomass, fresh cane yield and sucrose mass with reasonable estimated root mean square error (RMSE). Furthermore, Singels (2014) reported that Cheeroo-Nayamuth et al. (2000) concluded that the model’s performance was reasonable in simulation of LAI, above ground biomass, cane yield and sucrose yield for four crops grown in Mauritius after calibration. However, Keating et al. (1999) observed that the model’s simulation on effects of water stress on sucrose build-up was not accurate, even though it accurately simulated the LAI and biomass responses. The model over-estimated yields towards the end of the season, most likely due to poor simulation of LAI and culm senescence (Keating et al., 1999).

3.1.3.2 AquaCrop

FAO’s AquaCrop, is one of the crop models that has been successfully used on different crops around the world (Heng et al., 2009). It is a water-based crop

model that simulates plant processes at the canopy level for a point in the field. It considers climate, crop characteristics, field, and management inputs to simulate crop growth and hydrological processes on a daily time step (Raes et al., 2009). AquaCrop considers water fluxes to determine crop yield responses based on daily transpiration (Raes et al., 2009) and exploits the strong connection between transpiration and biomass accumulation to estimate biomass production and yield (Singels, 2014). The robustness of AquaCrop makes it easy to adjust for a wide variety of crop types including grains, tubers, and forage crops (Steduto et al., 2012). Furthermore, it accommodates a wide variety of soils, field management conditions, irrigation techniques and strategies as well as initial conditions.

Pérez-Ortolá et al., (2015) described AquaCrop as a crop model that has capability to accurately simulate crop response of biomass, canopy cover and yield to variations in weather and irrigation on a daily time scale given the limited input data requirement necessary for parameterising the model. While Steduto et al., (2012) indicated that AquaCrop is known for its simplicity, robustness and accuracy in simulation process, Linker et al., (2016) recommended the AquaCrop model as an effective tool for prediction of both total biomass and final yield in response to various irrigation strategies with reasonable accuracy. Bahmani and Eghbalian (2018) concluded that the AquaCrop model was an appropriate tool to simulate sugarcane yields and water productivity under deficit irrigation conditions as the model simulated both yield and water productivity with reasonable levels of accuracy.

3.1.3.3 Canesim

The quest to make sugarcane modelling more accessible, by focusing on simplified data requirements and a user friendly interface, led to the development of Canesim model (Singels, 2014). This is a daily time step, point-based simulation model driven by water, temperature and radiation (Singels and Paraskevopoulos, 2017). It circumvents the requirements for (1) detailed input data, (2) simulation of layer specific water redistribution and extraction and (3)

leaf and tiller development (Singels, 2014) by using a single layer soil module and a thermal time driven canopy cover development (Singels & Donaldson, 2000). The model requires minimum input data on soil available water holding capacity, daily temperature, rainfall, and reference cane evaporation (McGlinchey & Inman-Bamber 1996) as reported by (Singels, 2014).

Canesim model has been used in various applications for sugarcane. For example, Singels & Smith, (2006) used a web-based version of Canesim known as MyCanesim to provide operational irrigation scheduling advice to a group of small-scale farmers in Pongola, South Africa. Paraskevopoulos & Singels, (2014) used the Canesim model to benchmark crop yield response to irrigation scheduling scenarios in 15 sugarcane fields in South Africa. Canesim was also used to study the effects of sugarcane lodging on yields and profitability as influenced by crop cycle, climate and genotype (Paraskevopoulos et al., 2016).

In the validation of the Canesim model, Singels et al. (1998) reported on the prediction of soil water content (SWC) to within 3 to 6 mm of available water in a 1.2 m soil profile, while Singels & Donaldson, (2000) reported that the model estimated the fractional interception (FI) of photosynthetically active radiation (PAR) with a relative error of 21%. It was also able to predict culm and sucrose mass with reasonable accuracy (RMSEs of 4.49 and 2.55 t/ha, respectively) on the dataset that was also used for the validation of the Canegro model (Singels & Bezuidenhout, 2002). In their simulation of NCo376, Singels & Paraskevopoulos (2017) concluded that Canesim was acceptable for aerial dry mass and stalk dry mass estimation and reasonable for sucrose yield and content prediction. They reported that the observed and simulated areal and stalk biomasses were strongly correlated (R^2 of 0.9229 and 0.8837, respectively) while observed and simulated sucrose yields and sucrose content were well correlated (R^2 of 0.8693 and 0.7211, respectively).

3.1.3.4 DSSAT Canegro

The Canegro model was first published by Inman-Bamber (1991) and later, the biomass accumulation and partitioning algorithms were amended by Singels &

Bezuidenhout (2002). The model considers daily weather data, cultivar and field soil properties and management data, as inputs, to simulate sugarcane crop growth and development (Singels et al., 2008). It has since become one of the leading and extensively used crop model for sugarcane research and management (O'Leary, 2000; Singels et al., 2008). It is embedded within the Decision Support Systems for Agrotechnology Transfer (DSSAT) (Singels et al., 2008).

DSSAT Canegro determines canopy development at the tiller and leaf levels, intercepted radiation from leaf area index (LAI), biomass build-up by the radiation use efficiency/respiration approach, biomass apportioning to plant components using a source-sink method and water balance by the use of soil-plant-atmosphere continuum principle (Singels et al., 2008). Photosynthetically active radiation (PAR) use efficiency, which is affected by air temperature, water stress and growth respiration determines the biomass accumulation in Canegro (Singels & Bezuidenhout, 2002). The effects of water stress on photosynthesis and canopy development are determined by using two water stress factors which are determined by the relationship between transpiration rate and root water uptake (Dias & Sentelhas, 2017).

Oliveira et al. (2018), Jones et al. (2015), Singels et al. (2014) and Knox et al. (2010), used DSSAT Canegro model to assess climate change impacts on sugarcane production in Brazil, South Africa, Australia and Swaziland, respectively. The model was also used to assess the influence of deficit irrigation on accumulation and partitioning of sugarcane biomass under drip irrigation in commercial varieties (Dias & Sentelhas, 2019; Santos et al., 2019). The model was as well employed to assess potential and attainable yields in South Africa (Inman-Bamber, 1995) as well as determining the optimum harvest age and the milling season length for whole farms in South Africa (Bezuidenhout et al., 2002; Inman-Bamber, 1994). McGlinchey & Inman-Bamber, (1996) used the DSSAT Canegro model to assess the effects of irrigation scheduling on water use efficiency and yields in South Africa.

Singels & Bezuidenhout (2002) used 19 cultivars observed in four experiments at three sites in South Africa to validate the Canegro model. The model predicted aerial dry mass, culm dry mass, and sucrose with respective RMSEs of 6.94, 5.48 and 2.6 t/ha and concluded that the performance of the model was reasonable. Singels et al. (2010) compared the simulated above ground biomass, green leaf area index (GLAI); stalk mass and sucrose mass with measured data from Australia, Brazil, South Africa, Thailand, and Zimbabwe. It was established that the model estimated the parameters with RMSE ranging from 11 to 45%, 14 to 26%, 13 to 34%, and 7 to 34% for GLAI, biomass, stalk dry mass, and sucrose mass, respectively (expressed as a percentage of the mean measured value). It was concluded that the model performance was reasonable considering the wide differences in cropping situations and variety types in which it was tested. However, it was observed that the model needed improvement in dynamic tiller development algorithm for adequate simulation of temperature and radiation effects.

Figure 3-4 shows the summarised data requirements for the DSSAT Canegro model. Specifically, it requires data on soil (depth, texture and colour) and plant (varieties and genetic make-up) characteristics, climate (including daily rainfall, minimum and maximum temperature, relative humidity, windspeed and solar radiation) and crop husbandry practices (including planting date and harvesting dates, fertilizer application, and irrigation).

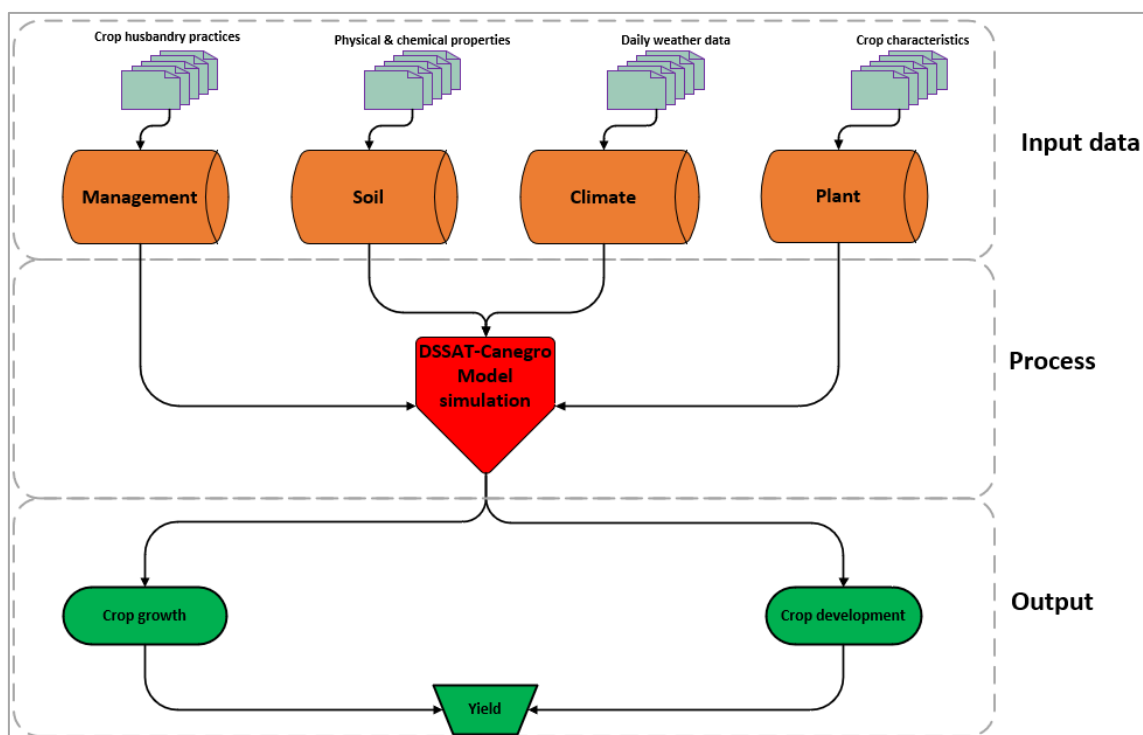


Figure 3-4: Summarised DSSAT Canegro model simulation and data requirements

3.1.4 Model Selection

A summary of the four crop models and how they compare to each other in terms of meeting specific selection criteria for this research are presented in Table 3-1. As can be observed, both the DSSAT Canegro and APSIM – Sugarcane models have fallen short of only one parameter (data requirement and batch processing, respectively), making them joint top-most suitable models. O’Leary (2000) described both APSIM-Sugarcane and DSSAT Canegro as the most preferred and widely used models for the simulation of sugarcane growth and development. Jones et al. (2021) and O’Leary (2000) established no significant differences in performance between APSIM-sugarcane and DSSAT Canegro models. Thus, a trade-off was made between running the simulations in batches with a high data requirement model or running a single simulation at a time with minimum data requirement model. While minimal data requirement would be an important factor in the choice of the model, the current study demanded an evaluation of different combinations of irrigation scenarios (different irrigation applications) that required running the simulations in batches. This could only be accomplished easily with

batch processing. The DSSAT Canegro model met these criteria and was therefore considered the most appropriate model for use in this study.

Table 3-1: Comparative assessment of each crop model against defined selection criteria for this study

Parameter	DSSAT Canegro	APSIM-Sugarcane	Canesim	AquaCrop
Growth engine	Carbon-driven (Singels et al., 2008; Singels, 2014)	Radiation-driven (Jiang et al., 2017)	Carbon-driven (Singels & Paraskevopoulos, 2017)	Water-driven (Steduto et al., 2009)
Daily time-step simulation	✓ (Singels et al., 2008; Singels et al., 2010)	✓ (O'Leary, 2000)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Pérez-Ortolá et al., 2015)
Biomass/yield simulation	✓ (Singels et al., 2008)	✓ (Singels, 2014)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Steduto et al., 2009)
Canopy cover/LAI development simulation	✓ (Singels et al., 2008)	✓ (Singels, 2014)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Steduto et al., 2009)
Scale of simulation	Canopy level (Singels et al., 2008)	Canopy level (Singels, 2014)	Canopy level (Singels & Paraskevopoulos, 2017)	Canopy level (Steduto et al., 2009)
Soil moisture simulation	✓ (Singels et al., 2008)	✓ (Singels, 2014)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Steduto et al., 2009)
Data requirement (input parameters)	X High (Todorovic et al., 2009)	✓ Minimal (Dias & Sentelhas, 2017)	✓ Minimal (Singels, 2014)	✓ Minimal (Steduto et al., 2009)
Soil characteristics handling	✓ (Singels et al., 2008)	✓ Singels, 2014)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Steduto et al., 2009)
Crop water stress simulation	✓ (Singels et al., 2008)	✓ (Singels, 2014)	✓ (Singels, 2014)	✓ (Steduto et al., 2009)
Batch processing ability	✓ (Singels et al., 2008)	X	X	X
Irrigation scheduling	✓ (Singels et al., 2008)	✓ (O'Leary, 2000)	✓ (Singels & Paraskevopoulos, 2017)	✓ (Steduto et al., 2009)
Phenology simulation	✓ (Singels et al., 2008)	✓ (Singels, 2014)	X	X
Easy and free model accessibility/availability	✓ (DSSAT Foundation, 2021)	✓ (Holzworth et al., 2014; Sabatier et al., 2015)	X	✓ (FAO, 2021)
Developer's support availability and accessibility	✓ (DSSAT Foundation, 2021)	✓ (APSIM, 2021)	X	✓ (FAO, 2021)

3.1.5 Aim and Objectives

The aim of this chapter was to select an appropriate crop model and assess its suitability for the simulation of cane yield response to water application. Specifically, the chapter set out to answer the following questions:

- i. What could be an appropriate crop model for simulation of cane growth and development based on selected criteria including simulation timestep, scale of simulation, data requirement and availability, batch processing ability, support availability and ease of model accessibility?
- ii. What is the performance of the selected model in terms of ability in simulating cane yields for modelling the impact of irrigation heterogeneity on cane yields, energy and irrigation water uses?

3.1.6 Methodology

3.1.7 Study Site

The performance assessment of the DSSAT Canegro model was based on datasets collected at Nchalo estate (Figure 3-5) in the southern region of Malawi, about 50 km south of Blantyre. It is Malawi's largest sugar producer, with about 13,500 ha of irrigated sugarcane (Banda et al., 2019). It also processes irrigated sugarcane from additional 2,885 ha owned by out-grower farmer cooperatives.

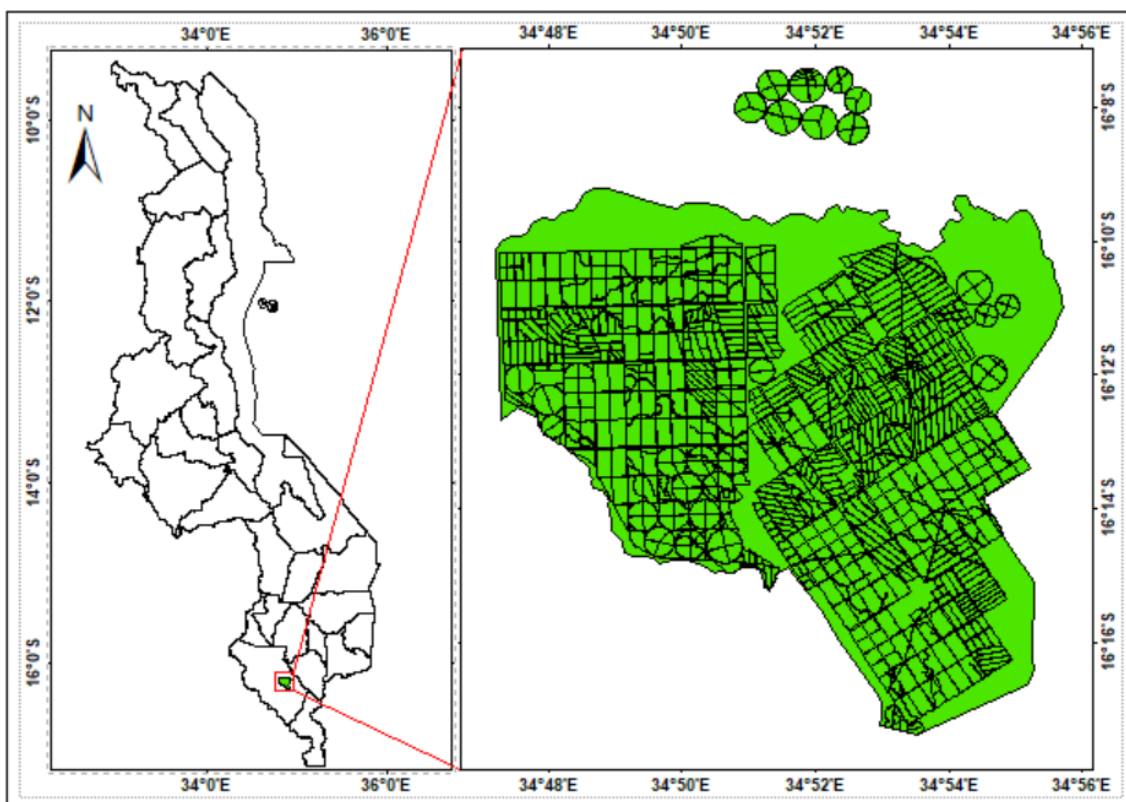


Figure 3-5: Map of Malawi showing the location of Nchalo estate

3.1.8 DSSAT Canegro Model Performance Assessment

The required datasets for the DSSAT Canegro model were collected from the Nchalo estate records database including historical data on cane yields. The model performance was assessed by comparing the simulated cane yields against observed yields on a fresh weight basis. It is important to note that in this study, the DSSAT Canegro model was used to simulate cane yield response to water using the available datasets rather than trying to assess the model's performance or goodness of fit for the study site under specific conditions. Thus, no calibration of the model was made. However, the model was validated with datasets for three irrigation systems running with each running for nine years. Cane yields for NCo376 variety were obtained together with other data (soil, management practices, crop characteristics and climate) to simulate cane yields for eight cropping seasons between 2010/11 and 2018/19 for three fields under three different irrigation systems – centre pivot, furrow and sprinkler (Figure 3-6).

The soil input parameters included soil depth, soil colour, soil textural class and drainage characteristics. The management practices included irrigation application (amount and timing), crop nutrition and crop husbandry practices (growth start and harvesting dates, row spacing). The climate data included daily precipitation, daily minimum and maximum temperatures, daily relative humidity, daily windspeed, daily solar radiation and daily sunshine hours. For the crop characteristics, default crop coefficients for reference variety (NCo376 cultivar) were used. This was done due to unavailability of crop coefficients data. Furthermore, appropriate adjustments were made to the model parameters to account for whether the simulation was for ratoon or plant cane.

A statistical comparison between the simulated and observed yields for each season and irrigation system were made to assess the utility and performance of the crop model. The performance and the utility of the model was assessed by conducting a paired t-test to compare the closeness with which the model simulated average yields were in relation to historical (observed) average yields with default crop coefficients.

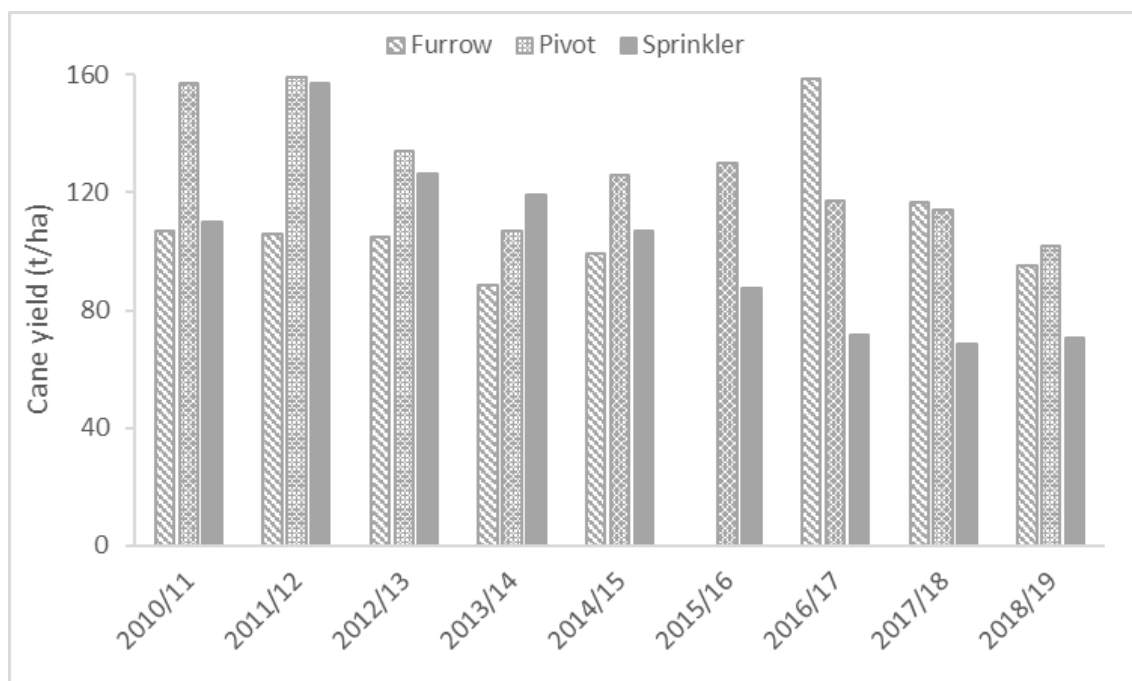


Figure 3-6: Historical cane yields between 2010/11 and 2018/19 seasons for three fields under three different irrigation systems at Nchalo estate

Plant population decline and the amount of yield that is left behind due to inefficient harvesting and haulage mechanisms are seldom addressed by crop models. These, however, have the potential to affect the performance of a given model. To address this challenge, datasets on plant population decline and amount of cane left behind the fields during cane harvesting and haulage (left-over cane) were also collected for the analysis. However, the available data on plant population decline and left-over cane only spanned between 2017 and 2019 for all the irrigation systems.

3.1.9 Results

3.1.1 Model Performance Assessment

Figure 3-7 shows the graphical presentation of observed and simulated cane yields for the three systems (centre pivot, furrow and sprinkler) over the period under consideration. The statistical comparison (t-test) of the observed and simulated yields across irrigation systems showed that there were insignificant differences ($p>0.05$) between individual systems (Figure 3-8). Furthermore, no significant differences ($p>0.05$) in yields were observed between the observed and simulated yields under the centre pivot and furrow irrigation systems, while the observed and simulated yields for the sprinkler system showed significant differences ($p<0.05$). The crop model simulated the cane yields with RMSE values of 19.56 t/ha, 32.72 t/ha and 48.94 t/ha for centre pivot, furrow and sprinkler systems, respectively (

Table 3-2).

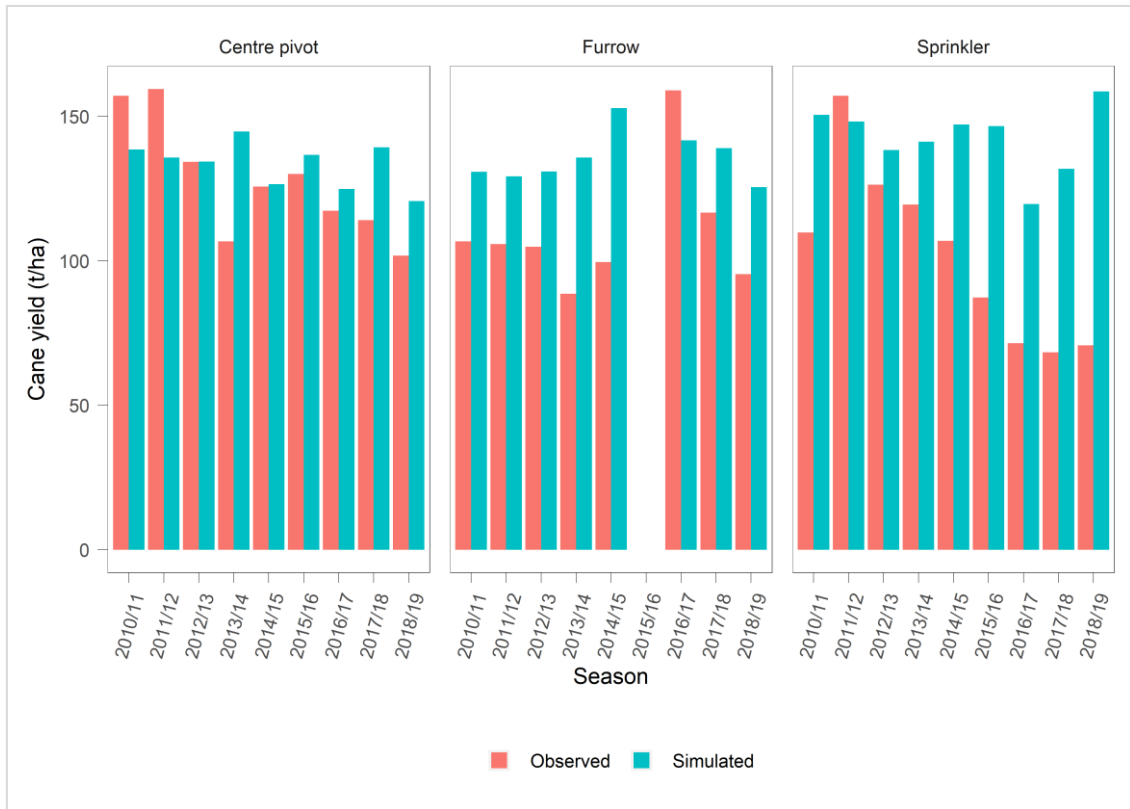


Figure 3-7: Observed and simulated cane yields for the three irrigation systems (Centre pivot, furrow and sprinkler) between 2010/11 and 2018/19 cropping seasons. Note that in 2015/16 season, there were no observed and simulated yields under furrow system because the field was left fallow

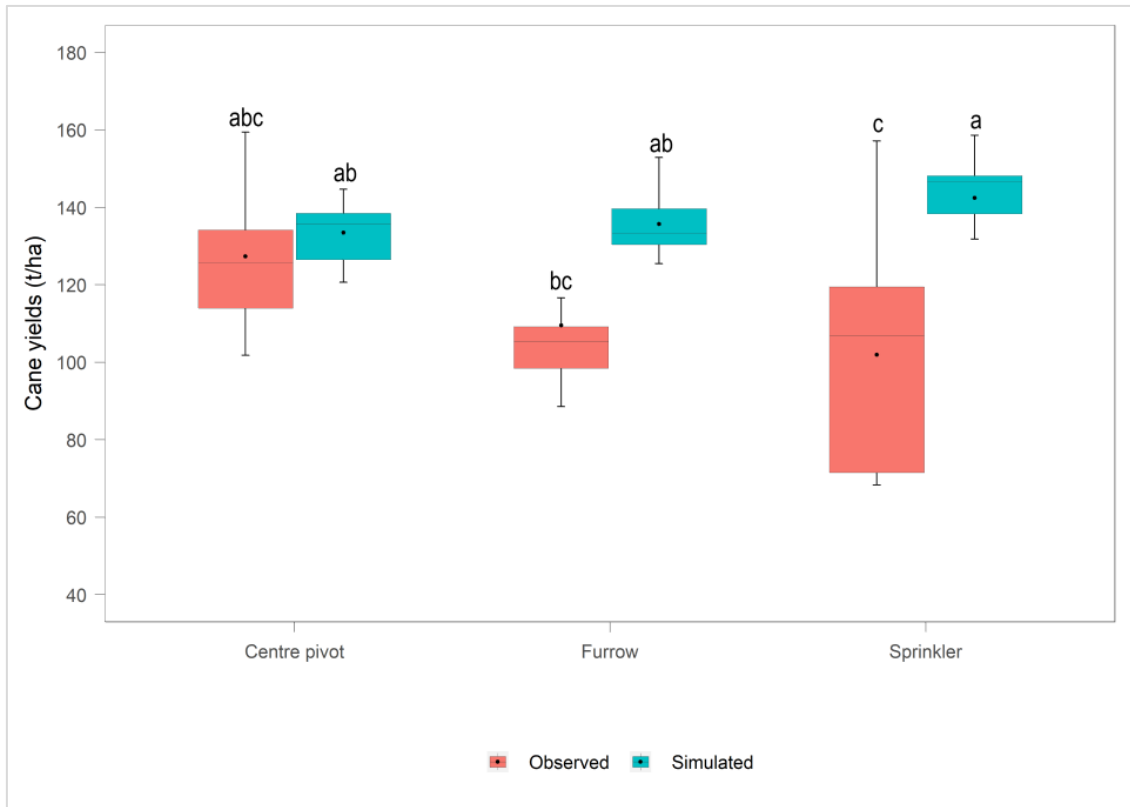


Figure 3-8: Comparison of observed and simulated cane yields under each irrigation system between 2010/11 and 2018/19 seasons

Table 3-2: Residual mean standard error for the observed and simulated cane yields for each irrigation system

Irrigation system	RMSE (t/ha)	RMSE % of observed yield
Centre pivot	19.56	15.4
Furrow	32.72	29.9
Sprinkler	48.94	48.0

The analysis of plant population decline under the respective irrigation systems between 2017 and 2021 showed that the plant population decline under sprinkler

fields was significantly higher ($p < 0.05$) compared to the centre pivot but not significantly different ($p > 0.05$) from the furrow irrigated fields (Figure 3-9). Further analysis of the amount of cane left behind in the fields during harvest and after haulage from 2018 to 2021 (Figure 3-10) showed that fields under the sprinkler system had significantly higher left-over cane compared to fields under the centre pivot but were not different to that of the furrow system. No significant differences in left-over cane were observed between fields under centre pivot and furrow systems.

