

Benchmarking sugarcane irrigation management practices in Sub-Saharan Africa

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ABSTRACT

In many countries, irrigation is an essential component of sugarcane production to ensure consistently high yields. However, our evaluation of opportunities to improve irrigated cane production, based on data from selected estates across sub-Saharan Africa (SSA), characterised the region to have lower-than-expected yields ranging between 83.9 and 108.9 t/ha, excessive irrigation consumption and lower than potential water productivities – ranging between 5.0 and 7.8 kg/m³. Benchmarking irrigation performance across the sugarcane sector using a set of key performance indicators (KPIs) confirmed that there were a number of challenges linked to disparities in cane yields, water productivity and the environmental impacts of production. This confirmed that relying on continued expansion of cultivated areas simply to increase sugarcane production is an unsustainable long-term strategy. Performance gaps in relation to low yields, water productivity and inadequate irrigation management practices leading to excessive irrigation water use were identified as key signs of inadequate management practices. These aspects not only have significant implications on the sustainability of sugar business operations, but also on the environmental impacts of irrigated production. The study provides valuable insights on the interventions needed to improve irrigated sugarcane production across SSA with a focus on improving yields, and reducing irrigation and energy use at the business or estate level.

1. Introduction

Sugarcane is an internationally important source of food (sucrose), bio-ethanol and electricity and thus a significant contributor to the economies of many countries globally (Singels et al., 2021). The crop is grown in more than 100 countries (Singels et al., 2021) and in 2022, 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). Global average cane yield (production per unit area) has increased by 41% between 1961 and 2022, equivalent to an increase of 0.4 t/ha per year. Sugarcane production trends in Africa, over the same period, indicate an overall average increase of > 1 million t/year (FAOSTAT, 2022). However, this increase has been due to an expansion in the overall cultivated and harvested area, rather than an uplift in productivity and, unlike the global trend, the African yield trend over the same period shows an average reduction of 0.03 t/ha per year.

Africa has high potential for increasing sugarcane production due to its suitable soils, available water resources for irrigation, wet and hot summers that are suitable for plant growth, cool, sunny and dry winters

that provide excellent conditions for conversion to sucrose and relatively low costs of production. Africa is also strategically close to European markets (Tyler, 2008), and thus an important region for agricultural expansion (Hess et al., 2016) which has a potential to boost economic growth and development in the region.

In many African countries, irrigation is a key determinant for improving cane 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), equivalent to 209 m³/t, (Gerbens-Leenes and Hoekstra, 2012) making sugar production a major consumer of blue (freshwater) resources. Thus, the expansion of cropped areas to increase cane production in Africa would require withdrawals of significant additional volumes of water. This would likely intensify competition for water amongst existing sectors including manufacturing industries, hydro-power generation, domestic water supplies and to support environmental flows. Thus, the dependency on expansion of cropped areas to support increased cane production has implications that are more significant for irrigated agriculture compared to the

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productivity increase due to improved yields.

Although sub-Saharan Africa is not considered water poor (Lautze and Giordano, 2007) since it contains 9% of the world's freshwater resources, coupled with a low per capita rate of water withdrawals, irrigated sugarcane production has significant potential to alter local water balances and thus, impact on the dynamics, quality, and quantity of water supplies for water at the watershed scale (Hess et al., 2016). Both cane production and sugar processing can have significant impacts on water resources (Hess et al., 2014). 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 in the long-term.

Irrigation systems comprising infield equipment, pumping and conveyance systems and flow control structures provide the means for supplying supplemental water to a crop. While the system is designed to apply water via either surface or overhead methods, it is important that the system is designed to take account of crop water needs and local soil characteristics, to minimise water losses and/or crop stress due to an inadequate water supply. Thus, the choice and performance of a particular irrigation system has an important bearing on the final yield. This entails that in irrigated production, an irrigation system and its management practices offer options for yield improvement where yields are lower than what might be achieved from best management practices.