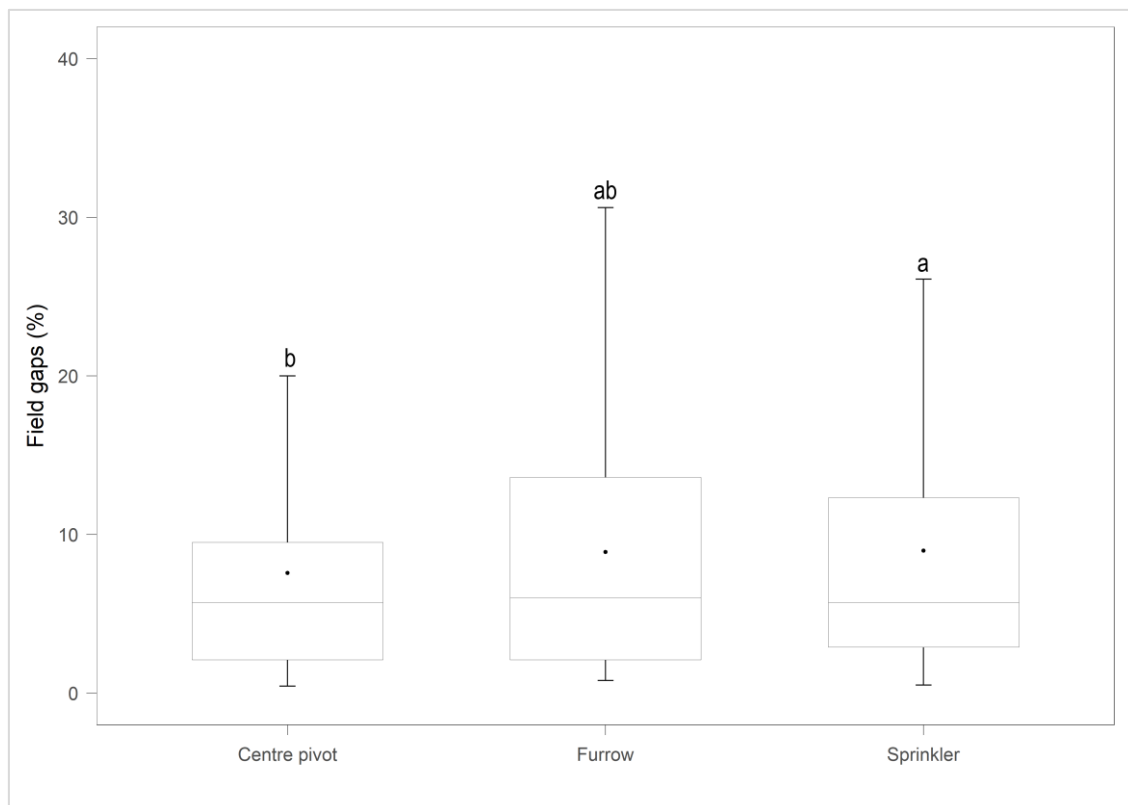


Figure 3-9: Comparison of plant population decline under the three systems between 2017 and 2021

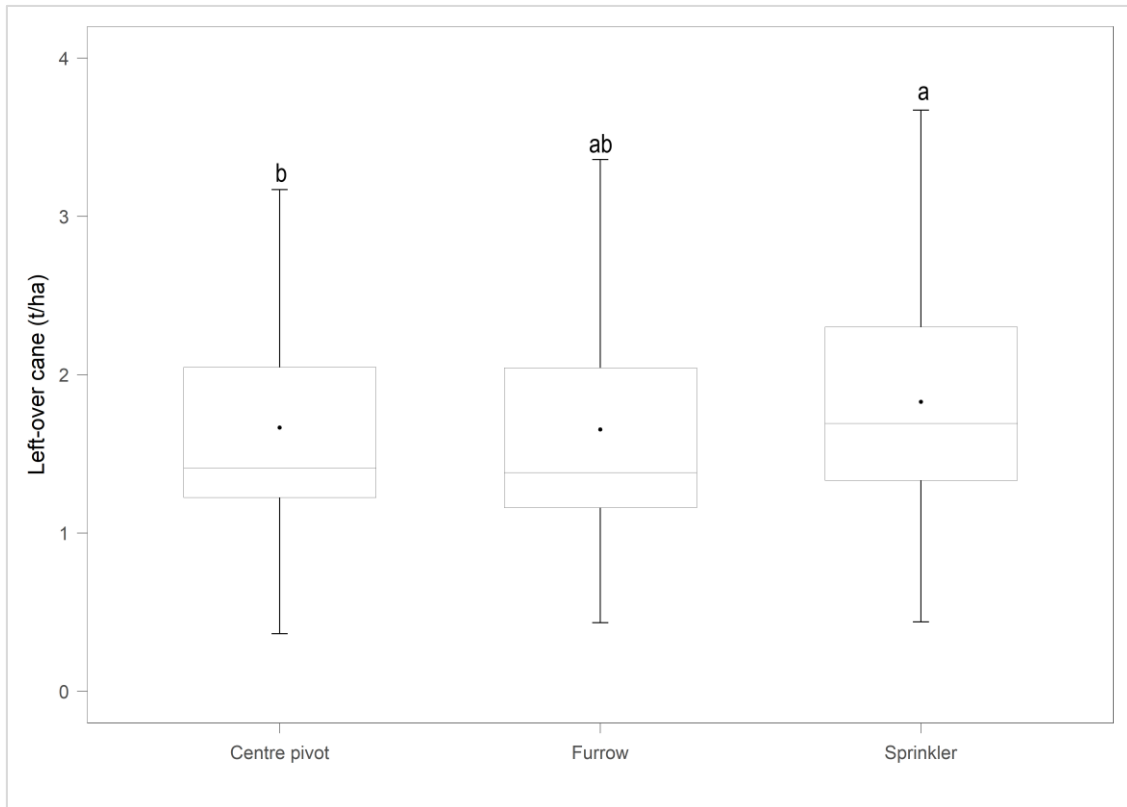


Figure 3-10: Comparison of left-over cane under the three systems between 2018 and 2021

3.1.2 Discussion

The comparison of the different sugarcane models, based on the defined criteria, showed that DSSAT Canegro model was suitable for simulating cane yield response to water. Furthermore, the simulations showed that the DSSAT Canegro model estimated cane yields with no significant differences between observed and simulated yields under two systems (centre pivot and furrow). The observed average yields under the sprinkler systems were significantly lower than the corresponding simulated yields. The sprinkler system had shown that it also had significantly higher plant population decline and left-over cane than the centre pivot systems and was not different from the furrow system. The RMSE results, however, were in agreement with findings reported in the literature (Singels, 2014). The significant difference in observed and simulated cane yields for sprinkler fields were potentially due to the combined impacts of plant

population decline and the left-over cane trends rather than due to poor model performance.

The model has been reported to be highly accurate in simulating cane yields (Coelho et al., 2020; Mishra et al., 2019). Coelho et al., (2020) established that, for better performance, the model's cultivar parameters need to be parameterised. Cultivar parameters of the model regulate partitioning of biomass, growth and development of canopy and phenological phasing (Singels et al., 2008). Thus, the parameterisation of the cultivar related coefficients would be informed by experimental data. This is one of the reasons that inconsistencies are observed in the performance of the model under experimental and commercial field conditions (Dias & Sentelhas, 2017). Thus, while the model performance was considered satisfactory the use of default cultivar parameters may mean that model performance could be further improved.

3.1.3 Conclusions

The screening and assessment for an appropriate model identified DSSAT Canegro model as the most suitable model for this study requiring the simulation of cane yield response to water. This was based on rigorous comparison with several other potentially relevant sugarcane crop growth models. Furthermore, the model simulated cane yields for two different irrigation systems (centre pivot and furrow) over nine years each producing no significant differences between observed and simulated average yields while significant differences between observed and simulated average cane yields were reported for the sprinkler system due to a decline in cane plant population and significant amounts of left-over cane during harvesting and haulage.

Furthermore, the ability of the DSSAT Canegro model to simulate the cane yield response to water (as evidenced from its accuracy in simulating cane yields) means that it has the potential to simulate yields under varying levels of irrigation application. This ability is paramount for modelling the impacts of irrigation heterogeneity on cane yields, energy and water productivity. Thus, the DSSAT Canegro model was considered most suitable for this study.

Chapter 4. DEVELOPMENT OF A CONCEPTUAL MODELLING FRAMEWORK TO EVALUATE IRRIGATION HETEROGENEITY, SUGARCANE YIELD AND WATER PRODUCTIVITY RELATIONSHIPS

4.1 Introduction

The relationship between transpiration and yield (Steduto et al., 2007, 2012), entails that the more water is applied to the crop, the more yield will be realized until a point is reached when the law of diminishing returns is triggered. In extension, this further supports an assertion that a crop growing at any point in the field that gets inadequate water (less than the crop water requirement throughout the season) would not produce maximum potential yields. This entails that maximum yields at any point in the field can only be achieved when the given point in the field gets adequate water. Irrigation becomes necessary where rainfall does not fully meet the crop water requirements of the growing crops. The need for adequate water for maximum yield means that irrigation systems should be able to supply adequate water to every point in the field for maximum yield. Applying adequate water to every point in the field means uniform water application. In irrigated crop production, a relationship between water application uniformity and yield has been demonstrated for various crops including onions (Pérez-Ortolá et al., 2015) and sugarcane (Reinders, 1996; Solomon, 1998). Thus, understanding the relationship between level of water application uniformity and crop yields is paramount in improving crop yields and water productivity.

Solomon (1998) broadly defined irrigation uniformity as the spatial variation in distribution of water applied within a given command area. There are several indicators of water application uniformity with the Christiansen Coefficient of Uniformity (CU) and Distribution Uniformity (DU) being among them (ASEA, 2001; Pereira, 1999). CU is defined as a measure of average deviation from the mean water application depth (Griffiths, 2007). In essence, the CU is the average of absolute differences of individual application depths caught in each catch can

and the mean application depth divided by the mean application depth (Maroufpoor et al., 2010).

On the other hand, DU is defined as “a measure of the uniformity with which irrigation water is distributed to different areas in a field” (Burt et al., 1997). DU is the ratio of the lowest accumulated water depths caught in the distribution to the mean water depth caught in all the catch cans (El-Wahed et al., 2016). In other words, DU quantifies the average application depth in the low quarter of the field (Griffiths, 2007) as shown in equation (8). It gives an indication of the average amount of water applied in the inadequately irrigated areas of the field. By knowing the average amount of water received by the inadequately irrigated portions of the field, it helps one to gauge the extent of irrigation deficiency.

A direct relationship between water application uniformity and crop yield has been confirmed for various crops (Pérez-Ortolá et al., 2015; Reinders, 1996; Solomon, 1998). Although uniform water application on its own is not a guarantee for maximum yields, as it is also possible to have uniform under-irrigation or over-irrigation, maximum yields at field level are associated with uniform application of adequate water. Non-uniform water application results in water wastage in the over-irrigated spots and water stress in under-irrigated spots (El Chami et al., 2019; González Perea et al., 2018) – all of which result in yield losses and reduced profit margin. Uniformity in water application influences crop yields through the agronomic effects of under-irrigation and over-irrigation. Inadequate water leads to water stress and reduced crop yields while excess water reduce crop yields as a result of nutrient leaching, disease proliferation and/or growth stimulation failure of harvestable parts of the plants (Solomon, 1998). Thus, irrigation systems must be able to supply and apply water at the right time, rate and quantity, and within specified location (Eisenhauer et al., 2021) consistent with the soil hydraulic properties. Against these indicators (uniformity, timing, rate and quantity of application), irrigation systems can be evaluated to determine level of performance and impact on yields.

4.2 Aim and objectives

The aim of the research was to develop a conceptual framework for modelling the relationships between irrigation heterogeneity, sugarcane yields and water productivity. In the process, the study set out to answer the following research questions:

- i. Does non-uniform irrigation water application have any impact on field-scale cane yields?
- ii. What are the implications of non-uniform water application on water use and water productivity?

4.3 Methodology

The crop yield response to non-uniform water application was determined by modelling. The DSSAT Canegro model (Singels et al., 2008) was used to simulate cane yield response to varying levels of irrigation. The modelling used datasets obtained from Nchalo estate. The DSSAT Canegro model simulates yield response to water application at a given point in a field. In principle, it is assumed that every other point in the field receives the same amount of irrigation water as specified in the input tab of the model. However, considering the inherent irrigation application heterogeneities of irrigation systems and other factors that influence irrigation management, this assumption does not always hold. Depending on the type of irrigation system, several factors affect the uniformity with which the system applies water. Such factors include operating pressure, wind speed and direction, sprinkler spacing and configuration (for overhead systems); furrow length and slope, flowrate, soil type and management practices (for surface systems).

James (1993) demonstrated that for a normal distribution, the coefficient of variation (CV) is described by equation (5).

$$CV = \frac{\sigma}{D_a} = \frac{1 - CU}{0.798} \quad (5)$$

Where CU is the coefficient of uniformity that is typically used to describe the uniformity of water application, D_a is the mean water application depth and σ is the standard deviation of the water application depth.

The normal distribution assumption (adopted above) entails that when D_a and CU are known, then the application depth in each percentile (of the normal distribution function) can be estimated from an inverse normal distribution function. With the knowledge of D_a , corresponding yield in each decile can be simulated. Thus, making it possible to estimate yield at field scale (Figure 4-1). This shows that during an irrigation event water application across the field follows a normal distribution function (represented by the normal distribution curve) and each depth of application results in a corresponding yield whose average would be average cane yield at field-scale.

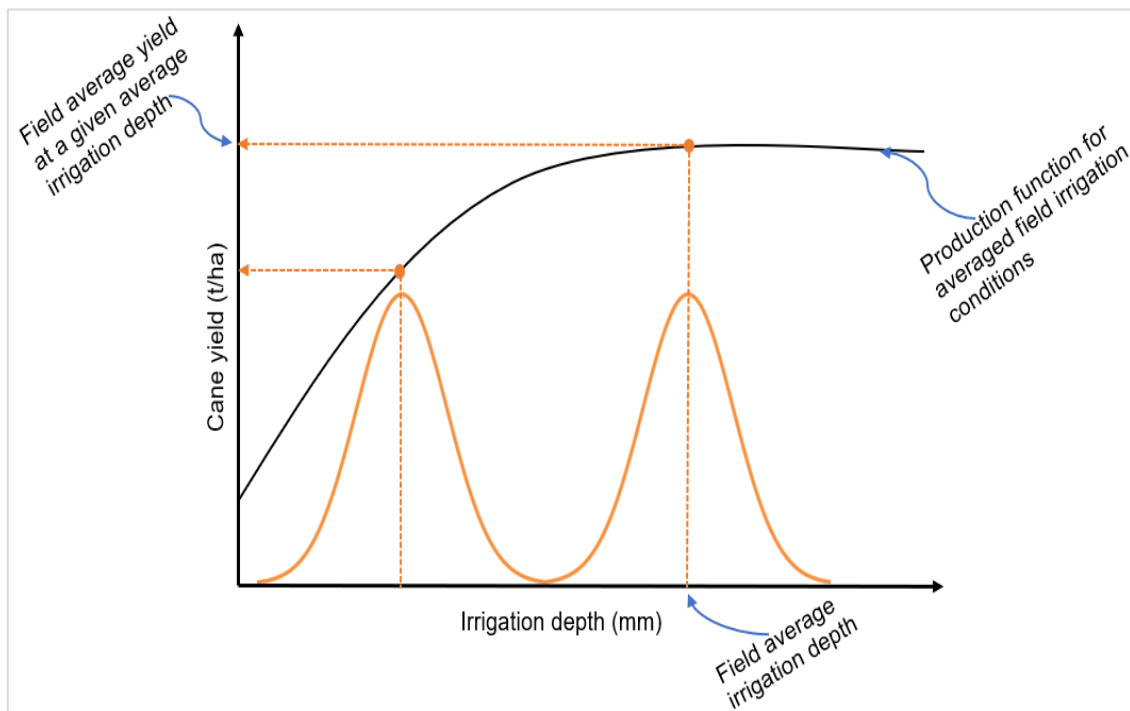


Figure 4-1: Graphical representation of the production function between cane yield (t/ha) and irrigation depth (mm) at the field scale (adapted from Banda, (2019))

4.3.1 Cane yield-water production function

In the DSSAT Canegro model, an optimised irrigation schedule under three irrigation systems (centre pivot, furrow and sprinkler) was generated by setting the model to automatically trigger irrigation application when required (Figure 4-2); that is to say that if the crop required a given amount of water, for example, but the soil moisture could not provide that amount due to soil moisture deficit, then the irrigation system provided the deficit. The optimised irrigation schedule ensured that the crop did not experience any water stress and this assumed an ideal irrigation depth was applied at a given timing which in turn determined the of potential cane yield. A series of simulations were then run with the optimised schedule with application depths ranging between 120% and 5% of the full irrigation depth at 5% interval. While the irrigation depths were changed, the timing of application were left unchanged. This was done to capture impacts of both over and under-irrigation. The simulation outputs included cane yields for each application depth, which in turn resulted in the generation of a cane yield – water production function.

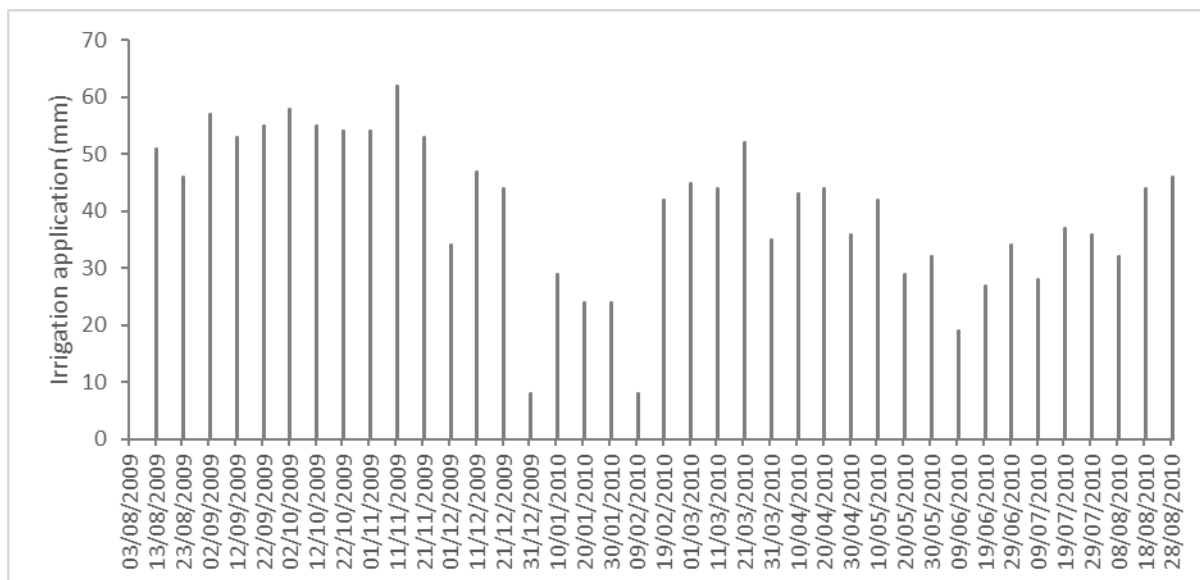


Figure 4-2: An optimised irrigation schedule generated from the DSSAT Canegro model. The simulation of cane yields was based on a year of average irrigation requirements as determined from DSSAT Canegro. The average irrigation year was determined from irrigation requirements for 9 years between 2002 and 2020

(Table 4-1). While the soil, climate and management parameters used in the simulation were collected from Nchalo estate, default input cultivar characteristics for NCo376 were used. The estate also grows NCo376 variety and default cultivar coefficients were used in the simulation due to the unavailability of experimental data for the same. The detailed input parameters for the simulation are provided in the Appendix. Table 4-1: Irrigation water requirements (ranked) for Nchalo estate between 2002 and 2020 to identify typical ‘wet’, ‘average’ and ‘dry’ years

Season	Precipitation (mm)	Transpiration (mm)	Potential ET (mm)	Effective Irrigation (mm)	Season classification
2018/2019	1113	1505	1876	1498	Wet year
2011/2012	874	1476	1831	1512	Wet year
2014/2015	1098	1431	1784	1531	Wet year
2013/2014	644	1472	1826	1535	Wet year
2012/2013	680	1502	1848	1620	Wet year
2016/2017	872	1566	1970	1627	Average year
2010/2011	493	1523	1886	1654	Average year
2006/2007	1000	1578	1957	1656	Average year
2007/2008	751	1568	1942	1669	Average year
2017/2018	804	1544	1956	1672	Average year
2008/2009	557	1577	1949	1674	Average year
2005/2006	947	1633	2012	1694	Average year
2009/2010	469	1560	1939	1754	Average year
2019/2020	622	1574	1966	1763	Average year
2015/2016	453	1620	1932	1766	Dry year
2001/2002	692	1633	2072	1806	Dry year
2003/2004	483	1603	2011	1806	Dry year
2004/2005	464	1644	2012	1835	Dry year
2002/2003	669	1688	2089	1879	Dry year
Means for wet season	552	1638	2023	1539	
Means for average season	724	1569	1953	1685	
Means for dry season	882	1477	1833	1818	

4.3.2 Cane yield – CU production function

Having established the average optimum application depth, standard deviations for a range of CU values were then determined using equation (6). The standard deviations for each CU in turn gave corresponding water application depth for each of the percentile across the normal distribution function. The water application depths and their corresponding cane yields for each CU value were then estimated from the cane yield-water production function. CU and cane yield relationship was then established and the extent to which water application uniformity CU impacted on cane yields and irrigation water use were determined by plotting the cane yield against its corresponding CU value.

$$\sigma = D_a \frac{1 - CU}{0.798} \quad (6)$$

where D_a , CU and σ are as defined in equation (5)

4.3.3 Irrigation uniformity impact on water use

Martin et al. (2010) built on the work of Clemmens (1992) and developed an enhanced water balance model that had capabilities of partitioning irrigation water application into net infiltration, deep percolation and surface runoff based on normal distribution function. The approach was adopted in this research in the assessment of the impact of irrigation uniformity on water use. The approach requires the knowledge of required adequacy (proportion of the field area to be irrigated) required application depth, the CU and surface loss fraction (a fraction of the total water supplied that is lost to surface runoff). An application adequacy of 100% was used since the simulation strives for yield maximization at field level (every point in the field should be adequately irrigated). The required irrigation application depths and the surface runoff fraction for each of the three systems were determined from the DSSAT Canegro simulation. Two CU values (50% and 90%) were selected for the demonstration of how irrigation water requirements change as the CU changes.

4.4 Results

4.4.1 Cane Yield Response to Water Application

The yield response to varying water application levels under furrow, centre pivot and sprinkler are shown in Figure 4-3. The simulation of the yield response to water showed that under average irrigation requirement conditions, the full irrigation requirement for centre pivot, furrow and sprinkler systems were 1563 mm, 1542 mm and 1559 mm, respectively. The differences in the annual irrigation requirements were mainly due to differences in soil types across the fields on which the modelling of the three systems were based. The average potential yields for the respective full irrigation depths were 144 t/ha, 148 t/ha and 142 t/ha

under centre pivot, furrow and sprinkler systems. The respective rainfed cane yields under the three irrigation systems (as indicated by the y-intercept of each plot) were 31 t/ha, 50 t/ha and 33 t/ha. The relationship between relative irrigation application (amount of irrigation water applied in relation to full irrigation amount) and cane yields were as indicated under each plot. However, the equations are only valid when the relative irrigation application is between 0 and 1. There were no significant differences ($p>0.05$) in both average water productivity and marginal yield benefit realized from marginal irrigation depth among the three irrigation systems. While the mean water productivity for centre pivot, furrow and sprinkler systems were 15 kg/m³, 16 kg/m³ and 17 kg/m³ respectively, a unit change in irrigation application depth resulted in 0.06 t/ha yield change in centre pivot, 0.05 t/ha yield change in furrow and 0.05 t/ha yield change in sprinkler, on average up to the 120% crop irrigation requirements.

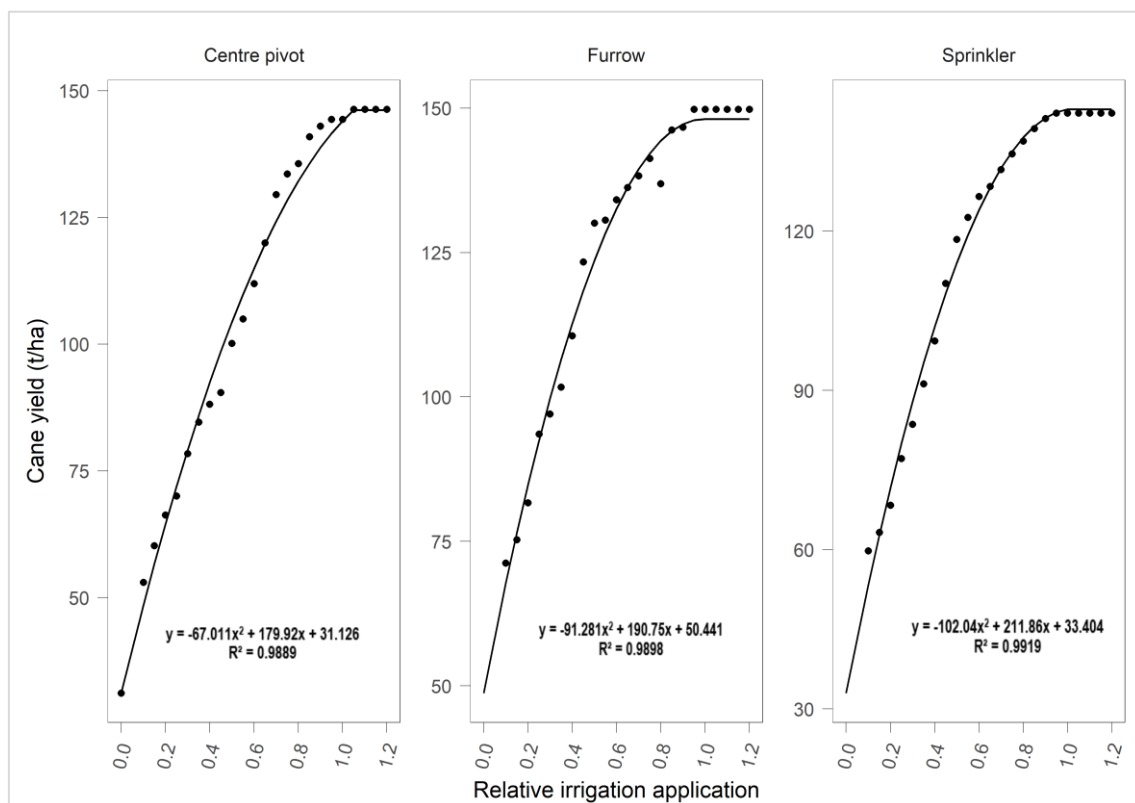


Figure 4-3: Cane yield – water relationship under each of the three irrigation systems

4.4.2 Cane Yield Response to Irrigation Heterogeneity

The impact of irrigation non-uniformity on cane yield is shown in Figure 4-4. As can be observed, the minimum and maximum application depths respectively increase and decrease as the CU increases. As expected, the cane yields also follow a similar trend (Figure 4-5). Cane yields across the field flatten as the CU increases. The portion of the field that gets the least water (10th decile) gives low yields while the area of the field that gets the most water (90th decile) gives high yields.

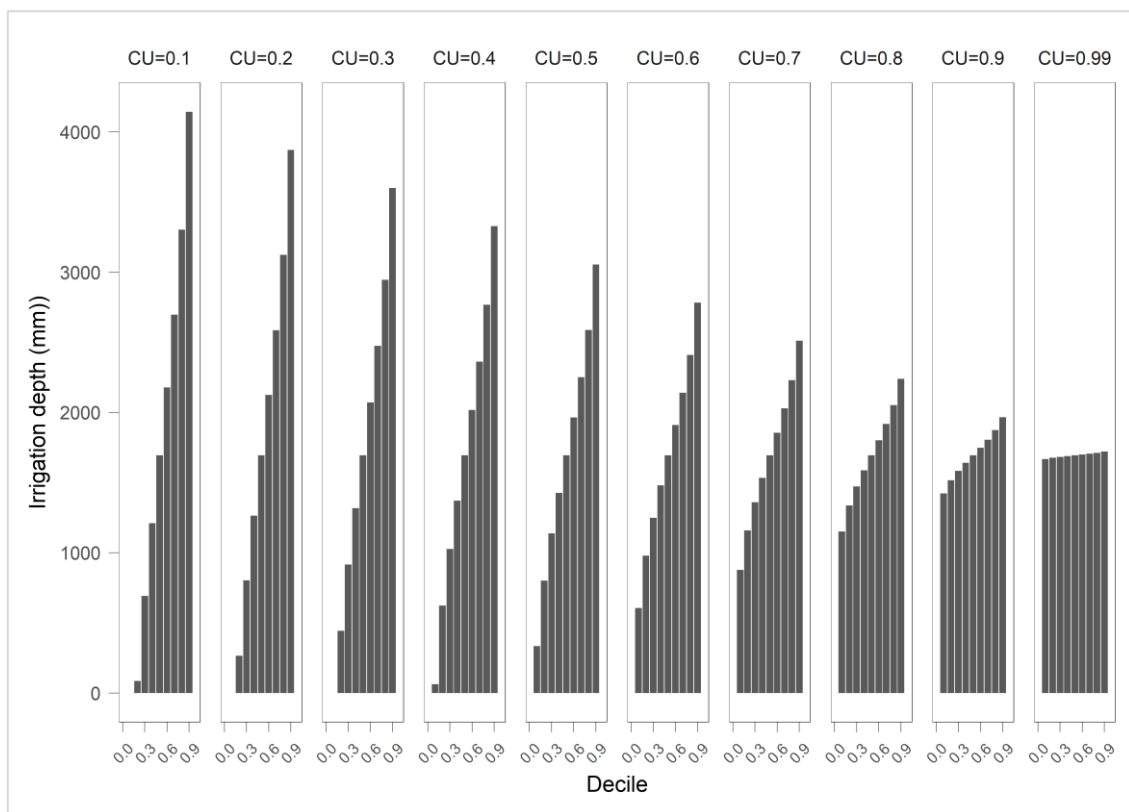


Figure 4-4: Impacts of irrigation application uniformity (CU) on irrigation application depth (mm) distribution across a representative field (based on the centre pivot system simulation)

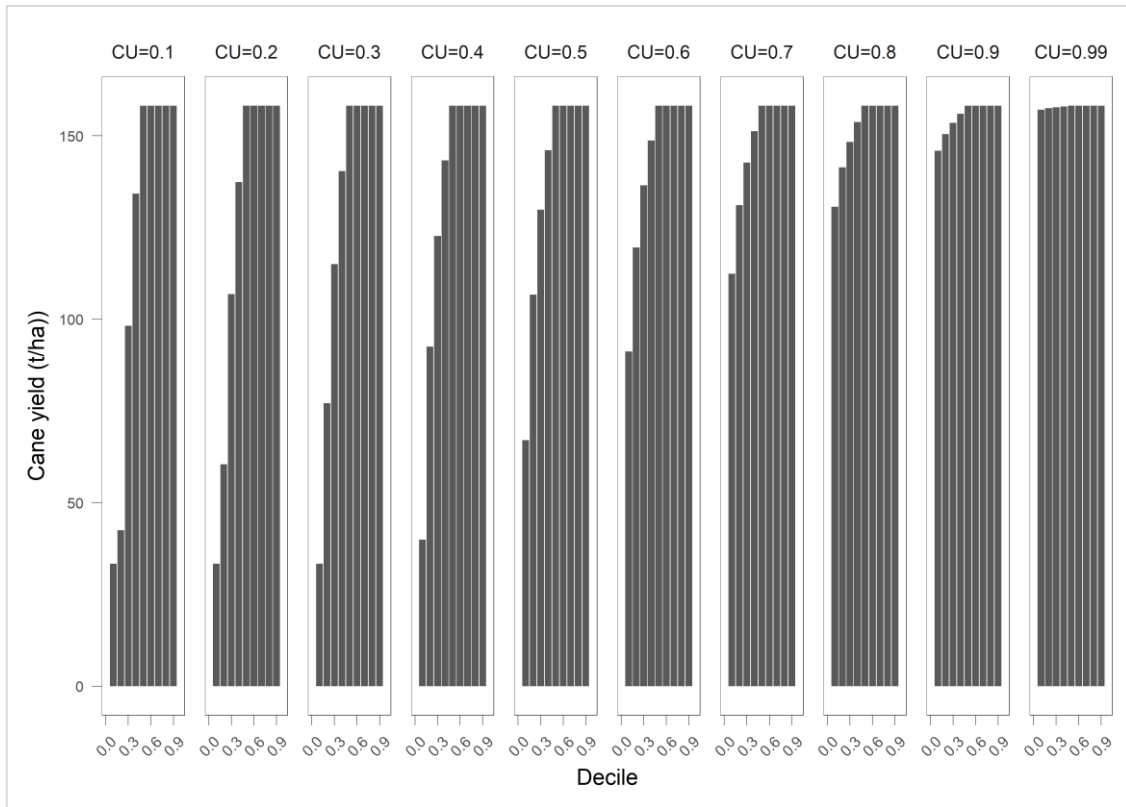


Figure 4-5: Impact of irrigation application uniformity on cane yield distribution across a field (based on centre pivot simulation)

The relationships between cane yields and irrigation application uniformity under each of the three systems are shown in Figure 4-6**Error! Reference source not found..** No significant differences in both average CU productivity (average yield per unit CU) and CU marginal yield benefits (unit change in yield per unit change in CU) were observed among the irrigation systems ($P>0.05$). On average, the CU productivity for centre pivot, furrow and sprinkler systems were 3.34 t/ha, 2.36 t/ha and 3.31 t/ha, respectively and a unit change in CU resulted in marginal yield benefits of 0.49 t/ha for the centre pivot system, 0.50 t/ha for furrow system and 0.40 t/ha sprinkler system. A function describing each graph is indicated in the respective plot. By the definition of CU and its calculation, it is not possible to have a zero or less than zero CU. Thus, it is important to note that although the trendline stretches back to zero, on the x-axis (CU values), the function becomes invalid when applied up to the zero value.

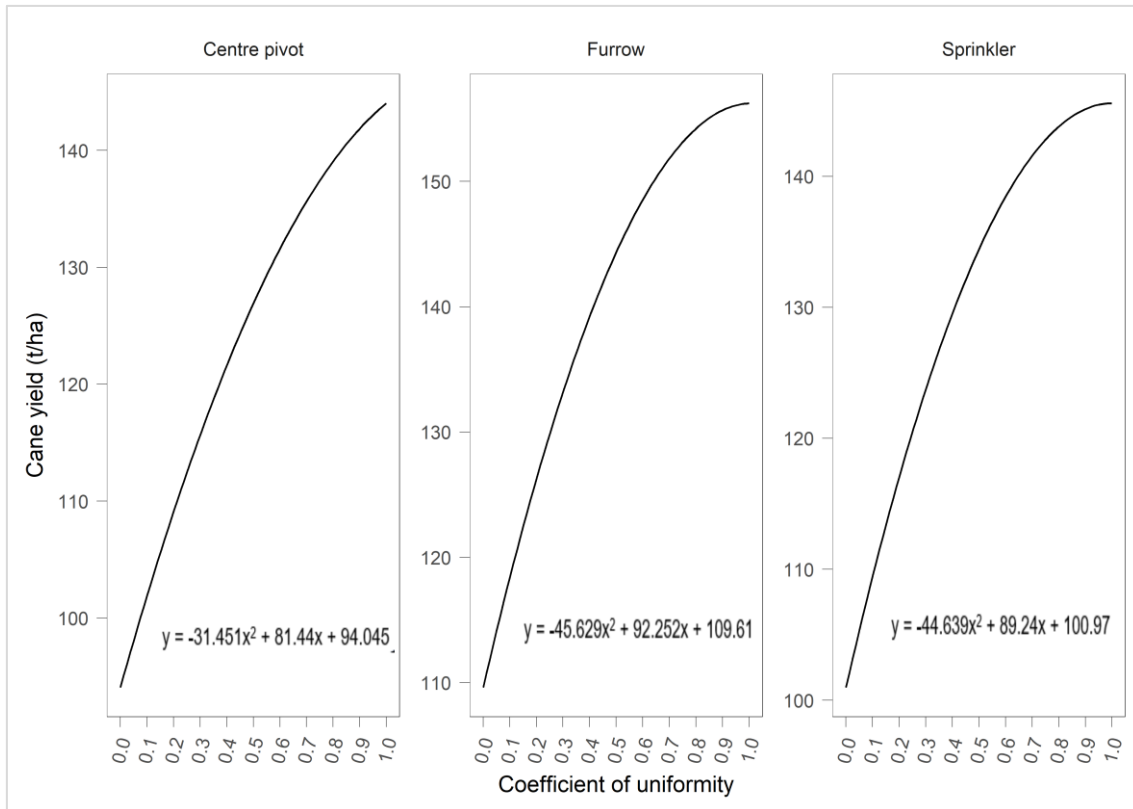


Figure 4-6: Relationship between average cane yield at the field level and irrigation application uniformity (CU) for each respective irrigation system

4.4.3 Irrigation Heterogeneity Impact on Water Use and Productivity

Figure 4-7 shows the distribution of irrigation water across the field under the three irrigation systems. The dotted line in each graph indicates full irrigation depth (in this case 1563 mm for centre pivot, 1542 mm for furrow and 1559 mm for sprinkler). The results show that at 90% CU, a farmer would be required to apply up to 2000 mm (about 450 mm more) to meet the target full irrigation depth while a total of 4000 mm would be required to meet the same target if the irrigation system is operating at a CU of 50%. Further, the results show that even after applying the 4000 mm about 5% of the field area would still not receive any water while more than 50% of the field area would likely lose water to run-off and deep percolation. It was also observed that both the 90% and 50% CU values would lead to water loss due to run-off and deep percolation, but the water loss under the 50% CU was about eight times higher than that under the 90% CU. Similarly,

the analyses show that there are some areas of the field that receive less than the full irrigation depth, leading to water stress of varying degrees across the field. However, such areas are higher (about eight-fold more) under 50% CU than the 90% CU.

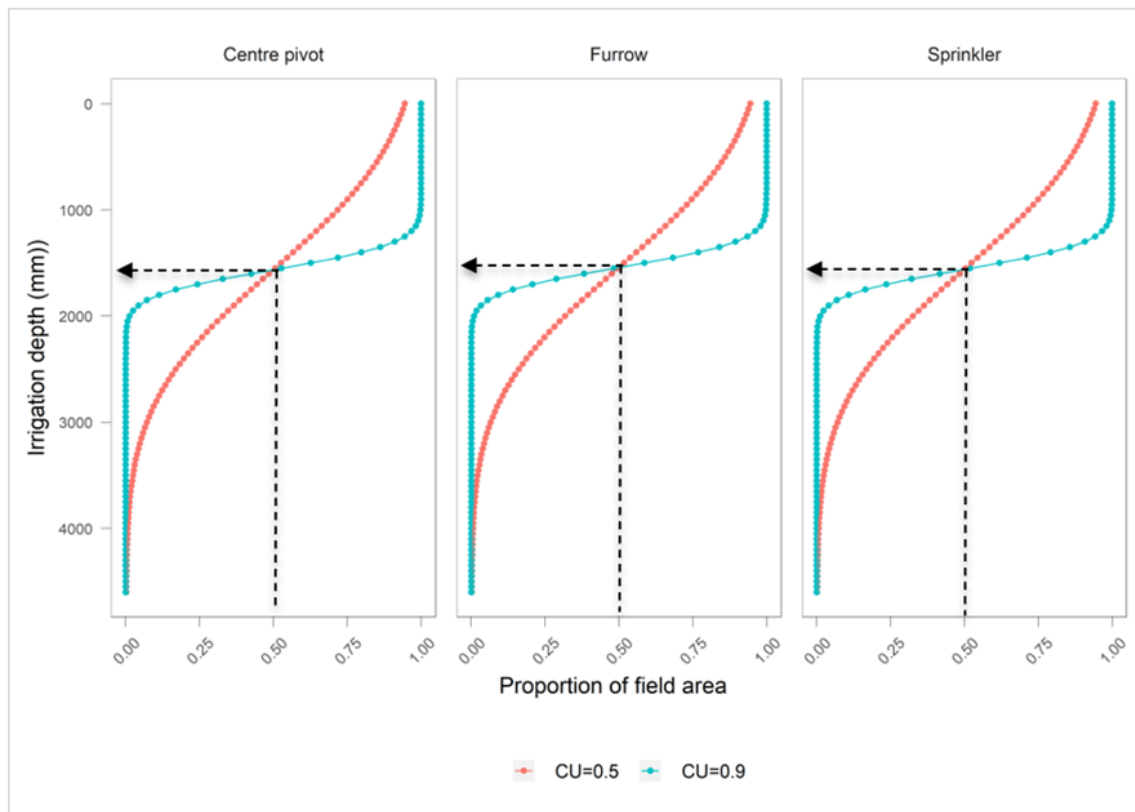


Figure 4-7: Modelled irrigation water distributions under the three contrasting application systems for two different assumed CU values based on a normal distribution function.

4.5 Discussion

The irrigation water requirements (1542 – 1563 mm) and the average cane yields (142 – 148 t/ha) established in this study, fall within the ranges reported in literature (Baillie, 2004; Knox et al., 2010; Waclawovsky et al., 2010). On the other hand, the water productivity figures are relatively higher than those reported by Svendsen et al., (2009) for the Malawi context. However, the difference in water productivity could be because the simulations (in this study) were run for a single

year based on average climate conditions that did not account for all the possible variations in climate.

It has been noted that higher CUs minimise cane yield variations across the field. However, it is also important to note that uniform water application (due to higher CU) is not synonymous with adequate water application; as it is also possible to have a uniform irrigation that is either an under or /over application. Thus, at field level, yields can only be maximised when each part of the field receives adequate water which can only be achieved by ensuring that the irrigation is applied with at high levels of uniformity (CU).

At the maximum CU (99%), the maximum cane yields were determined to be 153 t/ha for centre pivot, 145 t/ha for furrow and 156 t/ha for sprinkler. The marginal cane yield from the corresponding CU change means that a percent reduction in CU across all the systems will reduce the cane yields by 0.3%, on average. These results are in agreement with results reported by Baillie (2004), Reinders (1996) and Solomon (1998).

As observed, during an irrigation event some areas receive more than the scheduled irrigation application depth whilst others receive less than the scheduled irrigation application depth with CU controlling the extent of the over/under irrigation. This entails that water loss due deep percolation and surface run-off occurs in the over-irrigated areas while the under irrigated areas experience varying degrees of water stress. These water-stressed areas of the field are likely to produce lower than the potential yield for fully irrigated fields than areas that receive sufficient water. A farmer might deliberately choose to apply more water to compensate for poor CU values, however, the observation that at lower CU values even when a farmer puts more water to meet the full irrigation depth some parts of the field would still not receive adequate water is likely to have more significant implications on water use and productivity. The use of more water would have a bearing on cost of water pumping (energy, water and labour costs) while the yields at field level might still not be at its maximum as some areas of the field might still not give the maximum yield output.

4.6 Conclusions

In conclusion, a model with cane yield response to water and enhanced water balance simulation capabilities was developed. The model was developed by using DSSAT Canegro model and Martin et al. (2010)'s enhanced water balance model. The combination approach incorporated both DSSAT Canegro's cane yield simulation capabilities and the capabilities of partitioning irrigation water application into net infiltration, deep percolation and surface runoff based on normal distribution function. The model was then used to simulate cane yield response to varying irrigation water depths and impacts of irrigation uniformity on cane yields and irrigation water use.

The model confirmed that cane yield response to varying irrigation water levels follows a quadratic function and confirmed that irrigation non-uniformity impacts on the amount of water supply by determining the amount of water that a given point in the field receives. By determining the water supply to each part of the field, the irrigation uniformity is also a determinant of average yield at the field level.

Farmers can opt to apply more water than the target application depths to compensate for low CU values. However, the amount of water required for compensation of poor CU values increases as the CU value lowers which might have significant implications on irrigation operating costs.

Chapter 5. QUANTIFYING THE IMPACTS OF IRRIGATION HETEROGENEITY ON SUGARCANE YIELDS AND WATER PRODUCTIVITY: A CASE OF NCHALO ESTATE IN MALAWI

5.1 Introduction

Sugar is an important commodity crop for Malawi's economy. It contributes about 10% to the national GDP, 35% of total exports and between 9 and 12% of total foreign exchange earnings (Chinsinga, 2017; MITC, 2023). Malawi's annual sugar production stands at an average of 300,000 t (Kamphoni, 2022) which represents about 3% of Africa's total production. Three factories are responsible for all the sugar production and supplies in Malawi including Dwangwa, Nchalo and Salima. Illovo Sugar Africa owns about 76% of the Dwangwa and Nchalo estates while AUM Sugar Company owns 60% of Salima sugar estate with the Malawian government owning the remainder. Illovo's Dwangwa and Nchalo sugar mills produce more than 80% of sugar in Malawi. About 60% of the sugar production is consumed by local markets (both households and industry) with the balance being exported (Kamphoni, 2022). The USA, EU, and regional markets are the main target markets for Malawian sugar.

All of Malawi's sugar is produced from sugarcane. The three estates grow as well as procure sugarcane from out-grower farmers. Nchalo is the largest estate in terms of landholding. Respectively, Dwangwa, Nchalo and Salima sugar estates own about 6,500 ha, 13,500 ha and 1,000 ha of farmland on which they grow irrigated sugarcane. Nchalo estate is also responsible for processing sugarcane from an additional 2,885 ha of irrigated sugarcane grown by out-grower farmer cooperatives. It [Nchalo estate] therefore provides a significant contribution to Malawi's sugar production and national economy.

Nchalo estate grows sugarcane under centre pivot, drip, furrow and sprinkler irrigation systems. The estate utilises water from Shire River, the only outlet of Lake Malawi, for its irrigation and domestic uses. The estate's water abstraction

licenses show that the estate is entitled to abstract up to 2,322,000 m³/day for irrigation uses.

The Lake Malawi-Shire River hydrological system offers enormous benefits to the Malawi's economy. The Shire River provides over 90% of the hydropower generated and used in Malawi, provides irrigation water to more than 20,000 ha along the lower shire valley, contributes in excess of 48,000 tonnes of fish annually which is about 60% of animal protein in Malawi (Shela, 2000). It is also home to about 600 fish species out of which more than 200 are endemic to the lake. It also offers ideal grounds for fish breeding and spawning. The system also offers water transport route alternatives to and from Mozambique and Tanzania, handling in excess of 200,000 passengers and 100,000 tonnes of goods in the process, annually. It is also a source of water for domestic and industrial uses to urban and rural areas including the city of Blantyre. It hosts some of the best tourist attraction centres in Malawi including Lake Malawi and Liwonde national parks. The Lake Malawi national park was listed as UNESCO's World Natural Heritage.

To a large extent, the flows in the Shire River depend on water levels in Lake Malawi (Kumambala & Ervine, 2010; Shela, 2000). Historical data have identified declining water levels in Lake Malawi over the past two decades, with the lowest water levels being recorded in 2017. Several studies have also projected that the water levels will continue to decline in the future (Bhave et al., 2020, 2022; Jury, 2014; Kumambala & Ervine, 2010; Mtilatila et al., 2020; Mulumpwa et al., 2018; Shela, 2000), not reaching its historical maximum level recorded in the 1980s (Kumambala & Ervine, 2010) and even reaching point of no outflow (Bhave et al., 2020).

Meteorological data from Nchalo estate indicate that between 1971 and 2019 it received an annual average rainfall of 700 mm with December, January, February and March receiving most rain (Figure 5-1). With an average crop water requirement of over 1500 mm (Chapter 4), it confirms that irrigation is a necessary requirement for sustaining yields in this region. The Shire River's high dependence on the Lake Malawi's water levels for its flows has exposed the

vulnerability of the Nchalo estate to several factors including rising temperatures, declining rainfall and catchment degradation which have been prevalent in recent times. The combined influence of these factors has caused low flow regimes in the Shire River, which have posed an immense uncertainty to the Malawi's sugar industry. An analysis of the water level trends at the Nchalo estate's main water intake point along the Shire River has shown that the estate experienced severe water shortages that disrupted irrigation schedules between 2016 and 2019 (Figure 5-2). These were also the periods where the estate recorded lowest cane yield averages in about three decades. This demonstrates how much the sugar production at Nchalo estate depends on the water levels in the Lake Malawi and how vulnerable the same is to the climate shocks. The impacts of low water levels are even more compounded when you consider that 100% of the energy for irrigation at the estate comes from the same river. Thus, low water flow regimes in the river generally intensifies the competition for water allocation between irrigation and power generation. That the sugar production at the estate highly depends on the water levels at the lake Malawi which has been established to be under threat of further decline in the future, calls for the need to cushion the cane production from the impacts of future inadequate water supplies.

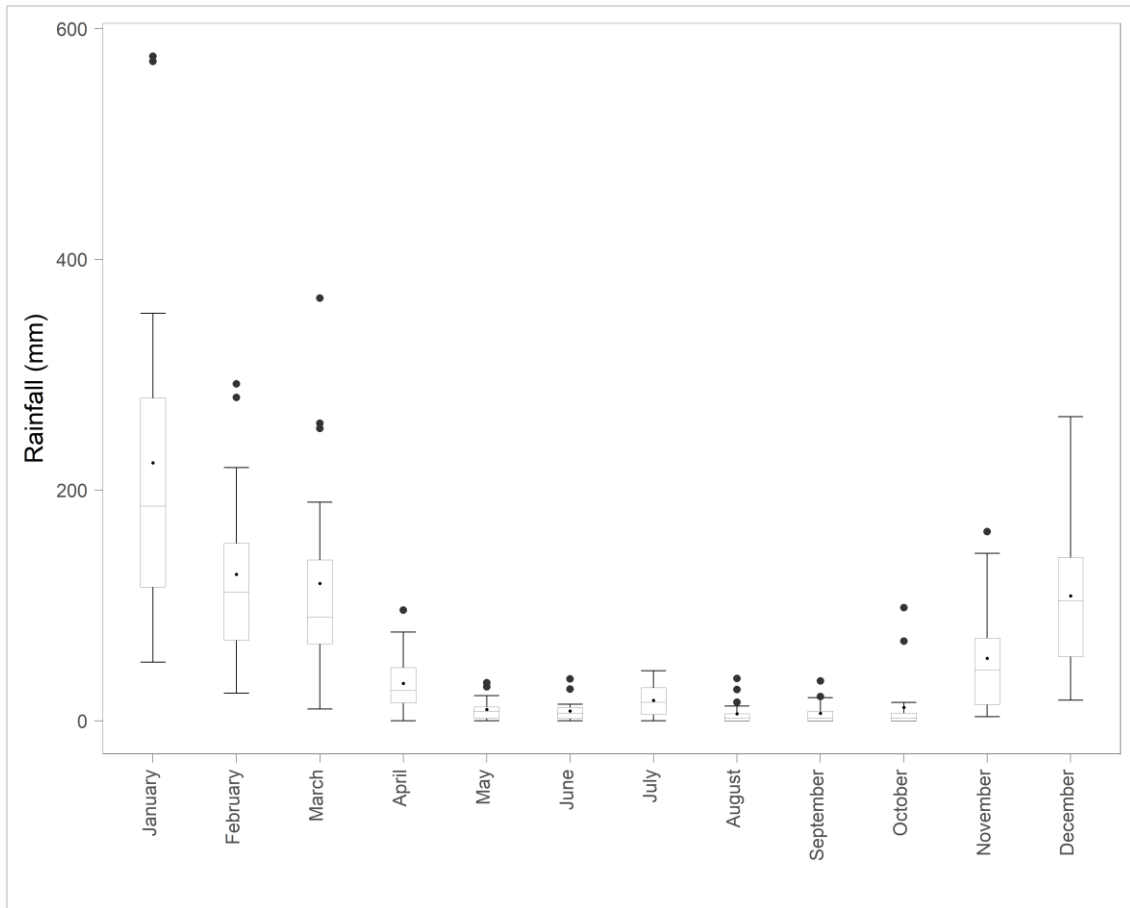


Figure 5-1: Rainfall distribution for Nchalo estate derived from monthly rainfall data from 1971 to 2019. The points within the boxes represent monthly average rainfall between 2000 and 2019, the points outside the boxes represents outlier rainfall figures (values beyond the 10th and 90th percentiles) recorded over the same period.

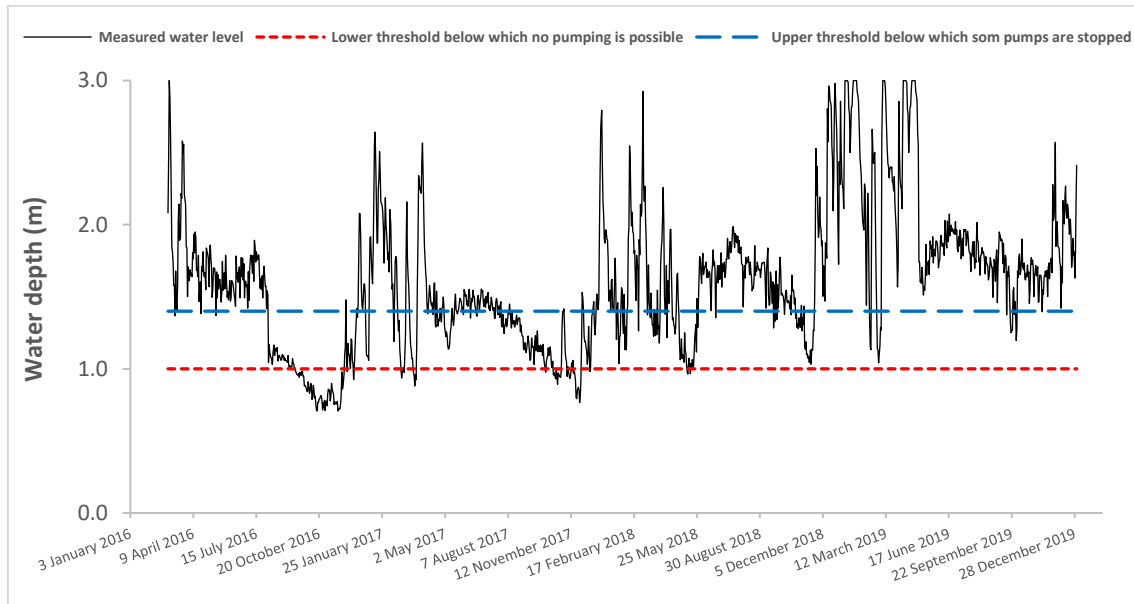


Figure 5-2: Daily water levels recorded at Nchalo estate's main water intake between 2016 and 2019. At both the upper and lower water depth thresholds, water volumes at the intake reservoir are not sufficient to run all six pumps. As such, the thresholds were technically determined to reduce pump breakdowns/wear and tear and economic inefficiencies associated with frequent engagements/disengagements of the pumps.