Improvements in irrigation system performance have been shown to improve yields (Baillie, 2004; Holzapfel et al., 1985; Inman-Bamber et al., 1998; Pérez-Ortolá et al., 2015; Reinders, 1996). Increasing and sustaining high cane yields thus require a commitment to driving continuous improvements in irrigation system performance. The need to enhance irrigated production in the face of reducing water resources (Cai and Rosegrant, 2003; Neupane and Guo, 2019) means it is 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. Furthermore, the need for more intensified production to meet food requirements for a growing population demands more sustainable exploitation of 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 optimally. Thus, a sustainably managed farm unit maximises financial outputs, while safeguarding the preservation and protection of the environment in the pursuit to meet society needs (Dillon et al., 2009). Identifying appropriate technology and management options to improve crop yields, water and energy use and productivity are key challenges facing the agricultural sector in SSA. The study aimed to identify areas where improvements in irrigated sugarcane production were required, by evaluating water management practices through the use of selected key performance indicators. These were used to provide insights into current water management practices, the variation in performance across different production sites and to identify opportunities for improving irrigation management to offset the declining trend in cane yields across the SSA region.

2. Materials and methods

2.1. Study area

The study was undertaken across five sugarcane estates located in eastern and southern Africa. The countries included Eswatini, Malawi, Tanzania and Zambia. These are significant cane producers that collectively represented > 15% of global sugarcane production between 2000 and 2022 (FAOSTAT, 2022). Whilst the specific locations of each site are not important, to maintain confidentiality, the individual estates involved in the study were numbered 1–5.

2.2. Identifying performance gaps

The study employed a benchmarking approach to identify opportunities for improvement of cane yields and water use. The need to establish performance 'gaps' to inform the processes required for continuous improvement and to ensure sustainable agricultural production, led to the development of methods for assessing and/or evaluating on-farm performance including benchmarking. Malano and 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 key performance indicators (KPIs) of interest against known standard or point of reference or benchmark (Malano, Burton, et al., 2004). Such comparison seeks to establish the extent and direction of deviation from the point of reference (performance gap). The application of benchmarking in agriculture has gained worldwide attention (Knox et al., 2013; Malano, et al., 2004) and is a well-established technique. It has been applied in different sectors including agriculture (Borgia et al., 2013; Devkota et al., 2019; Lewandowska-Czarnecka et al., 2019; Muema et al., 2018), environmental performance assessment (Grinsven et al., 2019; Mua et al., 2017), healthcare (Dewan et al., 2000), power generation (Andersson et al., 2018; Maldonado, 2015), education (Herman et al., 2010; Jaap and Hendriks, 2004) and water supply (Suchacek et al., 2018) and irrigation system performance (Knox et al., 2013).

The benchmarking process involved (i) definition of appropriate KPIs based on the study objectives, (ii) data identification and planning – where data availability, integrity and consistency in terms of type; format and periods of availability among entities under observation were ascertained, (iii) data collection process – which involved retrieval of the required datasets (from databases and responsible individuals – interviews) while ensuring that data consistency and integrity were preserved and (iv) data analysis – where differences, trends and rates of change, gaps in performance were determined from the defined KPIs across the entities.

2.3. Defining key performance indicators

The KPIs used in the study were related to agricultural productivity, irrigation management and water supply. Table 1 summarises the KPIs and data requirements for their computation.

Table 1

Key performance indicators (KPIs) used for the benchmarking assessment and their 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 Total cane yield (t) Total harvested area (ha) Seasonal irrigation water use (mm) Total effective rainfall (mm)
	Water productivity (kg/m ³)	Seasonal crop water requirement (ET _c – mm) Seasonal irrigation water use (mm) Seasonal effective rainfall (mm)
Irrigation system operation	Relative water supply	Seasonal crop water requirement (ET _c – mm) Seasonal irrigation water use (mm) Seasonal effective rainfall (mm)
	Relative irrigation supply	Seasonal crop water requirement (ET _c – mm) Seasonal irrigation water use (mm) Seasonal effective rainfall (mm)

2.3.1. Irrigation system productivity (SP)

Under similar operating and management conditions, no significant differences in performance would be expected where the same irrigation system is used. However, differences in performance would likely be an indicator of inadequate or inappropriate irrigation management practices. Thus, irrigation system productivity (SP, t/ha for a given irrigation system) was used as an indicator to assess irrigation system performance. The main irrigation systems across each of the estates were identified to determine their respective crop productivities. Irrigation system productivity was then compared to gauge system performance across each of the sugarcane estates.