Inadequate water supply and competition for water between different sectors are among the drivers for increased crop water productivity in irrigated crop production. Water productivity is the net benefit from using a given unit of water (Molden et al., 2010). In crop production, this could be extended to mean the amount of crop yield realised from using a given unit of water – crop yield per unit crop water use. In principle, increasing crop water productivity would mean using irrigation water efficiently while maximising crop yields. At field level, this would entail (i) maximising crop yield return from each part of the irrigated field area, (ii) maximising yield benefit from every drop of irrigation water by keeping all water losses to the minimum and (iii) maximise the use of rainfall. Maximising yield return from each part of the irrigated field area would mean ensuring each point in the field gets supplied with adequate water when needed. Timely supply of adequate water to each point in the field signals the need for uniform water application. In essence, improving water productivity would require the farmer to

determine and control irrigation water volumes, timing and rate of application of irrigation water in a manner that would reflect proper planning and efficiency.

5.1.1 Aim and Objectives

The aim of this chapter was to assess the impact of improving irrigation uniformity on sugarcane yields and water productivity at Nchalo estate. The research set out to answer the following questions:

- i. What are the typical ranges in irrigation application uniformity across typical irrigation systems used in sugarcane production at Nchalo estate and how does their relative performance impact on water and energy use?
- ii. To what extent would improvements in irrigation uniformity change cane yields, water productivity and energy use at Nchalo estate?
- iii. How would improving irrigation uniformity change the economics of sugarcane production?

5.2 Methodology

In order to evaluate the economic costs and benefits associated with improving irrigation uniformity, I envisaged that it is important to understand; (i) the cane yield response to water, (ii) the typical irrigation water distributions for different irrigation uniformities and (iii) the typical costs and benefits for a given application uniformity. In this study, the yield response to water was defined as the amount of yield realised from a given unit of water use (crop yield per unit of water use). The yield response to water determined the yield realised from a given water application while the water distribution response to irrigation uniformity (water distribution as a function of irrigation uniformity) determined the distribution of water across the field. The water distribution across the field was important in estimating the percentage of the field area that got at least the crop water requirement depth, thus being able to estimate the crop yield at field level. Again, the water distribution as a function of irrigation uniformity determined the amount of irrigation water that needed to be supplied to the field at a given application uniformity. In essence, the yield response to water and the water distribution in response to application uniformity determined the level of revenue and irrigation cost, respectively. The revenue and costs, in turn influence the gross margin of

improving irrigation uniformity from one level to another. Thus, three models were used in the assessment of the economic benefits associated with improving irrigation uniformity. These models were (i) a biophysical crop model (DSSAT Canegro), (ii) an irrigation water distribution model and (iii) an economic model (Figure 5-3). In the Figure 5-3, climate change influences both the crop and irrigation water requirements. The crop water requirements were determined by DSSAT Canegro which in turn determined the amount of crop yield from the given crop water requirements. The level of yield response to water (when the sugar recovery and sugar selling price are incorporated) determined the revenue realised from using a given amount of water. On the other hand, the irrigation water requirements were influenced by the irrigation system's efficiency (which to an extent depends on irrigation system type). The uniformity system influences how the water is distributed across the field. Martin et al., (2010)'s water balance and distribution model was used to determine water distribution across the field. The water distribution model determined the gross irrigation water requirements based on the level of irrigation uniformity. The gross irrigation water requirements in turn determined the energy requirements for water pumping. Both the irrigation and energy requirements (when labour and cost of energy were considered) determined the cost of irrigation. The revenue and cost were the necessary inputs to the economic model that eventually determined the gross margin of supplying a given irrigation water depth at a given level of irrigation uniformity.

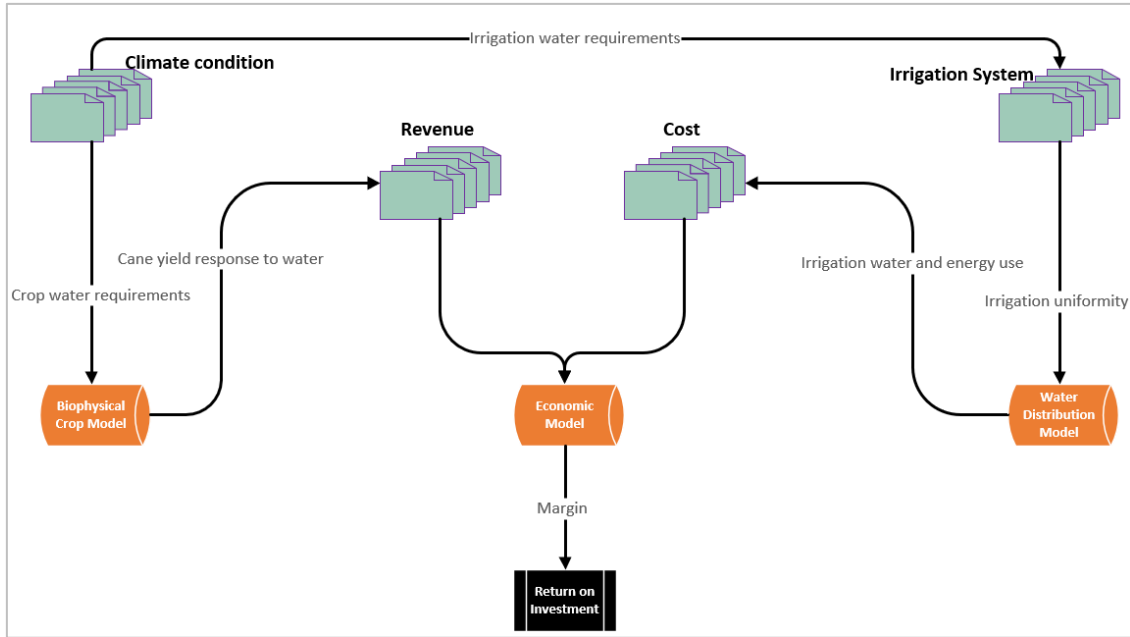


Figure 5-3: Models used in the assessment of the economic benefits associated with improvement of irrigation uniformity.

5.2.1 Irrigation Systems Evaluation

In Chapter 4, the impact of irrigation heterogeneity on cane yields, water use and water productivity were determined. However, it will be important to note that the impact of the irrigation heterogeneity on the mentioned parameters was determined from a range of CU theoretical values within the CU range. To have a practical application of the impact of the irrigation heterogeneity on cane yields, water and energy use as well as water productivity it meant that irrigation systems evaluations should be carried out. This aided in the establishment of the existing ranges of irrigation uniformity with which the irrigation apply the water to the field across systems and use them to determine how the improvement of the same would impact the yields, water and energy use as well as water productivity. therefore, it is also important to note that the CU ranges used in Chapter 4 and in this chapter were different.

Irrigation uniformity was defined as the spatial heterogeneity in irrigation water application across the field (Solomon, 1998). Determining such variation in water application meant conducting a series of in-field irrigation system evaluations to measure system performance and uniformity.

Three irrigation systems (centre pivot, furrow and sprinkler - dragline) were evaluated to determine their typical irrigation uniformities. A total of twenty-seven fields (4 centre pivots, 6 dragline fields and 17 furrow fields) were sampled and evaluated. Coefficient of uniformity (CU), distribution uniformity (DU) and adequacy of water application were the indicators that were used in the irrigation system evaluation. While the DU and CU were used to assess the uniformity with which each system applied the irrigation water, the adequacy reflected on the extent to which the systems met the intended irrigation application depths as it is also possible to uniformly under/over-irrigate. The CU, DU and adequacy were determined by equations (7), (8) and (9), respectively.

$$CU = \left[1 - \frac{\sum_{i=1}^N |X_i - \bar{X}|}{N \cdot \bar{X}} \right] \cdot 100 \quad (7)$$

$$DU = \left[\frac{\bar{X}_{25\%}}{\bar{X}} \right] \cdot 100 \quad (8)$$

$$Ad = \frac{\bar{X}}{X_{design}} \quad (9)$$

Where:

- Ad is the system adequacy
- X_i is the amount of water caught in the i^{th} collector (mm).
- $\bar{X}$ is the average amount of water caught in all collectors (mm)
- $\bar{X}_{25\%}$ is the average amount of water caught in the low quarter (mm)
- X_{design} is the intended/planned application depth of the system (mm)
- N is the total number of observations.

The uniformity evaluation for the overhead systems adopted the irrigation systems evaluation procedure defined in ASEA (2001).

The following steps were followed for the centre pivot system evaluation:

- i. Catch cans were laid out at 10 m spacing interval along the radius of the pivot

- ii. Pressure and design application depth were noted from pressure gauges installed at the lateral line connecting from the pump and control panel of the machine, respectively
- iii. Pivot was run until it had passed over all the catch cans
- iv. Water depth caught in each can was measured and recorded
- v. CU and DU were calculated from the recorded water depths

The following steps were followed for the evaluation of the sprinkler system:

- i. A flat area with no overgrown cane was identified.
- ii. Four sprinklers set up in a rectangle, spaced at 18 m x 15 m.
- iii. Catch cans spaced at 3 m x 3 m and laid out within the rectangle formed by the 4 sprinklers.
- iv. Pressure and flowrate of each of the four sprinklers was measured and recorded
- v. The irrigation system was run for an hour and depth of water caught in each can was recorded.
- vi. CU and DU were calculated from the recorded water depths

In both cases (centre pivot and sprinkler systems evaluation), average wind conditions (wind speed and direction) during the time of the field test were noted and recorded.

The surface system evaluation followed the guidelines applied by Hess et al. (2009) with pegs/markers installed at 10 m intervals along the furrow. For the furrow system evaluation, water was pumped into a test furrow using a syphon of known diameter and flowrate. The time taken for the water to advance to each marker was noted. The water flow was cut off when the water front reached the last marker along the furrow. The time taken for the water to infiltrate at each marker was recorded, this was the recession time. Advance and recession curves were developed for each of the sample fields. The contact time and infiltration depth at each marked point along the furrow were determined and the CU, DU and adequacy were then calculated.

Infiltration tests were conducted in furrow fields to determine typical infiltration rates. The infiltration tests were done with the aid of double ring infiltrometer. The

cylinders were driven into the soil to a depth of 30 – 50 mm as recommended by Hess et al., (2009). The cylinder sides were driven vertically into the ground with the aid of driving plate and mallet while ensuring minimal disturbances to the soils inside the cylinders. Where necessary, soil was tapped into the spaces between the soil and the cylinder walls to avoid exaggerated infiltration. Known quantities of water were added into the middle ring to a reasonable head above the soil surface and water was also be added into the outer ring to the same level as the inner ring while ensuring no disturbances to the soil. Time at the start of the test was noted and recorded. Known quantities of water was added at intervals, each time noting both the time taken and volume of water infiltrated. The heads in both the inner and outer rings were kept the same each time of refill. The process was run until the infiltration rate remained constant.

Kara et al., (2008) reported that Christiansen et al., (1966) developed an equation for the estimation of cumulative infiltration depth at a point as a function of infiltration opportunity time which is as represented by equation (10). Thus, the equation (10) was used to determine the cumulative infiltration depths at the marked points along the furrow.

$$I = at^b \quad (10)$$

Where I is cumulative infiltration in mm

t is the infiltration opportunity time in h (the difference between recession and advance time)

a and b are the constants for a given soil at specific soil moisture content.

When the logarithms of cumulated time and cumulated infiltration depths from the infiltration tests are plotted, they resultant graph is a straight line. Constants a and b are, respectively, the slope and y-intercept of the straight-line graph of the logarithms of the cumulative time and infiltration depth. Thus, a and b constants were estimated from the infiltration tests and aided the estimation of the infiltration

depths at the marked points along the furrows for the calculation of CU, DU and adequacy.

5.2.1.1 Test of Normality

The assumption that irrigation water application follows a normal distribution pattern needed to be validated and confirmed before analysing the data since the reliability of the results is highly dependent on the validity of the assumption. Testing for normality is an important step in data analysis, as this helps one to decide on the most appropriate method of data analysis or data transformation to check the reliability and validity of the results. In cases where data has been ascertained to follow normal distribution, parametric tests (including linear regression, ANOVA, t-tests) become appropriate for more powerful inferences about a population based on sample data (Tsagris & Pandis, 2021). On the other hand, where data has been proven to not follow any particular distribution, data transformation approaches can be applied to transform the data to follow a given distribution. Thus, the application of test of normality to the data, in this study, was to determine whether it would be appropriate to transform the data before analysis so as to exploit the power that comes with the use of parametric tests in enhancing the reliability of the results of the analysis. This is why the application depths for each system from the irrigation systems evaluation results were subjected to a test of normality to ascertain whether the water applications followed a normal distribution pattern.

The normality of the irrigation system evaluation datasets was assessed using Z-score. Z-scores for a given dataset was calculated by dividing the skewness of the dataset by its standard error (Ghasemi & Zahediasl, 2012; Mishra et al., 2019). The data is said to be normal when the Z – score is between -1.96 and +1.96 when the number of observations (n) are less than 50 and between -3.29 and +3.29 when n is 50 or more but less than 300 (Mishra et al., 2019). The Z-scores for the datasets were determined using the SPSS software (Frey, 2017).

5.2.1.2 Irrigation Uniformity Impact on Water and Energy Use

The amount of irrigation water applied under each irrigation system was determined from Martin et al. (2010)'s water balance model and distribution. The

model has capabilities of partitioning irrigation water application into net infiltration, deep percolation and surface runoff based on normal distribution function. The model also which incorporates irrigation uniformity in determining the gross irrigation requirements. The gross amount of irrigation water, in turn, was used to determine the energy requirement. For each system, water and energy use under the observed and improved irrigation uniformity conditions were then estimated from the model and statistically compared to each other cane yield response to irrigation non-uniformity.

The cane yield response to water for each of the three irrigation systems was estimated using the production functions developed in Chapter 4. The DSSAT Canegro model (used to develop the production functions) simulates yield response to water application at a point in the field. To account for deficiencies in water application due to non-uniform water application, it was assumed that the spatial distribution of water application follows a normal distribution. The use of the assumption incorporated the impact of non-uniform water application on cane yields at field level.

5.2.1.3 Impact of Irrigation Application Uniformity on Cane Yields

The cane yield under the observed irrigation uniformities for each of the irrigation systems were compared to cane yields under what is deemed attainable uniformities reported in literature. Several studies have reported potential CU values to be within the ranges of 86-94% for the centre pivot, 78-90% for the furrow and 81-91% for the sprinkler system (Burt et al., 1997; Clemmens & Dedrick, 1994; Reinders, 1996). In this study, the upper limit of the reported ranges for each system were regarded as the level to which each of the systems could be improved. Cane yields corresponding to the upper limit CU values for each system were determined and statistically compared (using analysis of variance - ANOVA) to the cane yields for the corresponding observed CU under each irrigation system. This comparison enabled the establishment of whether there were any significant differences in cane yields under the observed and the improved uniformities.

5.2.2 Economic Analysis

It is important to state that the analysis was conducted at the field scale. The field level analysis approach simplified the need to account for the contribution of individual pumps in a network towards water supplies to individual dams, fields and other uses other than irrigation (including domestic and factory uses). Such need for proper water accounting could be intricate, especially when and where such records are not available. Thus, consideration was only given to the irrigation water that reached the field edge of a given irrigation system.

5.2.2.1 Cost and Revenue

The data that were used to generate the cost and revenue functions for the sugarcane production were collected from Nchalo estate records. Further, it has to be noted that only in-field irrigation related costs were considered in this study, costs associated with other crop husbandry practices including land preparation, crop nutrition, weeding, harvest and transport were held constant. Both the unit costs and the revenue were calculated and determined on a per ha basis.

The revenue realised from sugar sales (MK/t) was the product of the sugar selling price (MK/t) and the sugar production function - while observing the limits within which the production function remains valid. The sugar production function was transformed from the sugarcane production function using the average sugar recovery percentage (equation (11)). The sugar recovery percentage data were obtained from the Nchalo Estate field records.

$$R(w) = P_s * \beta * y(w) = P_s * \beta * (c_1 w^2 + b_1 w + a_1) \quad (11)$$

Where:

R is the revenue realised from a tonne of sugar (MK/ha) as a function of water application w (mm),

P_s is the sugar selling price (MK/t) c_1 , b_1 and a_1 are constants defining the characteristics of the sugarcane production function.

β is the sugar recovery %

Cost is a linear function (English & Raja, 1996) with the slope indicating the marginal variable cost associated with pumping a given amount of water and the vertical intercept representing the fixed cost (equation (12)).

Where:

$$C(w) = b_2 w + a_2 \quad (12)$$

C is the cost (MK) associated with pumping (w) amount of water (mm),

b_2 is the marginal variable cost associated with pumping w amount of irrigation water (MK/mm)

a_2 is the fixed irrigation cost (MK).

The fixed cost of irrigation (a_2) was made up of cost of irrigation-related insurance and maintenance, taxes and/or levies. It has to be borne in mind, however, that the consideration of only the water that had reached the field edge made the fixed cost to be insignificant such that its impact on the total cost of irrigation operation was negligible.

The cost of irrigation to produce one tonne of sugar per ha includes the water cost (stipulated in the water abstraction licence), the cost of pumping and the cost for labour to manage the irrigation operation. The cost of water pumping is equivalent to the cost of energy (electricity). The energy cost included both off-peak and on-peak operations of the irrigation. The cost of electricity was deduced from irrigation electricity bill records that the estate paid to the power supply company. The labour cost was estimated from the number of people working on a given irrigation shift, the number of hours per shift, the total number of irrigation hours in a season and the labour rate per hour. The seasonal irrigation hours were estimated from the seasonal irrigation water requirements (volume) divided by the discharge rate of the irrigation system.

By incorporating CU, the relationships between CU and revenue - $R(CU)$ as well as CU and cost - $C(CU)$ were established. It was established in Chapter 4 that

the relationship between cane yield and CU follows a quadratic function. This entails that revenue associated with a given CU would be the product of the yield-CU production function, the selling price of the sugar and the sugar recovery % (equation (13)). Also, it has been observed that as CU changes the amount of irrigation water to achieve a given yield also changes. The change in irrigation water requirements with changes in CU means that cost of irrigation also changes with CU (equation (14)).

$$R(CU) = P_s * \beta * y(CU) = P_s * \beta * (c_3 CU^2 + b_3 CU + a_3) \quad (13)$$

$$C(CU) = b_4 CU + a_4 \quad (14)$$

Where,

a_4 and b_4 are the fixed and marginal costs of irrigation in MK and MK/mm, respectively.

5.2.2.2 Yield and Returns Maximising Irrigation Depth

In irrigated production, assuming other factors remain constant, and where water is not a limiting factor of production, it becomes economically sound that revenue from the irrigated crop is maximised and this can only be done by producing maximum yields as long as the marginal costs do not exceed the marginal benefits (English, 1990b; English & Raja, 1996). Thus, it is important for the farmer to know how much irrigation water needs to be supplied to achieve maximum yields. On the other hand, achieving efficient water use becomes imperative in cases where water is scarce, whereby farmers are required to maximise returns on every drop of water supplied to the crop rather than achieving maximum returns.

The irrigation depths that maximise cane yields and returns on irrigation were respectively determined by equations (15) and (16). Graphically, these are points on the graph at which the revenue function transitions from decreasing marginal returns to diminishing total returns and where the average net returns (ANR) function is tangent to the net irrigation returns (NIR) function, respectively. The

ANR was defined as the amount of money realised from applying a given amount of irrigation water depth whereas the NIR was defined as the difference between revenue and cost of applying a given irrigation water depth. The NIR and ANR are defined by equations (17) and (18), respectively.

$$w_{ym} = -\frac{b_3}{c_3} \quad (15)$$

$$w_{opt} = \sqrt{\frac{P_s a_3 - a_4}{P_s c_3}} \quad (16)$$

$$NIR = R - C \quad (17)$$

$$ANR = \frac{NIR - NR_{rainfed}}{w} \quad (18)$$

Where:

C is the cost of production

$NR_{rainfed}$ is the net return realised from rainfed production

R is the revenue

w_{ym} is the yield maximising irrigation depth

w_{opt} is the optimum irrigation depth

w is amount of irrigation water applied (mm)

a_3 , a_4 , c_3 and P_s are parameters as defined in equations (13) and (14).

5.3 Results

5.3.1 Irrigation Application Uniformity

5.3.1.1 Test of Normality

The test of normality for the irrigation systems evaluation is shown in Table 5-1. The Z-scores showed that all centre pivot fields followed normal distribution

pattern in water application, all 6 dragline fields, except one, showed non-normality and 4 furrow fields out of 13 showed non-normality. This represents 100% normality in centre pivot system, 77% in furrow system and 17% normality in sprinkler system (Table 5-1).

Table 5-1: Numerical normality test results for the three irrigation systems evaluated

System	Field Number	Number of observations (n)	Flowrate (l/h)	Furrow length (m)	Pressure (kPa)	Mean wind speed (km/h)	CU (%)	DU (%)	Adequacy (%)	Mean depth (mm)	Standard Error (mm)	Skewness	Z-score	Test Statement
Centre Pivot	2141	61	-	-	420	1.0	82.4	67.7	82.8	15.66	0.664	1.99	3	Normal
	4123	71	-	-	280	3.0	81.5	68.5	75.9	15.56	0.438	-0.62	-1.42	Normal
	3221	95	-	-	280	0.5	84.5	52.9	71.2	13.32	0.492	-0.83	-1.69	Normal
	9007	86	-	-	258	2.0	82.6	65.8	66.9	13.38	0.396	-0.13	-0.33	Normal
Sprinkler	1232	38	-	-	235	4.0	61.7	45.2	58.4	3.523	0.223	0.16	0.72	Normal
	1234	38	-	-	210	7.9	59.6	42.6	47.7	2.877	0.2	0.63	3.15	Non-normal
	3251	38	-	-	285	8.3	67.1	51.1	64.1	3.871	0.269	0.73	2.71	Non-normal
	3254	38	-	-	150	8.3	60.0	44.2	45.8	2.767	0.227	0.8	3.52	Non-normal
	3252	38	-	-	420	10.1	79.6	62.0	63.9	3.855	0.179	-0.86	-4.8	Non-normal
	3253	38	-	-	180	11.2	67.2	52.2	51.4	3.105	0.228	1.44	6.32	Non-normal
Furrow	3701	19	14688	190	-	-	84.6	70.4	86.0	34.59	0.34	1.01	2.97	Non-normal
	1418	18	14688	180	-	-	93.3	88.0	92.4	33.13	0.69	-1.64	-2.39	Non-normal
	7508	21	14688	210	-	-	98.4	96.8	87.5	34.53	0.17	-0.81	-4.79	Non-normal
	7509	21	14688	210	-	-	98.1	95.3	90.1	28.09	0.19	-1.47	-7.62	Non-normal
	3704	17	14688	170	-	-	84.6	70.4	86.0	64.59	3.10	-1.38	-0.45	Normal
	1411	12	14688	120	-	-	92.6	88.8	94.9	30.73	0.77	-0.20	-0.26	Normal
	1409	18	14688	180	-	-	93.5	89.7	91.0	34.37	0.6	-0.48	-0.8	Normal
	1417	15	14688	150	-	-	87.6	79.2	69.7	61.30	2.39	-0.61	-0.26	Normal
	2418	13	14688	130	-	-	96.6	94.7	99.8	32.10	0.35	-0.49	-1.39	Normal
	2525	8	14688	80	-	-	95.7	91.3	73.8	36.68	0.78	-1.17	-1.50	Normal
	2516	17	14688	170	-	-	97.5	96.5	91.1	42.22	0.31	-0.35	-1.13	Normal
	2527	15	14688	150	-	-	92.8	87.2	84.7	26.94	0.61	-0.89	-1.47	Normal
	3538	11	14688	110	-	-	90.9	84.6	80.5	40.44	1.43	-0.95	-0.66	Normal
	3536	9	14688	90	-	-	97.5	96.9	87.1	20.99	0.22	0.30	1.36	Normal
	3528	10	14688	100	-	-	80.4	73.1	65.0	50.22	3.67	0.00	0.00	Normal
	6207	10	14688	100	-	-	78.7	67.7	58.6	43.43	3.61	-0.52	-0.14	Normal
	7204	12	14688	120	-	-	92.2	86.3	87.2	36.46	1.01	-1.09	-1.08	Normal

5.3.1.2 Irrigation Systems Evaluation

Results from the irrigation system evaluation are presented in Figure 5-4, Figure 5-5 and Figure 5-6. The evaluation showed significant differences ($p < 0.05$) in CU (Figure 5-4) across the three systems (centre pivot, furrow and sprinkler). The respective mean CU for centre pivot, furrow and sprinkler were 83%, 90% and 66% with the CU values ranging from 82% to 85% in centre pivot fields, 79% to 98% in furrow fields and 60% to 80% in sprinkler fields.

Figure 5-5 shows that while no significant differences ($P > 0.05$) in mean DU were observed between centre pivot and sprinkler irrigation systems, the mean DU in furrow system was significantly higher ($p < 0.05$) than mean DU for both sprinkler and centre pivot systems. The DU in furrow fields ranged between 68% and 97%, 53% and 69% in centre pivot fields and from 43% to 62% in sprinkler fields with respective mean CU values of 87%, 64% and 50%.

On the other hand, the adequacy with which each of the three systems applies irrigation showed that centre pivot and furrow systems had no significant differences. However, both the centre pivot and furrow systems applied the irrigation water with significantly higher adequacy ($p < 0.05$) than the sprinkler system. The adequacy of water application under centre pivot ranged between 67% and 82%, 59% and 100% in furrow system and 46% and 64% in sprinkler system with the respective mean adequacy values of 74%, 84% and 55%.

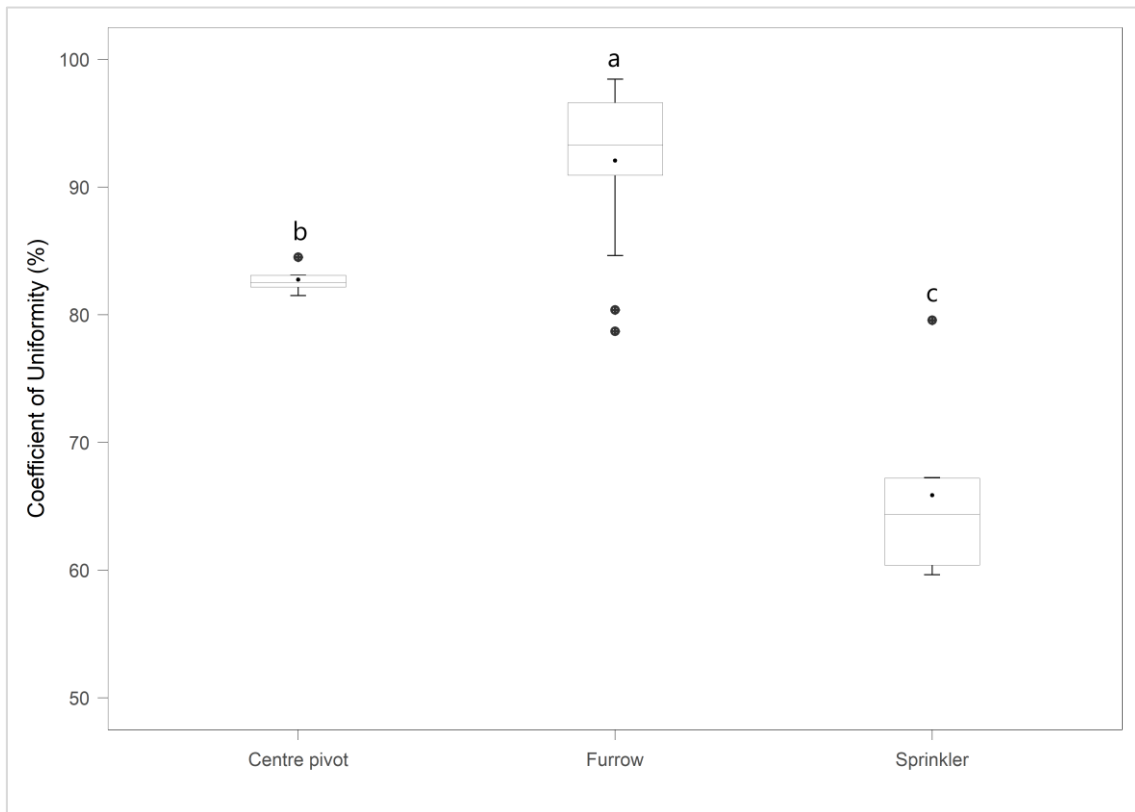


Figure 5-4: Box and whisker plot showing the coefficient of uniformity (CU) for centre pivot (n=4), furrow (n=17) and sprinkler (n=6) systems. The letters a, b and c show that all the systems are significantly different from each other and dots outside the boxes are outliers

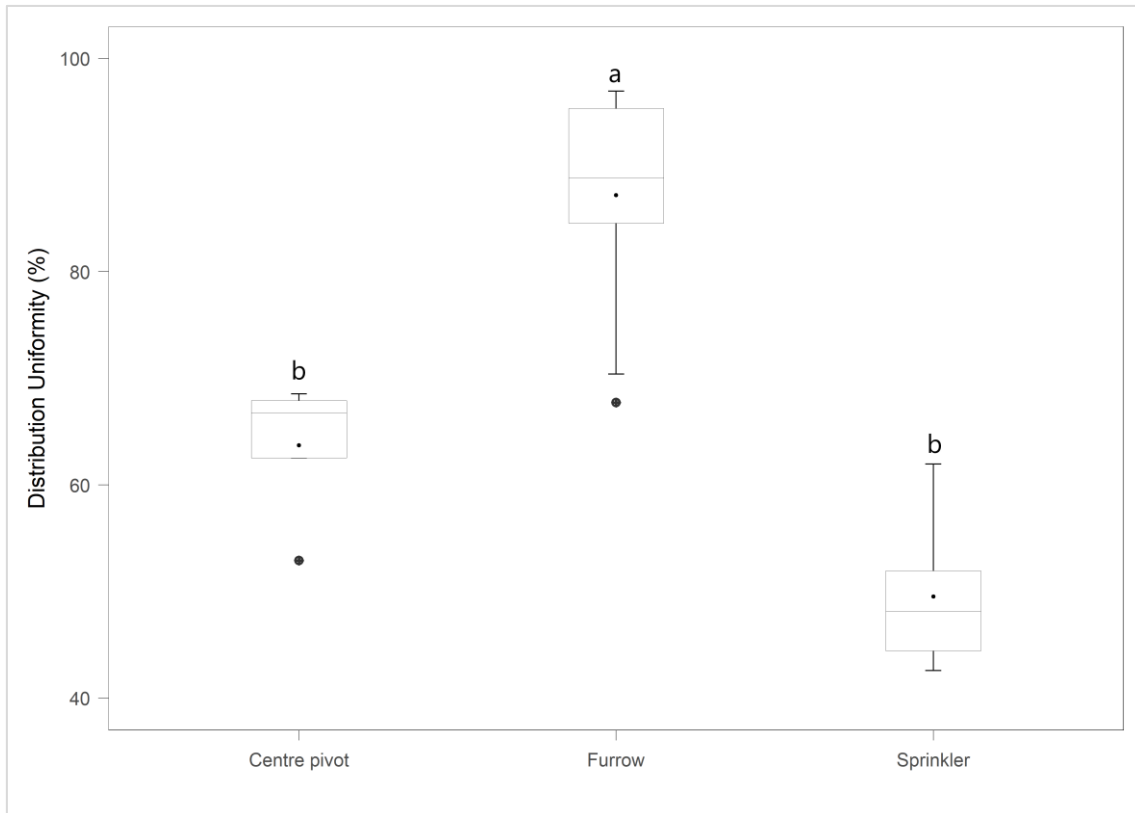


Figure 5-5: Distribution uniformity (DU) variation across systems (furrow – n=17, pivot – n=4 and sprinkler – n=6). The letters a, b and c show that all the systems are significantly different from each other and dots outside the boxes are outliers

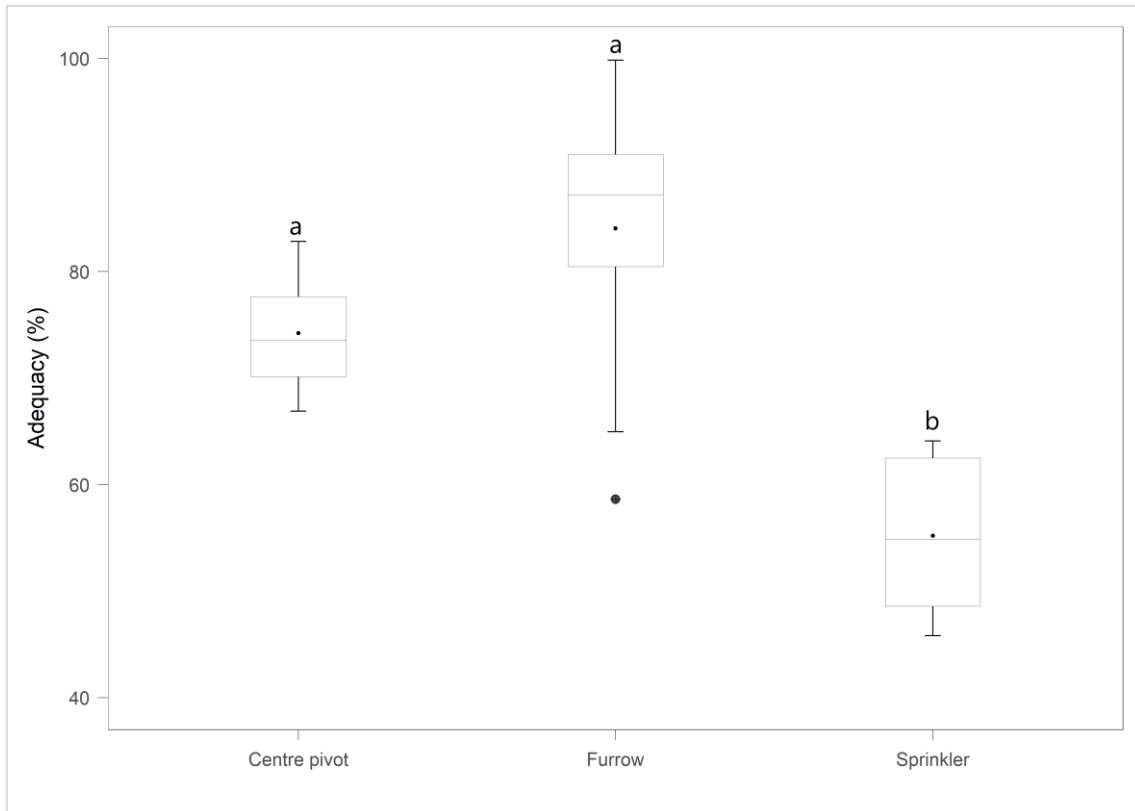


Figure 5-6: Variation of irrigation application adequacy across the three irrigation systems. The letters a, b and c show that all the systems are significantly different from each other and dots outside the boxes are outliers

5.3.1.3 Impacts of irrigation uniformity on water and energy use

The impacts of improving irrigation uniformity on water use is shown in Figure 5-7. The comparison of irrigation water use under observed irrigation uniformity and envisaged level of irrigation uniformity are represented by two graphs under each system. The dotted arrows show the average irrigation water requirements for each irrigation system. The results show that at the respective observed irrigation uniformities (80% for centre pivot, 90% for furrow and 66% for sprinkler), centre pivot system would require 2600 mm of irrigation water to meet the full irrigation water requirements (1563 mm), furrow system would use about 2000 mm against the required 1542 mm and sprinkler would require about 3800 mm to meet the required 1559 mm. On the other hand, all the systems would need about 2000 mm of irrigation water to satisfy the full irrigation requirements if they operated at the improved level of irrigation uniformities (95% for centre pivot, 90%

for furrow and sprinkler). This entails that improving the irrigation uniformities from 0.8 to 0.95 for the centre pivot system and from 0.66 to 0.9 in sprinkler system would reduce respective irrigation water uses by an average of 30% and 90%.

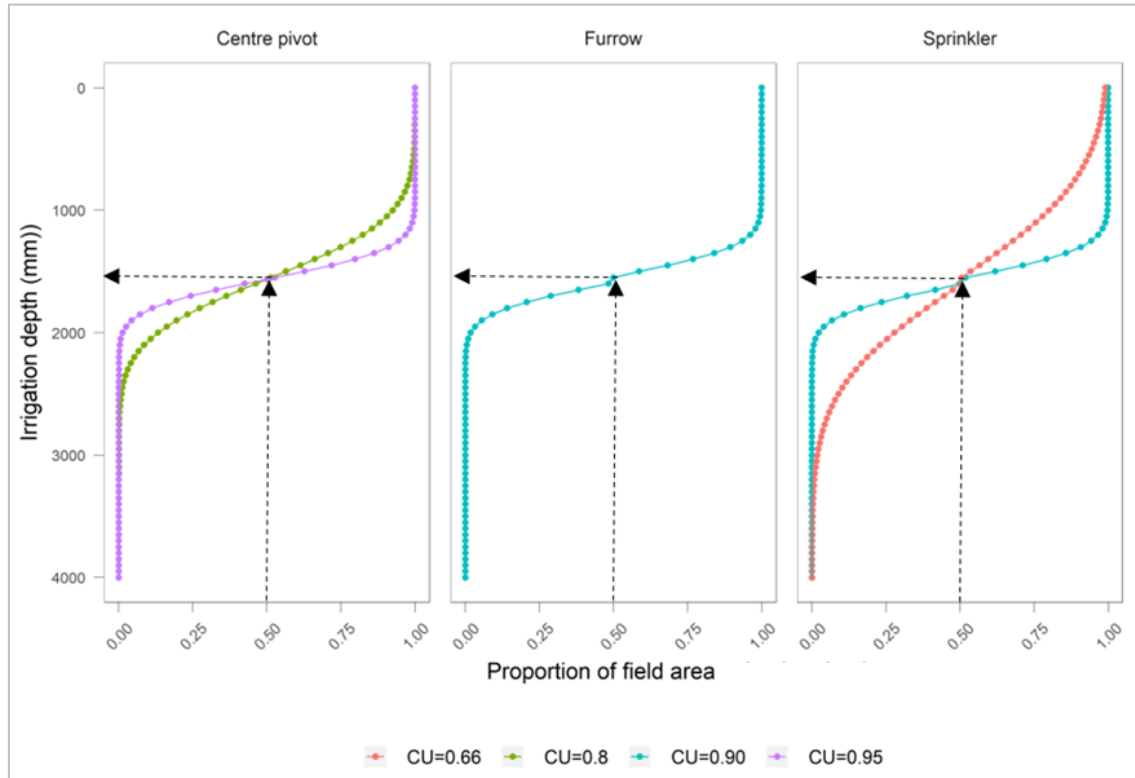


Figure 5-7: Impact of irrigation application uniformity improvement on irrigation water use

Figure 5-8 compares the response of energy use under observed and improved irrigation uniformities. The dotted arrows indicate the average energy requirements per ha for each system. It is also important to note that the analysis only considered the energy requirement for the water that has already reached the edge of the field under consideration (refer to subsection 5.2.2). The results show that to meet the average irrigation needs for each irrigation system (1563 mm – centre pivot, 1542 mm – furrow and 1559 mm - sprinkler), the energy requirements for each system would be 3750 kWh for centre pivot, 3700 kWh for furrow and 3740 kWh for the sprinkler system. While operating at the observed irrigation uniformities the centre pivot would require about 6175 kWh to pump

2600 mm, furrow would need about 5030 kWh to pump 2000 mm and sprinkler would need 9416 kWh to pump 3800 mm required to meet the respective full irrigation requirements. Operating the irrigation at the improved irrigation uniformity would result in the energy requirement being 4620 kWh for the centre pivot and 5030 kWh for the furrow and sprinkler systems.

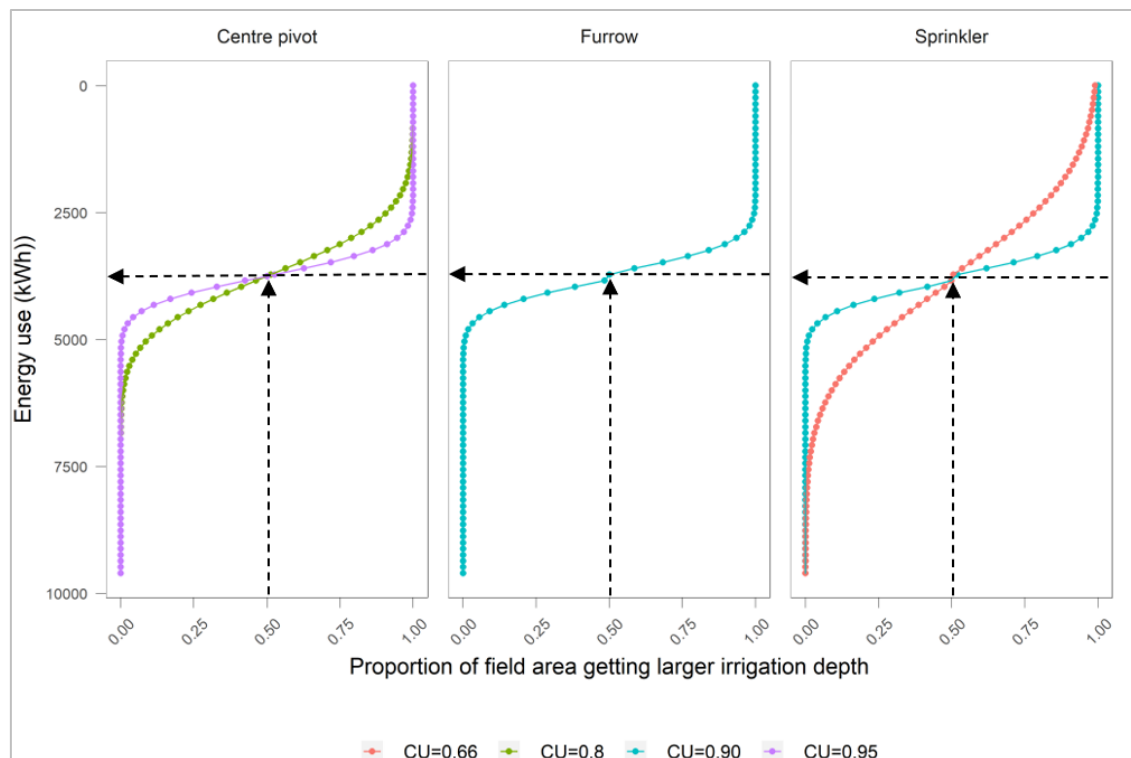


Figure 5-8: Energy use response to irrigation uniformity

5.3.1.4 Irrigation Uniformity Impact on Cane Yield

The cane yield response to irrigation uniformity is shown in Figure 5-9. This figure is identical to Figure 4-6, only that here an extension has been made to compare cane yields under the observed and improved irrigation uniformities for each respective irrigation system. The red arrows show the observed uniformity for each of the systems and their corresponding field average cane yields while the black dotted arrows indicate the improved irrigation uniformity and the associated cane yields. The results show that under the observed irrigation uniformities for each of the systems, centre pivot system yields 146.05 t/ha, furrow system yields 145.13 t/ha and 150.62 for the sprinkler system. Improving the irrigation uniformity to the respective levels under of the system, would improve the cane

yields to 151.18 t/ha under centre pivot, 145.13 t/ha in furrow system and 155.68 t/ha for the sprinkler system.

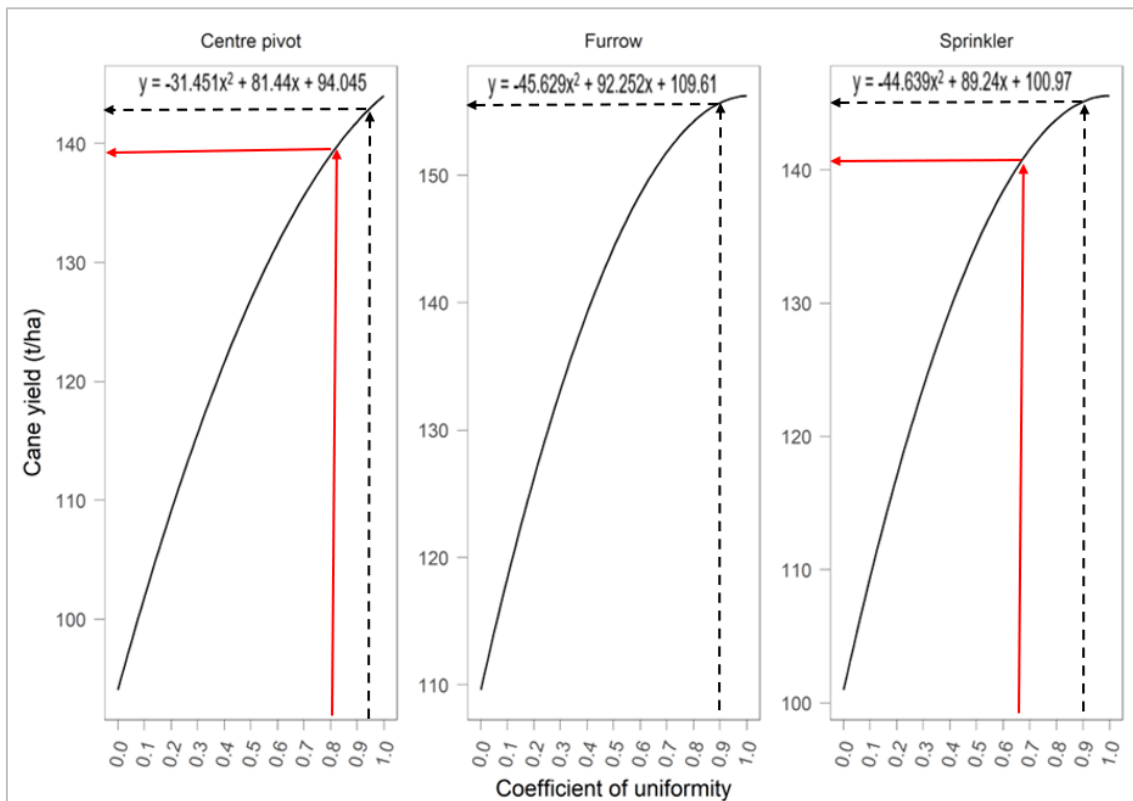


Figure 5-9: Cane yield improvement as a result of improvements in irrigation uniformity for the respective irrigation systems.

5.3.2 Economic Analysis

5.3.2.1 Cost and Revenue Functions

It was established that the estate pays 0.02 MK/m³ for every volume of water abstracted, 0.24 MK/m³ for energy use and 5.95 MK/m³ for labour in centre pivot operation, 3.57 MK/m³ for labour used in furrow system and 5.89 MK/m³ for labour use in sprinkler system. The difference in labour charges is due to differences in the flowrates and labour requirement for each of the systems. As could be observed, sprinkler system is more labour cost effective (5.89 MK/m³) than centre pivot (5.95 MK/m³) despite having lower flowrate (200 m³/h) than centre pivot's 360 m³/h – this is because centre pivot system at Nchalo estate had a higher labour requirement (5 man-days per shift) than sprinkler system's 4

man-days per shift. Thus, the marginal variable cost for each system was estimated by adding up the respective unit costs of water, energy and labour (Table 5-2). The cost functions for centre pivot, furrow and sprinkler systems are as indicated in equations (19), (20) and (21), respectively (the w is the amount of irrigation water abstracted and applied to the growing crop in mm).

Figure 5-10 shows the relationship between irrigation uniformity and irrigation water use. As can be observed, at 50% irrigation uniformity the farmer would be required to abstract and apply about 12000 mm to meet the full irrigation requirements for growing cane in an attempt to achieve maximum yields. Putting this in context, it would mean spending about 745, 200 MK/ha on centre pivot irrigation, an amount six times higher, due to poor irrigation uniformity. While the feasibility of irrigating 12000 mm in a season might not be attainable due to practical limitations, this, however, gives an indication of the extent and significance to which poor irrigation uniformities impact on irrigation water use and cost of water.

Equations (22), (23) and (24) are the cost functions expressed in terms of CU. These were generated by transforming the cost functions (equations (19), (20) and (21)) using the relationship between irrigation water application and irrigation uniformity as shown in Figure 5-10.

Table 5-2: Marginal variable costs (units) under each irrigation system

Irrigation System	Marginal Variable Cost (MK/m³)	Marginal Variable Cost (MK/mm)
Centre pivot	6.21 (£0.005 per m ³)	62.1 (£0.05 per mm)
Furrow	3.59 (£0.003 per m ³)	35.9 (£0.03 per mm)
Sprinkler	6.15 (£0.005 per m ³)	61.5 (£0.05 per mm)

$$C(w) = 62.1w + 0 \quad (19)$$

$$C(w) = 35.7w + 0 \quad (20)$$

$$C(w) = 61.5w + 0 \quad (21)$$

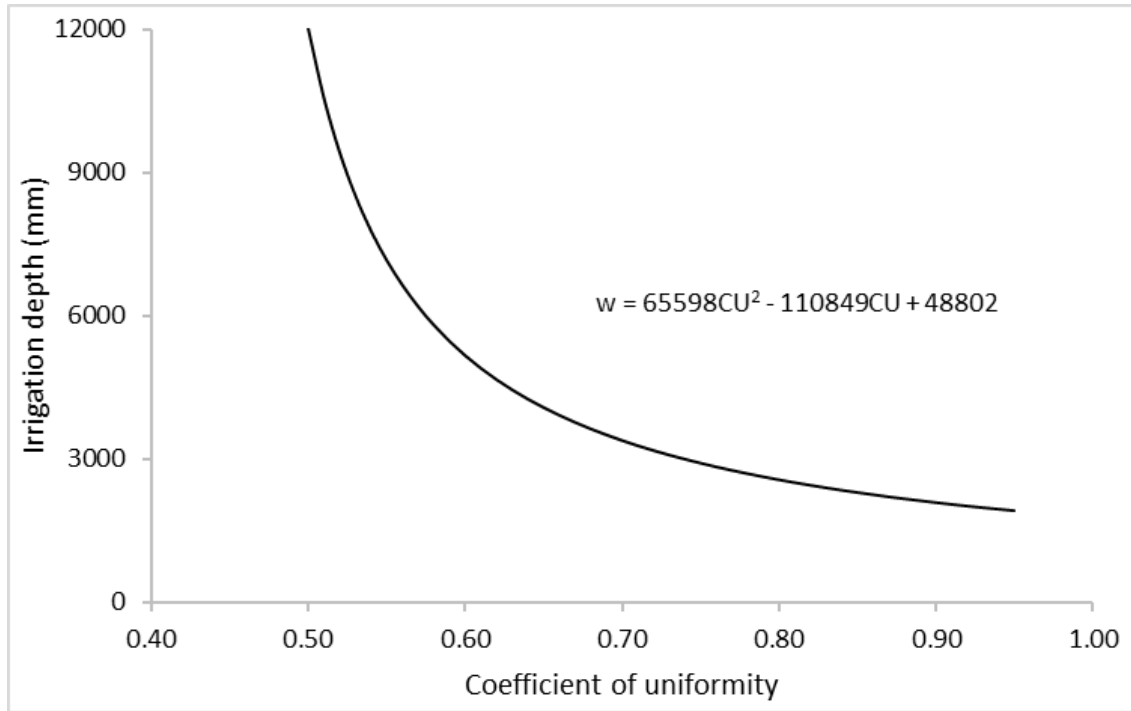


Figure 5-10: Relationship between irrigation application depth and irrigation application uniformity.

$$C(CU) = 4073635.8CU^2 - 6883722.9CU + 3030604.2 \quad (22)$$

$$C(CU) = 2341848.6CU^2 - 3957309.3CU + 1742231.4 \quad (23)$$

$$C(CU) = 4034277.0CU^2 - 6817213.5CU + 3001323.0 \quad (24)$$

The sugar recovery percentage was incorporated into the yield response to irrigation uniformity function for each system as shown in Figure 5-7 to generate the respective revenue function. It was established from the Nchalo estate records that the estate recovers sugar from the sugarcane at 13% on average while the prevailing selling price for the sugar was 1,031,491.08 MK/t. The

revenue functions for each of the centre pivot, furrow and irrigation systems are indicated by equations (25), (26 and (27, respectively. It is important to note that the equations are only valid as long as CU is greater than zero.

$$R(CU) = -3075039.95CU^2 + 9966256.5CU + 13579683.2 \quad (25)$$

$$R(CU) = -5985814.94CU^2 + 11966534.3CU + 13539455.1 \quad (26)$$

$$R(CU) = -6118567.84CU^2 + 12370425CU + 14698025.8 \quad (27)$$

5.3.2.2 Revenue and Net Returns Maximising Irrigation Depths

The yield and returns maximising irrigation depths are shown in Figure 5-11. As can be observed, the figure shows that the maximum revenue (19,570,716 MK/ha – about £15,124 per ha) could be attained when a total of 1541 mm of irrigation water was applied (solid curved line). On the other hand, the average net return could be maximised at 100 mm of irrigation depth with a corresponding average net return of 16,133 MK/mm – about £12.5 per mm (dotted straight line).

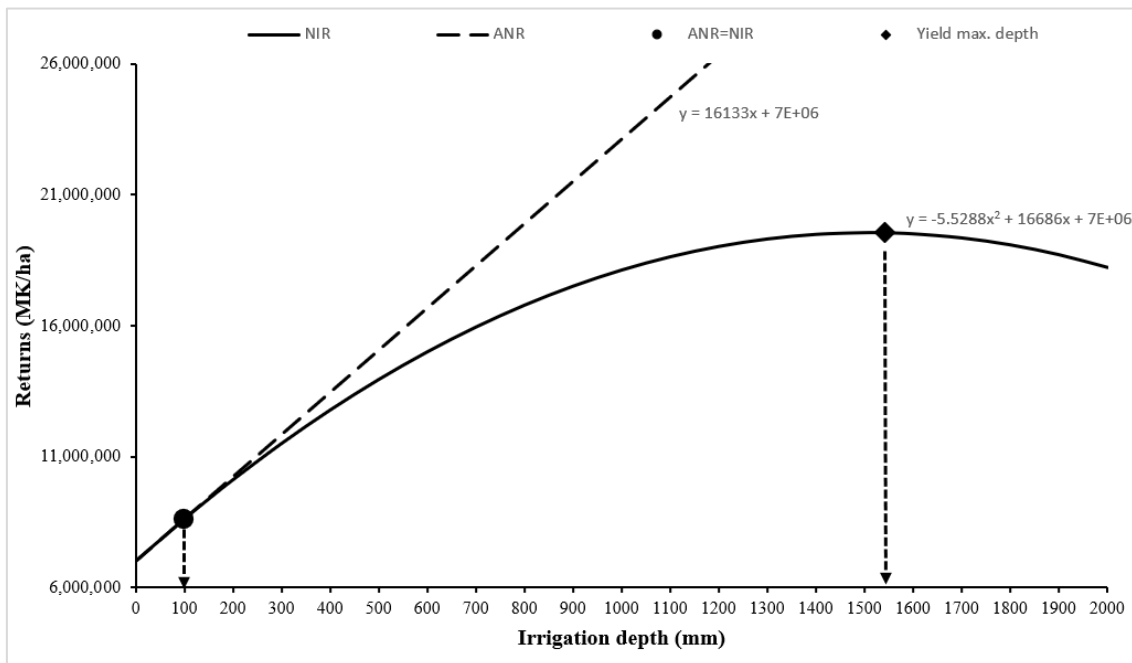


Figure 5-11: Net returns and average net returns on irrigation as a function of irrigation application depth

5.4 Discussion

The irrigation systems evaluation has shown that all the sprinkler fields that showed non-normality were evaluated in windspeeds range between 8 and 11 km/h. While wind speed impacts on the uniformity of irrigation water application (Faria et al., 2015; Dukes, 2006), the wind speed ranges under which the evaluation was conducted did not qualify for a range that could render the results invalid (ASEA, 2001). On the other hand, the furrow fields that showed non-uniformity in water distribution were those whose furrow length ranged between 180 and 210 m. This shows that furrow length has an impact on water distribution patterns. Overall, the results on the irrigation systems evaluation indicate that under normal operating conditions (pressure, wind speed, sprinkler spacing configuration, furrow length; among other factors), spatial distribution of irrigation water follows a normal distribution.