Irrigation system productivity for each estate was determined by Eq. (1):

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

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

2.3.2. Water productivity (WP)

Ali and Talukder (2008) defined water productivity as the amount of yield produced per unit volume of water consumed. Cai and 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 study the definition of water consumption proposed by Cai and Rosegrant (2003) was extended to represent the total volume of water available to the growing crop (including effective rainfall and net irrigation). The net water volume thus 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 potentially a result of appropriate irrigation management practices including correct scheduling (amounts and timings of water application), efficient application systems (less non-beneficial water consumption), and higher crop yields as a result of improved beneficial water consumption and reduced crop stress. Thus, in the comparison of water productivities across different estates, low water productivity would be an indication of poor irrigation water management practices.

Water productivity (WP) (kg/m^3) was determined by Eq. (2):

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

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

2.3.3. Relative water supply (RWS)

Sakthivadivel et al. (1993) and Kloezen and Garcés-Restrepo (1998) defined relative water supply (RWS) as the total amount of water made available to a crop from all possible sources including rainfall, groundwater and irrigation in relation to the theoretical crop water demand (ET_{crop}). It indicates the relative water abundance (or shortage) during the growing 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 and Garcés-Restrepo, 1998). It includes water supplies from sources that are almost impossible to schedule and control including rainfall and groundwater and hence is not necessarily a good measure of irrigation performance. However, it indicates the extent to which water is made available to the growing

crop which is the basis for sound water resources management – one needs to know the total available water resources to plan efficient water allocations. A RWS value > 1 indicates an over-supply and RWS value < 1 indicates insufficient water supply. The RWS values were determined by Eq. (3):

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

Where i_{net} was the net irrigation application (mm), r_{eff} was effective rainfall (mm) and ET_c was the crop water demand (mm) computed from cane reference evapotranspiration (ET_{cane}) following an approach by Inman-Bamber and McGlinchey (2003).

2.3.4. Relative irrigation supply (RIS)

Relative irrigation supply (RIS) represents the water supplied via irrigation in relation to irrigation water demand (Kloezen and Garcés-Restrepo, 1998) and indicates how well an irrigation system meets irrigation demands. While RWS takes into consideration the total crop water requirements, RIS is only concerned with the irrigation water demand component – the difference between total crop water demand and the water supplied from other sources including rainfall and groundwater (Kloezen and Garcés-Restrepo, 1998). It is a more appropriate 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, an RIS value > 1 signals over-irrigation and an RIS value < 1 implies under irrigation. The RIS values were calculated by Eq. (4):

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

Where the parameters i_{net} , r_{eff} and ET_c were defined in Eq. (3).

2.3.5. Data identification and collection

A questionnaire was developed and administered to each of 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. Following 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 to ensure consistency across the individual businesses. Through these meetings, it was established that the estate businesses used an information management system 'Canepro' (SQR Software, 2023) to handle all production records including irrigation, agronomic, labour utilisation and harvesting records. Canepro is a multifaceted management tool tailored and designed for multiple users linking different records across departments in a large sugarcane estate. Each estate had cropping and irrigation datasets that spanned different time periods. The disparities in data availability necessitated application of data quality checks including accuracy, completeness and consistency to ensure data quality and reliability for the benchmarking exercise.

In addition, each of the estates recorded 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 areas of cane cultivated and harvested under each type of irrigation system. All the estates used the cane reference evapotranspiration (ET_{cane}) developed by Inman-Bamber and McGlinchey (2003) for estimating cane crop water requirements. The daily ET_{cane} was estimated from daily weather data from automatic weather stations located on each estate – the ET_{cane} was used in the computation of RWS and RIS. Thus, all estates used a similar method for determining their irrigation water requirements. All estates generally adopted similar practices regarding record keeping, the determination of crop water

requirements, and irrigation scheduling practices. This consistency in practices across the estates was important as it provided a common basis for conducting the irrigation benchmarking analysis.