Further, both the CU and DU values from the system evaluation show that only sprinkler system fell below the attainable CU ranges reported by Burt et al., (1997); Clemmens & Dedrick, (1994) and Reinders, (1996). Although the wind speed conditions, under which the evaluation of the sprinkler system performance was conducted, might have had some impacts on the accuracy of the CU, Moazed et al., (2010) established no significant decrease in CU for wind speed below 7 m/s (25 km/h). This entails that, despite the impact of wind speed, the observed CU values under the sprinkler system were a true reflection of the performance of the system.

All the irrigation systems were found to apply less irrigation water depth than their respective design capacities. Non-uniform irrigation application coupled with inadequate irrigation water leads to compound yield losses. This means that even though the irrigation application uniformity could be improved, there is also a need to ensure that the adequacy of irrigation water application is also achieved.

Improving irrigation uniformities for each of the systems to the respective levels (95% for centre pivot, 90% each for furrow and sprinkler) would reduce irrigation water use by 30% in centre pivot and 90% in sprinkler system while striving to

supply full crop requirement depth to each part of the field. It would also see the energy use for irrigation reduced by 34% in centre pivot and 87% in sprinkler system while the cane yields would improve by 5.13 t/ha in centre pivot and 5.06 t/ha in sprinkler system.

In monetary terms, the improvement in irrigation uniformity would reduce irrigation related costs by 37,260 MK/ha (about £29 per ha) in centre pivot and 110,700 MK/ha (£86 per ha) in sprinkler system. Similarly, the improvement in irrigation uniformity would improve revenue by an additional 709,068 MK/ha (£548 per ha) in centre pivot system and 699,392 MK/ha (£540 per ha) in sprinkler system.

When water is not a limiting factor of production, yields would be maximised when 1541 mm is applied to the cane. This is the level of irrigation that would maximise the net return on irrigation an equivalent of 19,570,716 MK/ha (£15,124 per ha). On the other hand, the water use efficiency relative to average net returns were maximized at 100 mm. This means that water would be more of a limiting factor of cane production when the available water is less than 100 mm. At this point, the farmer would have to switch attention from maximising total returns by targeting to produce maximum yields to maximising the average net returns on every depth of water applied. Both the yield and average net returns maximising irrigation depth are in strong agreement with the findings reported by Banda et al. (2019).

5.5 Conclusions

It was established that the irrigation systems at Nchalo estate apply irrigation water with varying levels of uniformity and adequacy significantly different from one system to another. It was also established that the sprinkler irrigation system applied irrigation water with the lowest uniformity among the three irrigation systems while furrow system had the highest application uniformity. On average, the estate foregoes about 5.13 t/ha of cane yield in centre pivot and 5.06 t/ha in sprinkler system, by operating the systems at the observed levels of irrigation uniformities. Improving the operating levels of irrigation uniformity to the maximum attainable levels of uniformity would also reduce water use by 30% in

centre pivot and 90% in sprinkler system while the energy use would be reduced by 34% in centre pivot and 87% in sprinkler system. Similarly, by operating at the observed levels of irrigation uniformity, the estate forgoes revenue equivalence of about 709,067.60 MK/ha (£548 per ha) in centre pivot system and 699,392.21 MK/ha (£540 per ha) in sprinkler system while operating at the level that costs the estate additional 37,260 MK/ha (£29 per ha) in centre pivot and 110,700 MK/ha (£86 per ha) in sprinkler system.

Chapter 6. DISCUSSION

The overall aim of this PhD research was to evaluate the agronomic, environmental and economic impacts of improving irrigation uniformity in sugarcane production in sub-Saharan Africa (SSA). This was necessitated by the economic importance of the sugarcane crop and the need to maintain sustainable irrigated sugarcane production in the face of dwindling water resources and intense competition for the same water resources among disciplines.

The research set out to address the following key questions:

- i. Are there irrigation related opportunities for improving cane yields, water and energy use and productivity in SSA?
- ii. How does irrigation non-uniformity impact on cane yields, water and energy use and water productivity?
- iii. How does implementation of interventions to improve irrigation uniformity in the sugarcane industry in sub-Saharan Africa impact on the agronomic and economic benefits?

The overall aim of the research was addressed by:

- i. identifying irrigation-related performance gaps. This was done by benchmarking irrigation management practices across selected sugarcane estates in SSA. Among the irrigation related performance gaps that were identified included low irrigated yields, high irrigation water use and low water productivities. High irrigation water uses and low water productivities are likely a sign of poor irrigation management practices including poor scheduling techniques and inefficient irrigation systems. Irrigation non-uniformity is among the factors that make an irrigation system inefficient (Kranz, n.d.) and results in low yields (Pérez-Ortolá et al., 2015; Reinders, 1996) and high irrigation water use (Clemmens & Molden, 2007) thus, leading to low water productivity.
- ii. An irrigation systems evaluation was, thus, conducted across the different systems of irrigation on a case-study sugar estate in Malawi to establish the levels of irrigation uniformity with which the systems apply water. The impacts

of the irrigation non-uniformity on cane yields, water use and productivity were assessed through crop modelling. Cane yield response to varying levels water and uniformity was modelled using DSSAT Canegro coupled with a water balance model. The simulated cane yields associated with improved irrigation uniformity was compared with corresponding yields associated with the observed irrigation uniformities under each irrigation system.

- iii. Finally, the economic benefits associated with the implementation of the irrigation uniformity improvements were then evaluated, with the established impacts of irrigation non-uniformity on cane yields, water use and productivity in mind.

6.1 Agronomic Impacts of Irrigation Non-Uniformity

The modelling of yield response to water showed that yield decreases with irrigation non-uniformity and vice-versa. Similar trends were previously established in sugarcane (Baillie, 2004; Reinders, 1996), onions (Pérez-Ortolá et al., 2015), barley (El-Wahed et al., 2016) and lettuce (Brennan & Calder, 2006). On average, percent change in irrigation uniformity resulted in a 0.3% change in cane yield. This was in agreement with results reported by Baillie (2004), Reinders (1996) and Solomon (1998). The reduction in cane yields, as a function of irrigation non-uniformity, is a result of agronomic impacts of under and/or over-irrigation (nutrient leaching due to deep percolation – in the overirrigated areas, poor aeration in the root zone due to water stagnation – in the overirrigated areas, water stress due to inadequate water supply – in the inadequately irrigated areas, proliferation of pests and diseases due to water logging – in the overirrigated areas, salinity due to the rise of the water table – in the overirrigated areas). Poor irrigation uniformities widen the gap in irrigation application depths between the areas of the field that get at least the target application depth (adequately irrigated) and those that get less than the target application depth (inadequately irrigated). The differences in water application depths due to poor irrigation uniformity, also result in corresponding yield differences across the field which also widens with poor irrigation uniformity and thus resulting in low yield averages at the field scale. Further, when compared to potential performance indicators

reported in literature, actual indicators characterise SSA as a region of low water productivities with yields that are less than the world-wide good yield mark. Svendsen et al. (2009) reported that average sugarcane water productivities for Eswatini, Malawi, Tanzania and Zambia were 14.20 kg/m³, 11.56 kg/m³, 10.24 kg/m³ and 12.55 kg/m³ respectively. The estimated water productivities for all five estates were 4.96 kg/m³, 5.09 kg/m³, 7.52 kg/m³, 5.93 kg/m³ and 7.22 kg/m³ for Dwangwa, Kilombero, Nakambala, Nchalo and Ubombo estates, respectively. The estimated water productivities are less than the reported potential productivities for corresponding country. This is in agreement with Ritchie, (2022), Mukasa et al., (2017), Zamanillo et al., (2017) and Sadras et al., (2015) who also characterised SSA as a region of very low crop, land and water productivities relative to other regions.

While it is expected to have variations in cane yields and irrigation water use due to variations in climate, soils and potential yields across the region, significant differences in water productivity are not expected in irrigated cane production where proper irrigation water management practices are followed – proper irrigation water management practices ensure maximum yield benefit from irrigation, which should not significantly change with location. The variations in water productivity in the irrigated cane production is a sign that yield benefits from irrigation is not maximised (in the estates with low water productivities) due to poor irrigation water management practices (including poor scheduling and/or inefficient irrigation systems). However, such variations provide an avenue for performance improvement. While improvement in yields would accelerate the closure of the yield gap, which is wider in SSA (Mukasa et al., 2017; Ritchie, 2022; Sadras et al., 2015); improving water productivity would likely lead to efficient utilisation of irrigation water and maximising the yield benefits from irrigation and thus, avoiding incurring unnecessary irrigation related costs and maximising returns on production in the process.

Improved irrigation uniformity by itself is not guarantee for improved yields and water productivity. To fully benefit, it is important to ensure that other irrigation management practices, including appropriate irrigation scheduling practices, are

within acceptable ranges of performance. For example, a farmer who always applies irrigation water off-schedule would likely miss out on the benefits of improved irrigation uniformity no matter how good the irrigation uniformity is. It is therefore important that irrigated sugarcane production entities/estates should include irrigation related KPIs (including correct irrigation scheduling, relative irrigation supply, uniformity of irrigation water application and water productivity) in their performance monitoring metrics in order to enhance sustainability and productivity of the irrigated sugarcane production. Performance appraisals of farm managers at Nchalo estate where the major part of the thesis was carried out, as an example, dwell much on the tonnage of cane produced at the end of the cropping season while irrigation performance related metrics are not scrutinised in detail. Paying little attention to details of irrigation related performance indicators would likely lead to under/over-irrigation and thus under-exploitation of irrigation related yield benefits leading to low water productivities and poor returns on irrigated cane production.

The modelling of the impacts of irrigation non-uniformity on cane yields, irrigation water and energy use was generally based on CU values derived from field tests of a single event. Clemmens & Molden, (2007) indicated that water application variations due to an irrigation system's non-uniform application tend to be systematic and without overruling presence and occurrence of some randomness, the random tendence tend to be too insignificant to overshadow the systematic pattern. This entails that a field area that receives inadequate water during one irrigation event would still have a water deficit in the subsequent irrigation events. By extension, this also means that CUs drawn from a single event, might not be significantly different from CUs drawn from multiple events.

6.2 Environmental Impacts of Irrigation Non-Uniformity

The research showed that irrigation uniformity has potential benefits to the irrigated sugarcane production industry including reducing irrigation water and energy use. Similar benefits were also reported by Brennan, (2008), Brennan & Calder, (2006), Clemmens & Molden, (2007), as well as El-Wahed et al., (2016). Irrigation uniformity impacts on the distribution of irrigation water across the fields.

The modelling of the irrigation water distribution across the field showed that poor irrigation uniformities do not only reduce field-scale yield averages, it also widens the gap (in irrigation application depth) between the adequately and the inadequately irrigated areas; leading to water wastage in areas of the field that receive more than the target application depth (over-irrigation). Over-irrigation is undesirable as it is an indication of inefficient irrigation management practice that has a potential to waste water. Over-irrigation leads to surface runoff, and nutrient leaching due to deep percolation. All these are associated with potential increased environmental risks.

Surface runoff also contributes to erosion of topsoil, chemicals and/or undissolved fertilizers applied on the soil surface. The erosion of the topsoil and washing away of chemicals and fertilizers respectively lead to siltation and pollution of water channels and/or water bodies, leading to reduced capacities of water bodies and surface water quality degradation. Another common problem associated with soil erosion is eutrophication – significant growth of algae and other aquatic plants due to nutrient-enrichment of water bodies that leads to low levels of dissolved oxygen (Chislock et al., 2013). Eutrophication inhibits light penetration thereby causing die-offs of aquatic plants in the littoral zone, depletes inorganic carbon due to high levels of photosynthesis and raises pH to extreme levels – impacting the survival of pH sensitive aquatic organisms (Chislock et al., 2013). Deep percolation, on the other hand, leads to contamination of ground water resources as a result of nutrient/chemical leaching (Bayabil et al., 2022). Deep percolation could also lead to rising of the water table, which has a potential to cause salinity (Saidi & Hammami, 2016).

6.3 Economic Impacts of Irrigation Non-Uniformity

High irrigation uniformities reduced irrigation water used and variations in water application across the field which in turn resulted in uniform yield distribution across the field leading to high yield average across the field (Brennan, 2008; Brennan & Calder, 2006; El-Wahed et al., 2016; López-Mata et al., 2010; Nascimento et al., 2019; Ortega Álvarez et al., 2004). In this research, for example, a 10% improvement in irrigation uniformity (from 80% to 90%) led to

reduction in modelled water use by an average of 30% in centre pivot and a 30% (from 60% to 90%) improvement in uniformity under sprinkler system led to 90% reduction in irrigation water use while the cane yields improved by 5.13 t/ha in centre pivot and 5.06 t/ha in sprinkler system. The increase in yield means improved total returns and the reduction in water use has potential to reduced irrigation related costs including energy and labour for irrigation operation. The increase in total returns and reduced irrigation related costs led to wider gross margin (Ortega Álvarez et al., 2004). Energy use was reduced by 34% under the centre pivot system and 87% for the sprinkler system in response to 10% and 30% improvements in irrigation uniformity (from 80% to 90% and 60% to 90% in the respective irrigation systems), respectively. Consequently, the irrigation-related costs were reduced by 37,260 MK/ha in centre pivot and 110,700 MK/ha in sprinkler system and the revenue improved by an additional 709,068 MK/ha and 699,392 MK/ha in centre pivot and sprinkler system respectively.

6.4 Methodological Limitations

The methodological approaches employed in this research, as with any other modelling-based research, were informed by data availability. Efforts were made to ensure that appropriate methods were used based on the available data that was of high quality. In this research the financial and environmental indicators were not considered for the benchmarking exercise because the focus was mainly on irrigation management practices. While financial and environmental parameters are equally important indicators for irrigation systems performance, they were considered to be influenced by and dependent on irrigation water management practices. Thus, no attempt was made to collect appropriate datasets for the estimation of financial and environmental KPIs for the benchmarking exercise. The exclusion of the financial and environmental performance indicators in the benchmarking means that the research did not draw a conclusively dissected performance picture of the estates. Thus, there might have been a chance of reporting under-performance of some estates that are performing highly or obscuring an opportunity for improvement in the excluded performance indicators.

The DSSAT Canegro model requires some parameters that are not easily attainable outside experimental setup. Due to the nature of the study site (commercial sugar estate), some data for crop modelling were not readily available. Data on crop coefficients related to cultivar parameters that regulate partitioning of biomass, growth and development of canopy and phenological phasing (Singels et al., 2008), were not available. Such data is mostly acquired from experimental trials. Cultivar coefficients are a requirement input parameter for the DSSAT Canegro model and parameterisation of the cultivar coefficients improves model performance (Coelho et al., 2020). However, the unavailability of such data necessitated the use of default crop coefficients of a reference cultivar for the modelling.

While five estates were involved in benchmarking of irrigation management practices – to identify opportunities for performance improvement, the conclusions on the impacts of irrigation non-uniformity on cane yields, water and energy use and productivity were based on a single estate. This was due to practicality of conducting the assessment in all the estates within the 3-year timeline allocated for the research. It is important to note, however, that while the general trend in cane yield response to varying water and uniformity levels has a general application, the extent of the yields, water productivity and revenue improvement as well as the irrigation water and energy use and cost reductions, as a result of improvements in irrigation uniformity, are site specific and prevailing economic conditions (including cost of water, labour, energy and prices of sugar). Thus, improving irrigation uniformity might be economically viable option in some estates and not in others.

6.5 Areas for Future Research

Future research should aim at building on the scope and findings of this research while addressing the shortcomings of the methodological approaches used in this research. Thus, future research prospects should aim to (i) benchmark the performance of irrigation systems in the selected estates using financial and environmental performance indicators – this would likely develop an exhaustive understanding of opportunities for performance improvement in the cane

production, (ii) calibrate and validate the performance of the DSSAT model by firstly determining and parameterising the DSSAT Canegro cultivar-related parameters based on the study site and (iii) provide answers regarding irrigation uniformity improvement options, associated cost of uniformity improvement for each option and develop a framework for deciding the best option for given prevailing economic conditions.

Irrigation system performance, rather than irrigation system type, significantly affect cane yields (Mudima, 2002). It is for this reason that the key findings highlighted in thesis cannot be the basis for switching from one irrigation system to another. However, choice of irrigation system should be guided by such factors as they relate to physical, social, economic and environmental considerations.

Chapter 7. CONCLUSIONS

The research set out to provide answers to three questions that were key to the accomplishment of the aim of the study. The questions and their corresponding conclusions are as outlined in the subsequent paragraphs:

- i. Are there irrigation related opportunities for improving cane yields, water and energy use and productivity in SSA?*

It was established that there were opportunities to improve performance of irrigated cane production in the SSA region. Benchmarking of irrigation management practices, that was employed to identify opportunities for improving cane yields, water and energy use and productivity in selected countries in the region established that cane production is characterised by low cane yield averages that were below the 'good yield' mark reported in the literature that ranged between 84 t/ha and 109 t/ha, high irrigation water uses and water productivities lower than respective potentials that ranged between 5.0 kg/m³ and 7.8 kg/m³. Thus, the SSA region offers opportunities for the improvement of cane yields and water productivity as well as reduce irrigation water and energy use through improvement of irrigation system performance. The null hypothesis (there are no opportunities for improvement of cane yields, water and energy use and productivity in SSA) is rejected.

- ii. How does irrigation non-uniformity impact on cane yields, water and energy use and water productivity?*

Irrigation non-uniformity reduces field-average yields while increasing irrigation water and energy requirements. This implies that irrigation systems that operate at low uniformities are likely to lead to low field average crop yields, high irrigation water and energy uses and low water productivities, that lead to high irrigation related costs. The modelling of cane yield response to varying irrigation uniformities using DSSAT Canegro model coupled with a water balance model showed that a percentage change in irrigation uniformity changed average cane yield between a range of 0.2 t/ha and 0.5 t/ha and reduced both irrigation water and energy use by 3%. This finding satisfied the condition for the rejection of the

null hypothesis that stated that irrigation non-uniformity has no impact on cane yield, water and energy use and productivity.

- iii. *How does implementation of interventions to improve irrigation uniformity in the sugarcane industry in sub-Saharan Africa impact on the agronomic and economic benefits?*

The implementation of irrigation uniformity improvement interventions improves crop yields, reduces water and energy use and irrigation-related costs and thus leading to the rejection of the null hypothesis that stated that implementation of irrigation uniformity improvement interventions does not have agronomic, environmental and economic benefits. The agronomic and financial benefits of implementing irrigation uniformity improvement interventions; assessed using a combination of DSSAT Canegro model, water balance model and an economic model; showed that a percentage improvement in irrigation uniformity improved revenue by a range between 23,300 MK/ha and 70,900 MK/ha (about £18 – 65/ha) and reduced irrigation-related costs by 3,700 MK/ha (about £3/ha).

Overall, the research has contributed to science and knowledge of practice by developing new methodologies, establishing new findings and confirming already known theoretical knowledge and empirical evidence. In this research, two new methodological approaches were developed. One method combined the capabilities of DSSAT Canegro in simulating cane yield response to water and Martin et al., (2010) enhanced water balance model to simulate the impacts of irrigation non-uniformity on cane yields, water and energy use and productivity. The other method involved the integration of a financial model to determine the impact of irrigation non-uniformity on marginal returns. These methodological approaches were used and integrated in a novel way for the first time to study cane yield response to water and the financial impacts of irrigation uniformity on cane yields, water and energy yields.

This research has also provided new empirical evidence on the impacts of irrigation non-uniformity on yields, water and energy use, water losses and irrigation costs, revenues and returns. These are important for understanding options and responses associated with addressing agronomic and economic

factors linked to low irrigation uniformity. Finally, the research confirmed that there is a declining trend in cane yields in SSA (FAOSTAT, 2022). It also confirmed that irrigation application depths across fields typically follow a normal distribution and that the application uniformities of overhead irrigation systems are affected by wind speed and direction (Dukes, 2006; Faria et al., 2015, 2019) and operating pressure (El-Wahed et al., 2016; Maroufpoor et al., 2010) while the application uniformity of surface irrigation systems are also affected by furrow length (Burt et al., 1997).

REFERENCES

- Ainsworth, E. A., & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO₂]: Mechanisms and environmental interactions. *Plant, Cell and Environment*, 30(3), 258–270. <https://doi.org/10.1111/j.1365-3040.2007.01641.x>
- Ali, M. H., & Talukder, M. S. U. (2008). Increasing water productivity in crop production—A synthesis. *Agricultural Water Management*, 95(11), 1201–1213. <https://doi.org/10.1016/j.agwat.2008.06.008>
- Andarzian, B., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M. E., Barati, M. A., & Rahnama, A. (2011). Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agricultural Water Management*, 100(1), 1–8. <https://doi.org/10.1016/j.agwat.2011.08.023>
- Andersson, E., Arfwidsson, O., & Thollander, P. (2018). Benchmarking energy performance of industrial small and medium-sized enterprises using an energy efficiency index: Results based on an energy audit policy program. *Journal of Cleaner Production*, 182, 883–895. <https://doi.org/10.1016/j.jclepro.2018.02.027>
- APSIM-Initiative. (2021). *How do I download APSIM?* <https://www.apsim.info/download-apsim/downloads/>
- ASEA. (2001). Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles. In *ANSI/ASAE Standard S436.1*. American Society of Agricultural Engineers.
- Bahmani, O., & Eghbalian, S. (2018). Simulating the Response of Sugarcane Production to Water Deficit Irrigation Using the AquaCrop Model. *Agricultural Research*, 7(2), 158–166. <https://doi.org/10.1007/s40003-018-0311-0>
- Baillie, C. (2004). *Strategies for Maximising Sugarcane Yield with Limited Water in the Bundaberg District* [University of Southern Queensland]. https://eprints.usq.edu.au/1406/2/baille_craig_2004_whole.pdf

- Banda, M. M. (2019). *Economic Analysis of Deficit Irrigation in Sugarcane Farming Nchalo Estate, Chikwawa District in Malawi*. University of Nebraska - Lincoln (UNL).
- Banda, M. M., Heeren, D. M., Martin, D. L., Munoz-Arriola, F., & Hayde, L. G. (2019). Economic analysis of deficit irrigation in sugarcane farming: Nchalo Estate, Chikwawa District, Malawi. *2019 ASABE Annual International Meeting*. <https://doi.org/10.13031/aim.201900852>
- Bayabil, H. K., Guzman, S. M., Zazueta, F. S., & Haman, D. Z. (2022). Potential Impacts of Improper Irrigation System Design. *EDIS*, 2022(4). <https://doi.org/10.32473/edis-ae027-2022>
- Bezuidenhout, C. N., Singels, A., & Hellmann, D. (2002). Whole farm harvesting strategy optimisation using the CANEGRO model: a case study for irrigated and dryland sugarcane. *Proceedings of The South African Sugar Technologists' Association*, 250–259.
- Bhave, A. G., Bulcock, L., Dessai, S., Conway, D., Jewitt, G., Dougill, A. J., Kolusu, S. R., & Mkwambisi, D. (2020). Lake Malawi's threshold behaviour: A stakeholder-informed model to simulate sensitivity to climate change. *Journal of Hydrology*, 584, 124671. <https://doi.org/10.1016/j.jhydrol.2020.124671>
- Bhave, A. G., Conway, D., Dessai, S., Dougill, A. J., & Mkwambisi, D. (2022). Stress-testing development pathways under a changing climate: water-energy-food security in the lake Malawi-Shire river system. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 380(2221). <https://doi.org/10.1098/rsta.2021.0134>
- Borgia, C., García-Bolaños, M., Li, T., Gómez-Macpherson, H., Comas, J., Connor, D., & Mateos, L. (2013). Benchmarking for performance assessment of small and large irrigation schemes along the Senegal Valley in Mauritania. *Agricultural Water Management*, 121, 19–26. <https://doi.org/10.1016/j.agwat.2013.01.002>

- Bouman, B. A. M., van Keulen, H., van Laar, H. H., & Rabbinge, R. (1996). The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. *Agricultural Systems*, 52(2–3), 171–198. [https://doi.org/10.1016/0308-521X\(96\)00011-X](https://doi.org/10.1016/0308-521X(96)00011-X)
- Brennan, D. (2008). Factors affecting the economic benefits of sprinkler uniformity and their implications for irrigation water use. *Irrigation Science*, 26(2), 109–119. <https://doi.org/10.1007/s00271-007-0077-9>
- Brennan, D., & Calder, T. (2006). The economics of sprinkler irrigation uniformity: A case study of lettuce on the Swan Coastal plain. In *Water for a Healthy Country National Research Flagship*. CSIRO.
- Burt, C. M., Clemmens, A. J., Strelkoff, T. S., Solomon, K. H., Bliesner, R. D., Hardy, L. A., Howell, T. A., & Eisenhauer, D. E. (1997). Irrigation Performance Measures: Efficiency and Uniformity. *Journal of Irrigation and Drainage Engineering*, 6(123), 423–442.
- Cai, X., & Rosegrant, M. W. (2003). *World Water Productivity : Current Situation and Future Options*. 163–178.
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., ... Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland*. (P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, J. Romero, J. Kim, E. F. Haïtes, Y. Jung, R. Stavins, ... C. Péan (eds.)). <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Carr, B. M. K. V., & Knox, J. W. (2011). The Water relations and irrigation requirements of Sugarcane (*Saccharum Officinarum*): A Review.

- Experimental Agriculture*, 47, 1–25.
<https://doi.org/10.1017/S0014479710000645>
- Cheeroo-Nayamuth, F. ., Robertson, M. ., Wegener, M. ., & Nayamuth, A. R. . (2000). Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. *Field Crops Research*, 66(3), 225–243.
[https://doi.org/10.1016/S0378-4290\(00\)00069-1](https://doi.org/10.1016/S0378-4290(00)00069-1)
- Chico Zamanillo, D., Zhang, G., & Mathews, R. (2017). Water footprint as an indicator of agricultural productivity in African countries. *19th EGU General Assembly*.
- 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>
- Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge*, 4(4)(10).
- Christiansen, J. E., Bishop, A. A., Kiefer, F. W., & Fok, Y. S. (1966). Evaluation of intake rate constants as related to advance of water in surface irrigation. *Trans. ASAE*, 9, 671–674.
- Clemmens, A. J., & Dedrick, A. R. (1994). *Irrigation Techniques and Evaluations* (pp. 64–103). https://doi.org/10.1007/978-3-642-78562-7_4
- Clemmens, A. J., & Molden, D. J. (2007). Water uses and productivity of irrigation systems. *Irrigation Science*, 25(3), 247–261. <https://doi.org/10.1007/s00271-007-0067-y>
- Clemmens, Albert J. (1992). Irrigation uniformity relationships for irrigation system management. *Journal of Irrigation and Drainage Engineering*, 117(5), 682–699.
- Cock, J. H. (2003). Sugarcane growth and development. *International Sugar Journal*, 105(1259), 540–552.

<https://doi.org/10.1080/02571862.1991.10634587>

Coelho, A. P., Dalri, A. B., Fischer Filho, J. A., Faria, R. T. de, Silva, L. S., & Gomes, R. P. (2020). Calibration and evaluation of the DSSAT/Canegro model for sugarcane cultivars under irrigation managements. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 24(1), 52–58. <https://doi.org/10.1590/1807-1929/agriambi.v24n1p52-58>

de Wit, C. T. (1958). Transpiration and crop yields. *Versl. Landbouwk. Onderz*, 6(64), 18–20. <http://www.cabdirect.org/abstracts/19601700379.html>

Devkotaa, K. P., Pasuquina, E., Elmido-Mabilangana, A., Dikitanana, R., Singletona, G. R., Stuarta, A. M., Vithoonjitb, D., Vidiyangkurac, L., Pustikad, A. B., Afrianid, R., Lia, C., Listyowatid, R. S. K., Keerthisenae, Kieuf, N. T., Julia, A. M., Hug, R., Panh, J., & Beebouta, S. E. J. (2019). Economic and environmental indicators of sustainable rice cultivation: A comparison across intensive irrigated rice cropping systems in six Asian countries. *Ecological Indicators*, 105, 199–214. <https://doi.org/10.1016/j.ecolind.2019.05.029>

Dewan, N. A., Daniels, A., Zieman, G., & Kramer, T. J. (2000). The National Outcomes Management Project: A Benchmarking Collaborative. *Journal of Behavioral Health Services & Research*, 4(27), 431–36.

Dias, H. B., & Sentelhas, P. C. (2017). Evaluation of three sugarcane simulation models and their ensemble for yield estimation in commercially managed fields. *Field Crops Research*, 213, 174–185. <https://doi.org/10.1016/j.fcr.2017.07.022>

Dias, H. B., & Sentelhas, P. C. (2019). Dimensioning the Impact of Irrigation on Sugarcane Yield in Brazil. *Sugar Tech*, 21(1), 29–37. <https://doi.org/10.1007/s12355-018-0619-x>

Dillon, E. J., Hennessy, T., & Hynes, S. (2009). Towards Measurement of Farm Sustainability – an Irish case study. *International Association of Agricultural Economists Conference*.

DSSAT Foundation. (2021). *Models Overview*. dssat.net/models-overview/

- Dukes, M. D. (2006). Effect Of Wind Speed and Pressure on Linear Move Irrigation System Uniformity. *Applied Engineering in Agriculture*, 22(4), 541–548. <https://doi.org/10.13031/2013.21222>
- Dumont, T., Thong-Chane, A., Barau, L., Siegmund, B., & Hoarau, J.-Y. (2019). Genetic Variabilities and Genetic Gains for Yield Components in Regional Sugarcane Breeding Programmes on Réunion Island. *Sugar Tech*, 21(6), 868–878. <https://doi.org/10.1007/s12355-019-00718-9>
- Eisenhauer, D. E., Martin, D. L., & Heeren, D. M. (2021). *Irrigation Systems Management* (G. J. Hoffman (ed.)). American Society of Agricultural and Biological Engineers. <https://doi.org/10.13031/ism.2021>
- El-Wahed, A. M. H., Medici, M., & Lorenzini, G. (2016). Sprinkler Irrigation Uniformity: Impact on the Crop Yield and Water Use Efficiency. *Journal of Engineering Thermophysics*, 21(1), 117–125.
- El Chami, D., Knox, J. W., Daccache, A., & Weatherhead, E. K. (2019). Assessing the financial and environmental impacts of precision irrigation in a humid climate. *Horticultural Science*, 46(1), 43–52. <https://doi.org/10.17221/116/2017-HORTSCI>
- English, M. (1990a). Deficit Irrigation. I: Analytical Framework. *Journal of Irrigation and Drainage Engineering*, 116(3), 399–412. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1990\)116:3\(399\)](https://doi.org/10.1061/(ASCE)0733-9437(1990)116:3(399))
- English, M. (1990b). Deficit Irrigation. I: Analytical Framework. *Journal of Irrigation and Drainage Engineering*, 116(3), 399–412. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1990\)116:3\(399\)](https://doi.org/10.1061/(ASCE)0733-9437(1990)116:3(399))
- English, M., & Raja, S. N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management*, 32(1), 1–14. [https://doi.org/10.1016/S0378-3774\(96\)01255-3](https://doi.org/10.1016/S0378-3774(96)01255-3)
- FAO. (2021). *AquaCrop, the crop-water productivity model*. <http://www.fao.org/aquacrop/software/en/>

- FAOSTAT. (2022). *FAOSTAT statistical database*. <http://www.fao.org/faostat>
- Faria, L. C., Beskow, S., Colombo, A., Nörenberg, B. G., Rettore Neto, O., & Simões, M. C. (2015). Influence of the wind on water application uniformity of a mechanical lateral move irrigation equipment using rotating plate sprinklers. *Ciência Rural*, 46(1), 83–88. <https://doi.org/10.1590/0103-8478cr20141558>
- Faria, L. C., Nörenberg, B. G., Colombo, A., Dukes, M. D., Timm, L. C., Beskow, S., & Caldeira, T. L. (2019). Irrigation distribution uniformity analysis on a lateral-move irrigation system. *Irrigation Science*, 37(2), 195–206. <https://doi.org/10.1007/s00271-019-00619-5>
- Fortes, P., Simoes, S. G., Armada Brás, T., & Amorim, F. (2022). Competing water uses between agriculture and energy: Quantifying future climate change impacts for the Portuguese power sector. *Journal of Cleaner Production*, 371, 133629. <https://doi.org/10.1016/j.jclepro.2022.133629>
- Frey, F. (2017). <sc>SPSS</sc> (Software). In *The International Encyclopedia of Communication Research Methods* (pp. 1–2). Wiley. <https://doi.org/10.1002/9781118901731.iecrm0237>
- Gerbens-Leenes, W., & Hoekstra, A. Y. (2012). The water footprint of sweeteners and bio-ethanol. *Environment International*, 40, 202–211. <https://doi.org/10.1016/j.envint.2011.06.006>
- Ghasemi, A., & Zahediasl, S. (2012). Normality Tests for Statistical Analysis: A Guide for Non-Statisticians. *International Journal of Endocrinology and Metabolism*, 10(2), 486–489. <https://doi.org/10.5812/ijem.3505>
- González Perea, R., Daccache, A., Rodríguez Díaz, J. A., Camacho Poyato, E., & Knox, J. W. (2018). Modelling impacts of precision irrigation on crop yield and in-field water management. *Precision Agriculture*, 19(3), 497–512. <https://doi.org/10.1007/s11119-017-9535-4>
- Greaves, K. R. (2007). *Quantifying and Benchmarking Irrigation Scheme Performance with Water Balances and Performance Indicators* [University of

KwaZulu-Natal]. <https://ukzn-dspace.ukzn.ac.za/handle/10413/1516>

Griffiths, B. (2007). *In-field Evaluation of Irrigation System Performance within the Sugarcane Industry of the Southern-East Lowveld in Zimbabwe*. University of KwaZulu-Natal.

Grinsven, H. J. M. van, Eerdt, M. M. van, Westhoek, H., & Kruitwagen, S. (2019). Benchmarking Eco-Efficiency and Footprints of Dutch Agriculture in European Context and Implications for Policies for Climate and Environment. *Frontiers in Sustainable Food Systems*, 3:13. <https://doi.org/10.3389/fsufs.2019.00013>

Heermann, D., Wallender, W., & Bos, M. (1990). Irrigation Efficiency and Uniformity. In *Management of Farm Irrigation Systems* (pp. 125–149). ASAE.

Heng, L. K., Hsiao, T., Evett, S., Howell, T., & Steduto, P. (2009). Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agronomy Journal*, 101(3), 488–498. <https://doi.org/10.2134/agronj2008.0029xs>

Herman, J. L., Osmundson, E., & Dietel, R. (2010). *Benchmark Assessment for Improved Learning (An AACC Policy Brief)*.

Hess, T., Aldaya, M., Fawell, J., Franceschini, H., Ober, E., Schaub, R., & Schulze-Aurich, J. (2014). Understanding the impact of crop and food production on the water environment—using sugar as a model. *Journal of the Science of Food and Agriculture*, 94(1), 2–8. <https://doi.org/10.1002/jsfa.6369>

Hess, T., Knox, J., Weatherhead, K., Stephens, W., & Kay, M. (2009). *Management of Irrigation for the Sugar Industry* (pp. 77–102). Cranfield University. www.cranfield.ac.uk

Hess, T., Sumberg, J., Biggs, T., Georgescu, M., Haro-Monteagudo, 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>
- Holzapfel, E. A., Mariño, M. A., & Chavez-Morales, J. (1985). Performance irrigation parameters and their relationship to surface-irrigation design variables and yield. *Agricultural Water Management*, 10(2), 159–174. [https://doi.org/10.1016/0378-3774\(85\)90004-6](https://doi.org/10.1016/0378-3774(85)90004-6)
- Holzworth, D. P., Huth, N. I., DeVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P. M., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., ... Keating, B. A. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, 62, 327–350. <https://doi.org/10.1016/j.envsoft.2014.07.009>
- Inman-Bamber, N. G. (1991). A growth model for sugar-cane based on a simple carbon balance and the CERES-Maize water balance. *South African Journal of Plant and Soil*, 8(2), 93–99. <https://doi.org/10.1080/02571862.1991.10634587>
- Inman-Bamber, N. G. (1994). Temperature and seasonal effects on canopy development and light interception of sugarcane. *Field Crops Research*, 36(1), 41–51. [https://doi.org/10.1016/0378-4290\(94\)90051-5](https://doi.org/10.1016/0378-4290(94)90051-5)
- Inman-Bamber, N. G. (1995). Climate and Water Constraints to Production to the South African Sugar Industry. *Proceedings of The South African Sugar Technologists' Association*, 55–59.
- Inman-Bamber, N. G. (2007). Economic impact of water stress on sugar production in Australia. In R. C. Bruce (Ed.), *Proceedings of the 2007 Conference of the Australian Society of Sugar Cane Technologists* (pp. 167–175). CSIRO Tropical Agriculture.
- Inman-Bamber, N. G., & McGlinchey, M. G. (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, N., Singels, A., & Muchow, R. (1998). A Systems Approach to Benchmarking for Sugarcane Production in Australia and South Africa. *Proc S Afr Sug Technol Ass.*
- IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*.
- Jaap, S., & Hendriks, M. (2004). Benchmarking the Quality of Education. *European Educational Research Journal*, 3(1), 101–114. <https://doi.org/10.2304/eerj.2004.3.1.2>
- James, L. G. (1993). *Principles of Farm Irrigation System Design*. Krieger Publishing Co. Klocke.
- Jiang, R., Wang, T., Shao, J., Guo, S., Zhu, W., Yu, Y., Chen, S., & Hatano, R. (2017). Modeling the biomass of energy crops: Descriptions, strengths and prospective. *Journal of Integrative Agriculture*, 16(6), 1197–1210. [https://doi.org/10.1016/S2095-3119\(16\)61592-7](https://doi.org/10.1016/S2095-3119(16)61592-7)
- Jones, M. R., Singels, A., Chinorumba, S., Poser, C., Christina, M., Shine, J., Annandale, J., & Hammer, G. L. (2021). Evaluating process-based sugarcane models for simulating genotypic and environmental effects observed in an international dataset. *Field Crops Research*, 260, 107983. <https://doi.org/10.1016/j.fcr.2020.107983>
- Jones, M. R., Singels, A., & Ruane, A. C. (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>
- Jury, M. R. (2014). Malawi's Shire River Fluctuations and Climate. *Journal of Hydrometeorology*, 15(5), 2039–2049. <https://doi.org/10.1175/JHM-D-13-0195.1>

- Kamphoni, A. (2022). *Illovo Sugar Malawi Company Report*.
- Kara, T., Temizel, K. E., & Apan, M. (2008). Using Empirical Equations to Determine Appropriate Furrow Length Under Field Condition. *Pakistan Journal of Biological Sciences*, 11(2), 220–225. <https://doi.org/10.3923/pjbs.2008.220.225>
- Karimi, P., Bongani, B., Blatchford, M., & de Fraiture, C. (2019). Global satellite-based ET products for the local level irrigation management: An application of irrigation performance assessment in the Sugarbelt of Swaziland. *Remote Sensing*, 11(6). <https://doi.org/10.3390/rs11060705>
- Keating, B. ., Robertson, M. ., Muchow, R. ., & Huth, N. . (1999). Modelling sugarcane production systems I. Development and performance of the sugarcane module. *Field Crops Research*, 61(3), 253–271. [https://doi.org/10.1016/S0378-4290\(98\)00167-1](https://doi.org/10.1016/S0378-4290(98)00167-1)
- 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., E, M. S., 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, 267–288.
- KfW Development Bank. (2020). *The Renewable Energy Transition in Africa: Powering Access, Resilience and Prosperity*.
- Klausmeyer, K. J. (2005). *Irrigation Water Management*. nrcs.usda.gov/wps/portal/nrcs/detail/ks/newsroom/features/?cid=nrcs142p2_033544
- Kloezen, W. H., & Garcés-Restrepo, C. (1998). *Assessing irrigation performance with comparative indicators: The case of the Alto Rio Lerma Irrigation District, Mexico*.
- Knox, J. ., Daccache, A., Hess, T. ., Else, M., Kay, M., Burton, M., Thelwall, D., & Malano, H. (2013). *Benchmarking agricultural water use and productivity*

in key commodity crops (pp. 9–56). Cranfield University.

- Knox, J., 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.agry.2009.09.002>
- Kranz, B. (n.d.). *Irrigation Efficiencies*. University of Nebraska-Lincoln.
- Kumambala, P. G., & Ervine, A. (2010). Water Balance Model of Lake Malawi and its Sensitivity to Climate Change. *The Open Hydrology Journal*, 4, 152–162.
- Lautze, J., & Giordano, M. (2007). Demanding Supply Management and Supplying Demand Management. *The Journal of Environment & Development*, 16(3), 290–306. <https://doi.org/10.1177/1070496507306170>
- Lewandowska-Czarnecka, A., Piernik, A., & Nienartowicz, A. (2019). Performance indicators used to study the sustainability of farms. Case study from Poland. *Ecological Indicators*, 99, 51–60. <https://doi.org/10.1016/j.ecolind.2018.11.067>
- Linker, R., Ioslovich, I., Sylaios, G., Plauborg, F., & Battilani, A. (2016). Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato. *Agricultural Water Management*, 163, 236–243. <https://doi.org/10.1016/j.agwat.2015.09.011>
- Lisson, S. ., Brennan, L. ., Bristow, K. ., Keating, B. ., & Hughes, D. . (2003). DAM EA\$Y—software for assessing the costs and benefits of on-farm water storage based production systems. *Agricultural Systems*, 76(1), 19–38. [https://doi.org/10.1016/S0308-521X\(02\)00112-9](https://doi.org/10.1016/S0308-521X(02)00112-9)
- López-Mata, E., Tarjuelo, J. M., de Juan, J. A., Ballesteros, R., & Domínguez, A. (2010). Effect of irrigation uniformity on the profitability of crops. *Agricultural Water Management*, 98(1), 190–198. <https://doi.org/10.1016/j.agwat.2010.08.006>

- Malano, H. M., & Burton, M. (2001). *Guidelines for Benchmarking Performance in the Irrigation and Drainage Sector*. Food and Agriculture Organization.
- Malano, H. M., Burton, M., & Makin, I. (2004). Benchmarking performance in the irrigation and drainage sector: a tool for change. *Irrigation and Drainage*, 53(2), 119–133. <https://doi.org/10.1002/ird.126>
- Malano, H. M., Vlotman, W., Bos, M. ., & Molden, D. J. (2004). *Benchmarking of irrigation and drainage Projects*. <http://www.icid.org>
- Maldonado, D. (2015). *Industrial Energy Consumption, Benchmarking, and Analysis in the United States*. [University of Arkansas, Fayetteville]. <https://scholarworks.uark.edu/meeguht/48>
- Maroufpoor, E., Faryabi, A., Ghamarnia, H., & Moshrefi, G. Y. (2010). Evaluation of uniformity coefficients for sprinkler irrigation systems under different field conditions in Kurdistan Province (Northwest of Iran). *Soil and Water Research*, 5(No. 4), 139–145. <https://doi.org/10.17221/42/2009-SWR>
- Martin, D., Supalla, R., & Hergert, G. W. (2010). Advances in Deficit Irrigation Management. *5th National Decennial Irrigation Conference*. <https://doi.org/10.13031/2013.35870>
- Masilela, M. D. (2007). *Benchmarking operations and maintenance for small scale sugarcane schemes in Swaziland* [University of Dar es Salaam]. <http://41.86.178.5:8080/xmlui/handle/123456789/11542>
- McDonald, L. ., & Lisson, S. . (2001). The effect of planting and harvest time on sugarcane productivity. *Proceedings of the 10th Australian Agronomy Conference*.
- McGlinchey, M. G., & Inman-Bamber, N. G. (1996). Effect of Irrigation scheduling on water use efficiency and yield. *Proceedings South African Sugar Technologists' Association*, 55–56.
- Mishra, P., Pandey, C., Singh, U., Gupta, A., Sahu, C., & Keshri, A. (2019). Descriptive statistics and normality tests for statistical data. *Annals of*

- Cardiac Anaesthesia*, 22(1), 67. https://doi.org/10.4103/aca.ACA_157_18
- MITC. (2023). *Sugar Production and Consumption*. Malawi Investment and Trade Centre. <https://mitc.mw/trade/index.php/sugar-production-and-consumption.html>
- Moazed, H., Bavi, A., Boroomand-, S., Naseri, A., & Albaji, M. (2010). Effects of Climatic and Hydraulic Parameters on Water Uniformity Coefficient in Solid Set Systems. *Journal of Applied Sciences*, 10(16), 1792–1796. <https://doi.org/10.3923/jas.2010.1792.1796>
- Mokonoto, O. (2018). *Assessing Climate Change Impacts on Productivity of Sugarbeet and Sugarcane Using Aquacrop*. University of KwaZulu-Natal.
- Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, 97(4), 528–535. <https://doi.org/10.1016/j.agwat.2009.03.023>
- Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 281(980), 277–294. <https://doi.org/10.1098/rstb.1977.0140>
- Mtilatila, L., Bronstert, A., Shrestha, P., Kadewere, P., & Vormoor, K. (2020). Susceptibility of Water Resources and Hydropower Production to Climate Change in the Tropics: The Case of Lake Malawi and Shire River Basins, SE Africa. *Hydrology*, 7(3), 54. <https://doi.org/10.3390/hydrology7030054>
- Mua, W., Middelaara, C. E. van, Bloemhofb, J. M., Engelc, B., & Boera, I. J. M. de. (2017). Benchmarking the environmental performance of specialized milkproduction systems: selection of a set of indicators. *Ecological Indicators*, 72, 91–98.
- Muchow, R. C., Robertson, M. J., & Keating, B. A. (1997). Limits to the Australian sugar industry: climatic and biological factors. In B. A. Keating & J. R. Wilson (Eds.), *Intensive Sugarcane Production: Meeting the Challenges Beyond* (pp. 37–54). CSIRO Tropical Agriculture.

- Mudima, K. (2002). Socio-economic impact of smallholder irrigation development in Zimbabwe: A case study of five successful irrigation schemes. In H. Sally & C. L. Abernethy (Eds.), *Private Irrigation in sub-Saharan Africa; Proceedings of Regional Seminar on Private Sector Participation and Irrigation Expansion in sub-Saharan Africa*. International Water Management Institute, Food and Agriculture Organization of the United Nations and ACP-EU Technical Centre for Agricultural and Rural Cooperation.
- Muema, F., Home, P., & Raude, J. (2018). Application of Benchmarking and Principal Component Analysis in Measuring Performance of Public Irrigation Schemes in Kenya. *Agriculture*, 8(10), 162. <https://doi.org/10.3390/agriculture8100162>
- Mukasa, A. N., Woldemichael, A. D., Salami, A. O., & Simpasa, A. M. (2017). *Africa's Agricultural Transformation: Identifying Priority Areas and Overcoming Challenges* (pp. 1–16). Africa Economic Brief.
- Mulumpwa, M., Jere, W., Lazaro, M., & Mtethiwa, A. (2018). Modelling and forecasting Lake Malawi water level fluctuations using stochastic models. *African Journal of Rural Development*, 3(3), 831–841.
- Naranjo, L., Correa-Cano, M. E., Rey, D., Chengot, R., España, F., Sactic, M., Knox, J. W., Yan, X., Viteri-Salazar, O., Foster, W., & Melo, O. (2023). A scenario-specific nexus modelling toolkit to identify trade-offs in the promotion of sustainable irrigated agriculture in Ecuador, a Belt and Road country. *Journal of Cleaner Production*, 413, 137350. <https://doi.org/10.1016/j.jclepro.2023.137350>
- Nascimento, A. ., Schwartz, R. C., Lima, F. ., López-Mata, E., Domínguez, A., Izquier, A., Tarjuelo, J. ., & Martínez-Romero, A. (2019). Effects of irrigation uniformity on yield response and production economics of maize in a semiarid zone. *Agricultural Water Management*, 211, 178–189. <https://doi.org/10.1016/j.agwat.2018.09.051>
- Neupane, J., & Guo, W. (2019). Agronomic basis and strategies for precision water management: A review. *Agronomy*, 9(2).

<https://doi.org/10.3390/agronomy9020087>

O'Leary, G. J. (2000). A review of three sugarcane simulation models with respect to their prediction of sucrose yield. *Field Crops Research*, 68, 97–111.

Oliveira, L. A. de, Miranda, J. H. de, & Cooke, R. A. C. (2018). Water management for sugarcane and corn under future climate scenarios in Brazil. *Agricultural Water Management*.
<https://doi.org/10.1016/j.agwat.2018.01.019>

Ortega Álvarez, J. F., Tarjuelo Martin-Benito, J. M., De Juan Valero, J. A., & Carrión Pérez, P. (2004). Uniformity Distribution and its Economic Effect on Irrigation Management in Semiarid Zones. *Journal of Irrigation and Drainage Engineering*, 130(4), 257–268. [https://doi.org/10.1061/\(ASCE\)0733-9437\(2004\)130:4\(257\)](https://doi.org/10.1061/(ASCE)0733-9437(2004)130:4(257))

Paice, E. (2022, January 20). By 2050, a quarter of the world's people will be African – this will shape our future. *The Guardian*.
<https://www.theguardian.com/global-development/2022/jan/20/by-2050-a-quarter-of-the-worlds-people-will-be-african-this-will-shape-our-future>

Paraskevopoulos, A. L., & Singels, A. (2014). Integrating soil water monitoring technology and weather based crop modelling to provide improved decision support for sugarcane irrigation management. *Computers and Electronics in Agriculture*, 105, 44–53. <https://doi.org/10.1016/j.compag.2014.04.007>

Paraskevopoulos, A. L., Singels, A., Tweddle, P. B., & van Heerden, P. (2016). Quantifying the negative impact of lodging on irrigated sugarcane productivity: A crop modelling assessment. *Proceedings of the South African Sugar Technologists' Association*, 154–158.

Pereira, L. (1999). Higher performance through combined improvements in irrigation methods and scheduling: a discussion. *Agricultural Water Management*, 40, 153–169.

Perez-Ortola, M. (2013). *Modelling The Impacts of In-Field Soil and Irrigation Variability on Onion Yield* [MPhil dissertation, Cranfield University].

<http://dspace.lib.cranfield.ac.uk/handle/1826/8588>

- Pérez-Ortolá, M., Daccache, A., Hess, T. M., & Knox, J. W. (2015). Simulating impacts of irrigation heterogeneity on onion (*Allium cepa* L.) yield in a humid climate. *Irrigation Science*, 33(1), 1–14. <https://doi.org/10.1007/s00271-014-0444-2>
- 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. <https://doi.org/10.2134/agronj2008.0140s>
- Regoniel, P. A. (2013). *What is the Difference Between Benchmarking and Baselineing?* Research. <https://simplyeducate.me/2013/07/18/what-is-the-difference-between-benchmarking-and-baselining/>
- Reinders, F. B. (1996). Irrigation systems: Evaluation and Maintenance. *SA Irrig*, 1, 5–7.
- Ritchie, H. (2022). *Increasing agricultural productivity across Sub-Saharan Africa as one of the most important problems this century*. World in Data. ourworldindata.org/africa-yields-problem
- Sabatier, D., Martiné, J. F., Chiroleu, F., Roussel, C., Letourmy, P., van Antwerpen, R., Gabrielle, B., & Ney, B. (2015). Optimization of sugarcane farming as a multipurpose crop for energy and food production. *GCB Bioenergy*. <https://doi.org/10.1111/gcbb.12133>
- Sadras, V. O., Cassman, K. G. G., Grassini, P., Hall, A. J., Bastiaanssen, W. G. M., Laborte, A. G., Milne, A. E., Sileshi, G., & Steduto, P. (2015). *Yield gap analysis of field crops – Methods and case studies*, by. FAO.
- Saidi, A., & Hammami, M. (2016). Irrigation Uniformity Impacts on Water Use Efficiency and Soil Salinity: Case Study of Tomato Crop under Trickle Irrigation System in the NorthEast of Tunisia. *Journal of Hydrogeology & Hydrologic Engineering*, 05(01). <https://doi.org/10.4172/2325-9647.1000130>

- Sakthivadivel, R., Merrey, D. J., & Fernando, N. (1993). Cumulative relative water supply: A methodology for assessing irrigation system performance. *Irrigation and Drainage Systems*, 7(1), 43–67. <https://doi.org/10.1007/BF00880908>
- Santos, L. C., Coelho, R. D., Barbosa, F. S., Leal, D. P. V., Fraga Júnior, E. F., Barros, T. H. S., Lizcano, J. V., & Ribeiro, N. L. (2019). Influence of deficit irrigation on accumulation and partitioning of sugarcane biomass under drip irrigation in commercial varieties. *Agricultural Water Management*, 221(May), 322–333. <https://doi.org/10.1016/j.agwat.2019.05.013>
- Satpathy, A. (2023). *What is Baselining and what is a Project Baseline?* Blog.
- Shela, O. N. (2000). Naturalization of Lake Malawi Levels and Shire River Flows: Challenges of Water Resources Research and Sustainable Utilisation of the Lake Malawi-Shire River System. *1st WARFSA/WaterNet Symposium: Sustainable Use of Water Resources*.
- Shrivastava, A. K., Shrivastava, A. K., & Sushil, S. (2011). Sustaining sugarcane productivity under depleting water resources. *Current Science*, 101(6), 748–754.
- Singels, A. (2014). Crop Models. In P. H. Moore & F. C. Botha (Eds.), *Sugarcane: Physiology, Biochemistry, and Functional Biology* (First Edit, pp. 541–577). John Wiley & Sons, Inc.
- Singels, A., Annandale, J. G., De Jager, J. M., Schulze, R. E., Inman-Bamber, N. G., Durand, W., Van Rensburg, L. D., Van Heerden, P. S., Crosby, C. T., Green, G. C., & Steyn, J. M. (2010). Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *South African Journal of Plant and Soil*, 27(1), 49–65. <https://doi.org/10.1080/02571862.2010.10639970>
- Singels, A., & Bezuidenhout, C. N. (2002). A new method of simulating dry matter partitioning in the Canegro sugarcane model. *Field Crops Research*, 78(2–3), 151–164. [https://doi.org/10.1016/S0378-4290\(02\)00118-1](https://doi.org/10.1016/S0378-4290(02)00118-1)