2.4. Data analysis

Data analysis involved ranking and determining temporal and spatial variation trends. The temporal variations provided insights on the extent of intra-estate differences in performance while the spatial variations were an indication of the extent of performance differences over the period of interest. KPI values for respective estates were analysed and compared statistically using the R programming language, where possible, by irrigation system type. Statistical analysis of variance (ANOVA) was also applied to the derived KPI values to establish the statistical levels of significance ($p = 0.05$) in the observed variations between each sugarcane business. This helped in determining the extent of intra- and inter-estate performance for each KPI. A copy of the questionnaire used to collect the raw data for the benchmarking, including the R code for data analysis can be accessed via the GitHub link (<https://github.com/Vuttol/Benchmarking-Files>).

3. Results and discussion

The application of the data quality checks revealed inconsistencies between and within individual estate operations. While all estates had datasets up to 2019, they had different starting dates. For example, estate 1 had records from 1979, estate 2 (from 2001), estate 4 (from 1992), and estates 3 and 5 (from 2000). In addition, there were missing/incomplete records within individual estates. For example, while estate 1 recorded yield from 1979 to 2019, the estate's irrigation and climate data were only available from 2003. Similar issues were also observed for the other estates. However, the quality and reliability of the data (including aspects relating to data consistency, completeness and validity) across the estates improved after 2009 and consequently the period 2009–2019 was used for deriving the crop and irrigation related KPIs for each estate.

3.1. Irrigation systems, application and cane yield

Centre pivot, furrow and sprinkler systems were the dominant irrigation application methods used across most (80%) estates (Table 2). Estate 1 did not have sprinkler and/or drip irrigation systems installed. While the analysis included sprinkler systems, drip irrigation was excluded due to the short time over which it has been used on some estates.

Substantial variations in irrigation application ($p < 0.05$) were observed between estates for given irrigation systems (Fig. 1). Overall, centre pivot systems applied the most water while sprinklers applied the least. While variations in irrigation water use between estates is expected, due to location differences that influence irrigation requirements, it is unusual for irrigation amounts (depths applied) to vary significantly across systems where estates have similar agro-climatic conditions and soil characteristics. Intra-estate differences in irrigation application by system type (on the same crop) is an indication of inappropriate or inconsistent irrigation management practices, implying that

ET_{cane} is not being appropriately incorporated into the scheduling plan and/or being implemented in-field as expected. Sugarcane has growth stages that are highly sensitive to water stress (Banda et al., 2019; Carr and Knox, 2011) so a mismatch between irrigation requirements and actual applications (both in quantity and timing) can lead to significant yield loss. To maximise the yield (and quality) benefits of irrigation, there is need to meet the irrigation requirements at each growth stage – which can only be achieved by monitoring and meeting the crop water requirements (ET_{cane}) and irrigation demand.

Average cane yields showed significant variability between individual estates with yields ranging between 83.9 and 108.9 t/ha. There was no significant difference in yield between estates 4 and 5. In general, all estates reported average yields below 120 t/ha – a threshold which is internationally considered to be “good” yield 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 yield of 98 t/ha for irrigated cane in SSA. The commercial yield criterion implies only estate 2 falls outside the lower range; this could be due to a combination of irrigation practices, but also other agronomy and management factors.

3.1.1. Irrigation system productivity

Significant yield differences were also observed between application systems on individual estates (Fig. 2). The centre pivot system produced the highest average system productivity (at estates 2, 3, 4 and 5) while the sprinkler systems produced the lowest average system productivity with furrow systems falling in between. The system productivity for the centre pivot ranged between 92.9 and 110.6 t/ha. On the other hand, furrow irrigated fields showed significant differences ($p < 0.05$) in system productivity across all five estates, ranging from 85.5 t/ha and 111.8 t/ha. There were no significant differences in system productivity for sprinklers across all estates.