- Singels, A., & Donaldson, R. A. (2000). A Simple Model of Unstressed Sugarcane Canopy Development. *Proceedings of the South African Sugar Technologists' Association*, 151–154.
- Singels, A., Donaldson, R. A., & Smit, M. A. (2005). Improving biomass production and partitioning in sugarcane: Theory and practice. *Field Crops Research*, 92(2-3 SPEC. ISS.), 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., Jones, M. R., Porter, C., Smit, M. A., Kingston, G., Marin, F., Chinorumba, S., Jintrawet, A., Suguitani, C., van den Berg, M., & Saville, G. (2010). The DSSAT4.5 CANEGRO Model: A Useful Decision Support Tool for Research and Management of Sugarcane Production. *Proceedings of International Society of Sugar Cane Technologists*.
- Singels, A., Jones, M., & van den Berg, M. (2008). *DSSAT v4.5 - Canegro Sugarcane Plant Module: Scientific documentation*. International Consortium for Sugarcane Modelling (ICSM).
- Singels, A., Kennedy, A. J., & Bezuidenhout, C. N. (1998). IRRICANE: A Simple Computerised Irrigation Scheduling Method for Sugarcane. *Proceedings of the South African Sugar Technologists' Association*, 117–122.
- Singels, A., & Paraskevopoulos, A. (2017). *The CANESIM® Sugarcane model: Scientific documentation* (pp. 1–59). South African Sugarcane Research Institute. <https://sasri.org.za/wp-content/uploads/2020/03/The-Canesim-sugarcane-model-Scientific-documentation.pdf>

- Singels, A., & Smith, M. T. (2006). Provision of irrigation scheduling advice to small-scale sugarcane farmers using a web-based crop model and cellular technology: a South African case study. *Irrigation and Drainage*, 55(4), 363–372. <https://doi.org/10.1002/ird.231>
- Solomon, K. H. (1998). The Economics of Uniformity. *ITRC*, 104(3), 293–306.
- SQR Software. (2023). *The CanePro Estate*. SQR. <https://www.sqrsoftware.com/about-us/>
- Steduto, P., Hsiao, T. C., & Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrigation Science*, 25(3), 189–207. <https://doi.org/10.1007/s00271-007-0064-1>
- 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>
- Steduto, P., Hsiao, T., Fereres, E., & Raes, D. (2012). *Crop yield Response to Water*. Food and Agriculture organization of the United Nations.
- Stewart, L. K., Charlesworth, P. B., Bristow, K. L., & Thorburn, P. J. (2006). Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. *Agricultural Water Management*, 81(3), 315–334. <https://doi.org/10.1016/j.agwat.2005.05.002>
- Suchacek, T., Aldea, A., Bylka, J., Marko, I., & Tuhovcak, L. (2018). Comparative Analysis and Benchmarking of Water Supply Systems and Services in Central and Eastern Europe. *EWaS3 2018*, 597. <https://doi.org/10.3390/proceedings2110597>
- Svendsen, M., Ewing, M., & Msangi, S. (2009). *Measuring Irrigation Performance in Africa*. International Food Policy Research Institute (IFPRI).
- Thorburn, P. J., Biggs, J. S., Collins, K., & Probert, M. E. (2010). Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane

- production systems. *Agriculture, Ecosystems & Environment*, 136(3–4), 343–350. <https://doi.org/10.1016/j.agee.2009.12.014>
- Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.-T. A., Stöckle, C., & Steduto, P. (2009). Assessment of AquaCrop, CropSyst, and WOFOST Models in the Simulation of Sunflower Growth under Different Water Regimes. *Agronomy Journal*, 101(3), 509–521. <https://doi.org/10.2134/agronj2008.0166s>
- Tomlinson, I. (2013). Doubling food production to feed the 9 billion: A critical perspective on a key discourse of food security in the UK. *Journal of Rural Studies*, 29, 81–90. <https://doi.org/10.1016/j.jrurstud.2011.09.001>
- Tsagris, M., & Pandis, N. (2021). Normality test: Is it really necessary? *American Journal of Orthodontics and Dentofacial Orthopedics*, 159(4), 548–549. <https://doi.org/10.1016/j.ajodo.2021.01.003>
- Tyler, G. (2008). *The African Sugar Industry – A frustrated Success Story. Background paper for the Competitive Commercial Agriculture in Sub-Saharan Africa (CCAA) Study* (pp. 1–19).
- Vanuytrecht, E., Raes, D., Willems, P., & Geerts, S. (2012). Quantifying field-scale effects of elevated carbon dioxide concentration on crops. *Climate Research*, 54(1), 35–47. <https://doi.org/10.3354/cr01096>
- Waclawovsky, A. J., Sato, P. M., Lembke, C. G., Moore, P. H., & Souza, G. M. (2010). Sugarcane for bioenergy production: an assessment of yield and regulation of sucrose content. *Plant Biotechnology Journal*, 8(3), 263–276. <https://doi.org/10.1111/j.1467-7652.2009.00491.x>
- Waller, P., & Yitayew, M. (2016). *Irrigation and Drainage Engineering*. In Springer. Springer International Publishing. <https://doi.org/10.1007/978-3-319-05699-9>
- Webster, A. J., Thorburn, P. J., Roebeling, P. C., Horan, H. L., & Biggs, J. S. (2009). The expected impact of climate change on nitrogen losses from wet tropical sugarcane production in the Great Barrier Reef region. *Marine and Freshwater Research*, 60(11), 1159. <https://doi.org/10.1071/MF08348>

Williams, C. L., Emerson, R. M., & Tumuluru, J. S. (2017). Biomass Compositional Analysis for Conversion to Renewable Fuels and Chemicals. In *Biomass Volume Estimation and Valorization for Energy*. InTech. <https://doi.org/10.5772/65777>

APPENDICES

Appendix A : Data Collection Tools

A.1 Initial Questionnaire

Benchmarking the performance of irrigated sugarcane at Illovo Sugar - questionnaire for data collection.

On 12th December 2019 a new 3-year PhD research contract between Illovo Sugar (Africa) and Cranfield University was established. The aim of the research is to evaluate irrigation management practices at selected Illovo sites in Africa and identify measures to improve water and energy efficiency for sugarcane production.

The project will involve Mavuto Banda (PhD student) with supervision by Professor Jerry Knox and Professor Tim Hess from Cranfield University. The technical leads in Illovo include the Group Agriculture Engineering Specialist (Mr. Darran Boote), Agriculture Manager – Nchalo (Mr Keith Domleo) and Agriculture Engineer – Nchalo (Mr Jaco Burger).

One of the initial objectives of the research is to carry out a benchmarking exercise to establish current levels of performance and identify best practices among the estates across the Illovo (Africa) group. This preliminary questionnaire, aims to identify the types of data required and available. This will help in supporting future interviews/discussions with key informants at each estate and in developing more detailed questionnaire.

The findings from this benchmarking exercise will inform the research direction of the subsequent steps. The findings will also be shared with Illovo staff involved in irrigation management. It is emphasised that the data collected in this exercise and subsequent analyses will be solely used for the purposes of the PhD research. The contract between Cranfield and Illovo and the PhD student includes detailed provision for data protection and confidentiality. Thank you for your support in this research.

Directions for completing the questionnaire

1. The questionnaire has been developed with interactive capabilities, so it can be electronically completed saved and then sent without having to make a print out.
2. For most questions, please choose the appropriate answer(s) from given options. It is advisable that you properly check whether a given question requires them to select only one option or multiple options, type in your own words/figures or select an option from the dropdown menu.

3. Questions that require you to input your own words or figures have been customized to accept an appropriate input type e.g. numbers only, words only or a combination of both text and numbers. Please check you enter numbers/text in the appropriate format.
4. Please do not hesitate to contact Mavuto Banda via the email address provided below if you need clarifications on any of the questions.
5. After completing the questionnaire, save the file with a new filename and then email to m.banda@cranfield.ac.uk

Section A: Respondent Identification

A1. Name:

A2. Position:

Section B: Operation Identification Details

B1. Country:

B2. Estate:

B3. Total cane area (ha) on estate (exclude out grower area):

B4. Does the estate have data/maps (GIS files) showing estate boundaries, field boundaries, water abstraction points, storage reservoirs, canal/pipeline networks either in form of hardcopy (paper) maps or electronic/digital maps? (Select **ONE** applicable option below)

Yes

No

Section C: Irrigation Systems, Water Abstraction, Conveyance and Application

C1. Which of the following irrigation systems are used at the estate? Please tick all that apply (select **ALL** applicable options)

Basin

Border strip

Furrow

Sprinkler (hand moves, dragline and/or solid set)

Centre pivot

Linear move

Surface and/or subsurface drip

Other (Specify)_____

C2. What is the area (ha) under each irrigation system selected above?

(Enter the corresponding area for each system in the right-hand side)

Irrigation System	Area (ha)
Basin	
Border strip	
Furrow	
Sprinkler (hand moves, dragline or solid-set)	
Centre pivot	
Lateral move	
Surface/sub-surface	
Other	
TOTAL Area	

C3. Does the estate keep records of irrigation abstraction (volume and time) and monitor water use at selected points along the conveyance system? (Select **ONE** applicable option below)

Yes

No

C4. If yes to in (C3, in what format are these records? (Tick ALL applicable options)

Spreadsheet

Canepro

Books (hardcovers or similar)

Loose paper record

Other (Specify)_____

C5. How long has the practice of keeping such records been in place?

C6. Does the estate keep records of irrigation events (timing and amount of water applied during each irrigation event)? (Select **ONE** applicable option below)

Yes

No

C7. If yes to C6, in what format of recording are these records? *(Tick ALL applicable options)*

Spreadsheet

Canepro

Books (hardcovers or similar)

Loose paper record

Other (Specify)_____

C8. How long has the practice of keeping such records been in place?

C9. Does the estate conduct and keep records of field tests to evaluate irrigation uniformity (e.g. catch can tests, advance and recession etc.)?

Yes

No

C10. If yes to C9 above, in what format of recording are these records?
(Tick ALL applicable options)

Spreadsheet

Canepro

Books (hardcovers or similar)

Loose paper record

Other (Specify)_____

C11. If yes to C9 above, how frequent are these tests conducted?

C12. How long has the practice of keeping such records been in place?

C13. Does the estate keep records of irrigation system failure due to breakdowns, power failure and/or any other causes (Lost Time Available - LTA)?

Yes

No

C14. If yes in (C12) above, in what format of recording are these records?
(Tick ALL applicable options)

Spreadsheet

Canepro

Books (hardcovers or similar)

Loose paper record

Other (Specify)_____

C15. If yes in (C12) above, since when has the practice (of keeping such records) been in place?

C16. Which of the following are the sources of energy are used for irrigation pumping on the estate? (Tick ALL applicable options)

Hydro-electricity

Fuel (petrol/diesel)

Solar panels

Wind turbines

Other (specify)

C17. Does the estate keep records of irrigation related energy consumption (electricity bills, sunshine intensity/hours and/or fuel cost)?

Yes

No

C18. How long has the practice of keeping such records been in place?

C19. Does the estate keep 'first burn – first irrigation' record?

Yes

No

C20. How long has the practice of keeping such records been in place?

Section D: Crop Production

D1. Does the estate keep records of cane productivity (yield) at the field level (t/ha)?

Yes

No

D2. If yes in (D1) above, which of the following does the estate record?
(Tick ALL applicable options)

Growth start date

Date of harvesting

Tons cane per hectare

Tons sugar per hectare

Sucrose recovery

Moisture content at the factory

D3. If yes in (D1) above, since when has the estate been recording the production parameters?

Section E: Climate and Soil data

E1. Does the estate have a weather station?

Yes

No

E2. If yes to (E1) above, specify the type of weather station below *(Tick ALL applicable options)*

Automatic weather station

Manual weather station

Combination of both manual and automatic

E3. If yes to (E1) above, which of the following elements are recorded at the weather station? *(Tick ALL applicable options)*

Rainfall

Temperature (max and min)

Evapotranspiration (ET)

Relative humidity

Wind speed

Solar radiation

Sunshine hours

Soil temperature

Other (specify)

E4. How long has the practice of keeping such records been in place?

E5. Does the estate have field level records of soil characteristics (texture, organic matter content, soil depth, water holding capacity etc.)?

Yes

No

C4. If yes in (E5) above, what was the method of data collection for these records? *(Tick ALL applicable options)*

Field sampling and lab analysis

Electromagnetic induction (EMI) scanning

Other (Specify)_____

END of Questions – thanks for your time!

**Appendix B : Cost and Benefits Analysis Input
Parameters**

Irrigation systems under consideration			
Furrow			
Centre pivot			
Sprinkler			
	Unit	input value	Source of data
Irrigation system elements			
1. Furrow			
Application uniformity (CU)	decimal	0.90	field tests
Adequacy	decimal	0.84	field tests
flowrate	m ³ /h	43.20	Calculated
flow velocity	m/s	0.01	field tests
canal x-section area	m ²	1.20	field tests
2. Centre pivot			
Application uniformity (CU)	decimal	0.80	field tests
Adequacy	decimal	0.74	field tests
flowrate	m ³ /h	75.00	field tests
life span	yrs		Literature
3. Sprinkler			
Application uniformity (CU)	decimal	0.66	field tests
Adequacy	decimal	0.55	field tests
flowrate	m ³ /h	65.00	field tests
life span	yrs		Literature
Area under each irrigation system			
Furrow	ha	10.80	Nchalo estate records
Centre pivot	ha	30.40	Nchalo estate records
Sprinkler	ha	16.00	Nchalo estate records
Yields and prices			
1. Furrow			
cane yield	t/ha	142.00	Cane yield response to water simulated by DSSAT Canegro model
sugar recovery	%	13	Nchalo estate records
sugar yield equivalent	t/ha	18.46	Calculated
sugar selling price	£/t	1100	Nchalo estate records
2. Centre pivot			
cane yield	t/ha	124.89	Cane yield response to water simulated by DSSAT Canegro model
sugar recovery	%	13	Nchalo estate records
sugar yield equivalent	t/ha	16.24	Calculated
sugar selling price	£/t	1100	Nchalo estate records
3. Sprinkler			
cane yield	t/ha	134.82	Cane yield response to water simulated by DSSAT Canegro model
sugar recovery	%	13	Nchalo estate records
sugar yield equivalent	t/ha	17.54	Calculated
sugar selling price	£/t	1100	Nchalo estate records
Seasonal crop water requirements and water supply			
1. Furrow			
Potential ET	mm	1840.83	Simulated by DSSAT Canegro model
Precipitation	mm	755.70	Simulated by DSSAT Canegro model
Effective Irrigation	mm	1542.05	Simulated by DSSAT Canegro model
Transpiration	mm	1472.23	Simulated by DSSAT Canegro model
Soil Evaporation	mm	346.60	Simulated by DSSAT Canegro model
Runoff	mm	175.92	Simulated by DSSAT Canegro model
Drainage	mm	113.67	Simulated by DSSAT Canegro model
2. Centre pivot			
Potential ET	mm	1906.36	Simulated by DSSAT Canegro model
Precipitation	mm	717.40	Simulated by DSSAT Canegro model
Effective Irrigation	mm	1255.34	Simulated by DSSAT Canegro model
Transpiration	mm	1171.95	Simulated by DSSAT Canegro model
Soil Evaporation	mm	454.69	Simulated by DSSAT Canegro model
Runoff	mm	268.00	Simulated by DSSAT Canegro model
Drainage	mm	45.53	Simulated by DSSAT Canegro model
3. Sprinkler			
Potential ET	mm	1,760	Simulated by DSSAT Canegro model
Precipitation	mm	963	Simulated by DSSAT Canegro model
Effective Irrigation	mm	1,550	Simulated by DSSAT Canegro model
Transpiration	mm	1,419	Simulated by DSSAT Canegro model
Soil Evaporation	mm	319	Simulated by DSSAT Canegro model
Runoff	mm	111	Simulated by DSSAT Canegro model
Drainage	mm	169	Simulated by DSSAT Canegro model
Water allocation and abstraction			
Annual licensed volume	m ³	1,000,000.00	Nchalo estate records
Annual irrigation water use volume	m ³		Calculated/Simulated by Clemmens' statistical approach
Annual over-abstracted volume	m ³		Nchalo estate records
Over abstraction penalty	£/m ³	6	Nchalo estate records
Annual substription fees & levies	£	100	Nchalo estate records
Unit cost of water	£/m ³	0.08	Nchalo estate records
2. Centre pivot			
Annual licensed volume	m ³	1,000,000.00	Nchalo estate records
Annual irrigation water use volume	m ³		Calculated/Simulated by Clemmens' statistical approach
Annual over-abstracted volume	m ³		Nchalo estate records
Over abstraction penalty	£/m ³	6	Nchalo estate records
Annual substription fees & levies	£	100	Nchalo estate records
Unit cost of water	£/m ³	0.08	Nchalo estate records
3. Sprinkler			
Annual licensed volume	m ³	1,000,000.00	Nchalo estate records
Annual irrigation water use volume	m ³		Calculated/Simulated by Clemmens' statistical approach
Annual over-abstracted volume	m ³		Nchalo estate records
Over abstraction penalty	£/m ³	6	Nchalo estate records
Annual substription fees & levies	£	100	Nchalo estate records
Unit cost of water	£/m ³	0.08	Nchalo estate records
Energy tariffs and use			
1. Furrow			
Specific energy requirement	kWh/m ³	0.6	Nchalo estate records
Seasonal electricity use	kWh		Calculated
proportion of offpeak operation	%	75	Nchalo estate records
proportion of onpeak operation	%	25	Nchalo estate records
offpeak electricity unit cost	£/kWh	0.16	Nchalo estate records
onpeak electricity unit cost	£/kWh	0.5	Nchalo estate records
2. Centre pivot			
Specific energy requirement	kWh/m ³	0.6	Nchalo estate records
Seasonal electricity use	kWh		Calculated
proportion of offpeak operation	%	75	Nchalo estate records
proportion of onpeak operation	%	25	Nchalo estate records
offpeak electricity unit cost	£/kWh	0.16	Nchalo estate records
onpeak electricity unit cost	£/kWh	0.5	Nchalo estate records
3. Sprinkler			
Specific energy requirement	kWh/m ³	0.6	Nchalo estate records
Seasonal electricity use	kWh		Calculated
proportion of offpeak operation	%	75	Nchalo estate records
proportion of onpeak operation	%	25	Nchalo estate records
offpeak electricity unit cost	£/kWh	0.16	Nchalo estate records
onpeak electricity unit cost	£/kWh	0.5	Nchalo estate records
Labour requirements			
1. Furrow			
Nmbr of people per shift	Nmbr	2	Nchalo estate records
Nmbr of hours per shift	hr	8	Nchalo estate records
Total nmbr of irrigation hrs in a season	hr		
Labour rate (£/h)	(£/hr)	1.8	Nchalo estate records
2. Centre pivot			
Nmbr of people per shift	Nmbr	4	Nchalo estate records
Nmbr of hours per shift	hr	8	Nchalo estate records
Total nmbr of irrigation hrs in a season	hr		
Labour rate (£/h)	(£/hr)	1.8	Nchalo estate records
3. Sprinkler			
Nmbr of people per shift	Nmbr	2	Nchalo estate records
Nmbr of hours per shift	hr	8	Nchalo estate records
Total nmbr of irrigation hrs in a season	hr		
Labour rate (£/h)	(£/hr)	1.8	Nchalo estate records

Appendix C : DSSAT Canegro Input Parameters

File Type Seasonal

Experiment Name * 2010 - 2018 SEASONAL ANALYSIS (NCHALO ESTATE)

Experiment Identifier (file name)

Institute Code * CU

Site Code * NE

Year * 2021

Experiment Number * 1

Crop

General Information

People Mavuto Banda

Address Nchalo Estate, P/Bag 50, Blantyre

Site Nchalo Estate

Plot

Plot Information

Gross Plot Area per rep, m2

Rows per Plot

Plot Length, m

Plots Relative to Drains, degrees

Plot Spacing, cm

Plot Layout

Harvest Information

Harvest Area, m-2

Harvest Row Number

Harvest Row Length, m

Harvest Method

Additional Information

Fields

Add **Delete**

Level	Description
1	Pivot

Field Details **Additional Information**

Level 1 Field ID (8 characters) FLD_3222

Weather Station

Name *

Nchalo Estate Weather Station ILNE

Soil

Name *

Neocutanic (SOIL.SOL) CU-Nch3222

Surface Texture

Clay

Depth, cm **Surface stones**

150 0

Drainage

Drainage Type

Ditches

Drain Depth, cm **Drain Spacing, m**

75 50

Cancel **OK**



Initial Conditions

Level	Description
1	

Residue Profile

Level 1 Measurement Date (MM/dd/yyyy) 09/10/2010

Year

- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014

Previous Crop

Previous Crop Sugarcane

Root Weight, kg/ha -99

Nodule Weight, kg/ha -99

Rhizobia

(0 to 1 Scale, Default = 1)

Number 1

Effectiveness 1

Water table depth, cm 180

Crop residue, kg/ha -99

Residue

N % -99 P % -99

Incorporation

% -99 Depth, cm -99



Soil Analysis

Level	Description
1	

Level 1

Year

- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015

Analysis date (MM/dd/yyyy) 09/09/2010

Determination Method

pH

Phosphorus

Potassium

Soil Analysis Layers

Depth, base of layer, cm	Bulk density, moist, g cm ⁻³	Organic carbon, %	Total nitrogen, %	pH in water	pH in buffer	Phosphorus, extractable, mg kg ⁻¹	Potassium, exchangeable, cmol	Stable Organic Carbon, %
-99								



Environmental Modifications

Level	Description
1	

Environmental Modification Applications

Level 1 Year 2010

Date (MM/dd/yyyy)	Daylength (hours)	Radiation, MJ/m ² /d	Max Temp, C	Min Temp, C	Precipitation, mm	CO2, vpm	Humidity (%)	Wind, km/hour
09/09/2010	0 Add	0 Add	0 Add	0 Add	0 Add	0 Add	0 Add	0 Add



Cultivar

Level	Crop	Cultivar
1	Sugarcane	N0003



Planting

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon

Level 1

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

Planting Date (MM/dd/yyyy) *

09/10/2010

Emergence Date (MM/dd/yyyy)

-99

Planting Method *

Ratoon

Planting Distribution *

Rows

Row Spacing, cm *

165

Plant Population at Seeding, plants m-2 *

25

Row Direction, degrees from North *

-99

Plant Population at emergence, plants m-2

-99

Planting Depth, cm *

20



Irrigation

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon

Irrigation Applications

Level 1

Year

2010

Management

Efficiency fraction

1

Date (MM/dd/yyyy)	Amount of water, mm	Operation
09/11/2010	14.2	Sprinkler, mm
09/13/2010	14.2	Sprinkler, mm
09/14/2010	14.2	Sprinkler, mm
09/15/2010	14.2	Sprinkler, mm
09/17/2010	14.2	Sprinkler, mm
09/18/2010	14.2	Sprinkler, mm
09/19/2010	14.2	Sprinkler, mm
09/26/2010	14.2	Sprinkler, mm
09/27/2010	14.2	Sprinkler, mm
09/28/2010	14.2	Sprinkler, mm

160



Fertilizers

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon

Fertilizer applications

Level 1
Year 2010
Management On reported dates

Date (MM/dd/yyyy)	Fertilizer material	Fertilizer applications	Depth, cm	N, kg ha-1	P, kg ha-1	K, kg ha-1	Ca, kg ha-1	Other elements, kg ha-1	Other element code
10/21/2010	Ammonium sulfate	Broadcast, not incor	1	60	20	5	0	61	0
10/22/2010	Ammonium sulfate	Broadcast, not incor	1	53	0	0	0	61	0



Organic Amendments

Level	Description
1	

Organic Amendments Applications

Level 1
Year 2010
Management On reported dates

Date (MM/dd/yyyy)	Residue material	Amount, kg/ha	Nitrogen concentration, %	Phosph. concentration, %	Potass. concentration, %	Incorporation, %	Incorporation depth, cm	Method of incorp. code
09/09/2010								



Tillage

Level	Description
1	2nd ratoon

Tillage Applications

Level 1
Year 2011

Date (MM/dd/yyyy)	Tillage implement	Tillage depth
09/10/2010	V-Ripper	30



Harvest

Add

Delete

Level	Description
1	2nd ratoon harvest
2	3rd ratoon harvest
3	4th ratoon harvest

Harvest Numbers

Level 1

Year 2011

Crop Sugarcane

Management On reported date(s)

Date (MM/dd/yyyy)	Stage	Component	Size Group	Grain Harvest, %	Byproduct takeoff, %
08/05/2011	GS000	Harvest product	All	100	100

Add Harvest

Delete Harvest

Cancel

OK



Treatments

Level	Description	Cultivar	Field	Soil. Anal.	Init. Cond.	Plant.	Irrigat.	Fertil.	Resid.	Chem. App.	Tillage	Env. Mod.	Harv.	Sim. Contr.
1	2nd ratoon	1	1			1	1	1					1	1
2	3rd ratoon	1	1			2	2	2					2	2
3	4th ratoon	1	1			3	3	3					3	3
4	5th ratoon	1	1			4	4	4					4	4
5	6th ratoon	1	1			5	5	5					5	5
6	7th ratoon	1	1			6	6	6					6	6
7	8th ratoon	1	1			7	7	7					7	7
8	9th ratoon	1	1			8	8	8					8	8
9	10th ratoon	1	1			9	9	9					9	9

Select level for each experiment factor by clicking the mouse into the cell

Add

Delete

Cancel

OK



Simulation Options

Add

Delete

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

General

Options

Methods

Management

Outputs

Level 1

Simulation Start Date (MM/dd/yyyy) *

09/09/2010

Start

On specified date

Random number seed

2150

Crop Module

CANEGRO-Sugarcane

Runs

Years

1

Replications

1

Cancel

OK



Simulation Options

AddDelete

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

GeneralOptionsMethodsManagementOutputs

Options

Level 1

WaterYes

PotassiumNo

NitrogenNo

ChemicalsNo

SymbiosisNo

DiseasesNo

PhosphorusNo

TillageNo

CO₂Actual CO₂; Mauna Loa, Hawaii (Keeling et al.)

CancelOK



Simulation Options

AddDelete

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

GeneralOptionsMethodsManagementOutputs

Methods

Level 1

WeatherMeasured data

PhotosynthesisCanopy curve (daily)

Init. Soil Cond.As reported

HydrologyRitchie water balance

EvapotranspirationFAO-56

Method of Soil Organic MatterCeres (Godwin)

InfiltrationSoil Conservation Service

Soil evaporation methodSuleiman-Ritchie

Soil layer distributionModified soil profile

CancelOK



Simulation Options

AddDelete

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

GeneralOptionsMethodsManagementOutputs

Management

Level 1

PlantingIrrigation and Water ManagementFertilizerOrganic AmendmentsHarvest

Planting

On reported date

Date
Earliest (MM/dd/yyyy)01/01/2010
Latest (MM/dd/yyyy)01/01/2010

Soil temperature
Maximum, C40
Minimum, C10

Soil water

Lower, %40
Upper, %100
Depth, cm30

CancelOK

163



Simulation Options

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

General

Options

Methods

Management

Outputs

Management

Level 1

Planting

Irrigation and Water Management

Fertilizer

Organic Amendments

Harvest

Irrigation and Water Management

Automatic when required

Management depth, cm

100

End of application, growth stage

IB001

Threshold, % of max available

80

Amount, mm

10

End point, % of max. available

100

Efficiency fraction

1

Method

Sprinkler, mm



Simulation Options

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

General

Options

Methods

Management

Outputs

Management

Level 1

Planting

Irrigation and Water Management

Fertilizer

Organic Amendments

Harvest

Fertilizer

On reported dates

Depth, cm

30

Threshold, N stress factor

50

Amount per application

25

Material

End of applications, grows factor

IB001



Simulation Options

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

General

Options

Methods

Management

Outputs

Management

Level 1

Planting

Irrigation and Water Management

Fertilizer

Organic Amendments

Harvest

Organic Amendments

No applications

Incorporation Percentage, %

100

Incorporation, Days after Harvest

1

Incorporation Depth, cm

20



Simulation Options

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

General | **Options** | **Methods** | **Management** | **Outputs**

Management

Level 1

Harvest

On reported date(s)

Earliest

Latest date (MM/dd/yyyy)

Percentage of product harvested, %

Percentage of residue harvested, %



Simulation Options

Level	Description
1	2nd ratoon
2	3rd ratoon
3	4th ratoon
4	5th ratoon

Year

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

General | **Options** | **Methods** | **Management** | **Outputs**

Outputs

Level 1

Frequency of output (days) Overview Summary

Output files Format

Details

Growth	Yes	Nitrogen	Yes	Chemical	No
Carbon	No	Phosphorus	No	Operations output	No
Water	Yes	Diseases	No	Verbose	Minimal output