While the observed differences in system productivity among the estates could be due to differences in yield potential for the localities in which the cane was grown, they could also be due to irrigation management practices. For example, at estate 1 the system productivity under two different systems (centre pivot and furrow) were not significantly different despite the irrigation applications being significantly different. Estate 1 had access to abundant water supplies so water was not a limiting factor to cane production. When water availability is unconstrained, it is rational to aim for maximum crop yields (Banda et al., 2019) by meeting the full irrigation requirements. However, where objective irrigation scheduling techniques are not being practiced, farmers risk over-irrigation leading to lower water productivities, despite achieving maximum yields. This not only impacts on the economic viability due to a decline in yield returns associated with additional irrigation, but also has potential to create negative environmental impacts associated with over-abstraction. Over-irrigation can lead to surface runoff, increased soil erosion risks and nutrient leaching due to deep percolation. Collectively, these could cause increased siltation and pollution of water channels and/or water bodies, water quality degradation, eutrophication and salinity. Similarly, at the other four estates, the systems that applied the highest irrigation applications did not deliver the highest cane yields. Until a point where the concept of diminishing returns is triggered, more water would lead to more yields (English, 1990; English and Raja, 1996) with inflexion point in the yield-water production function representing the water-maximum yield combination. Given that the systems which applied the largest irrigation applications did not deliver the highest yields, the potential yield benefits from irrigation were not being maximised across the estates. This could be an indication of inadequate irrigation management practices across the estates, including ensuring that the timing and amounts of irrigation applied matched the intended schedules.

Sprinkler systems produced the lowest average cane yield across all estates. Elsewhere, sprinkler systems have been observed to perform

Table 2

Summary of the different irrigation systems used at each estate between 2009 and 2019.

Irrigation type	Irrigation system	Estate 1	Estate 2	Estate 3	Estate 4	Estate 5
Surface	Furrow	✓	✓	✓	✓	✓
Overhead	Sprinkler	-	✓	✓	✓	✓
	Centre pivot	✓	✓	✓	✓	✓
Micro	Drip	-	✓	✓	✓	✓

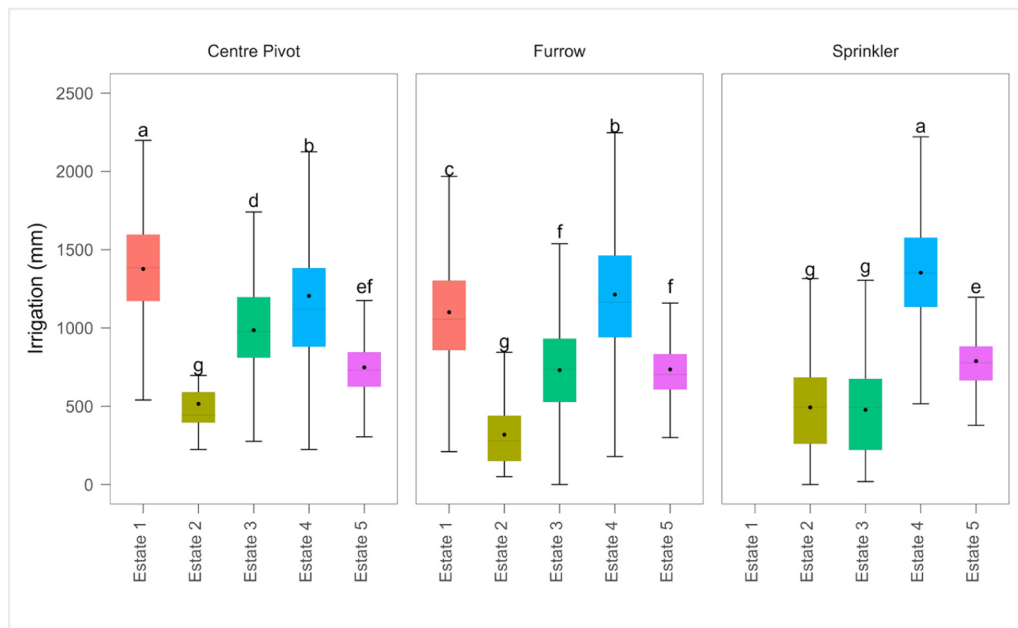


Fig. 1. Comparison of application depths (mm) between irrigation systems by estate (2009–2019). Letters on each boxplot denote significant differences between systems across the estates.

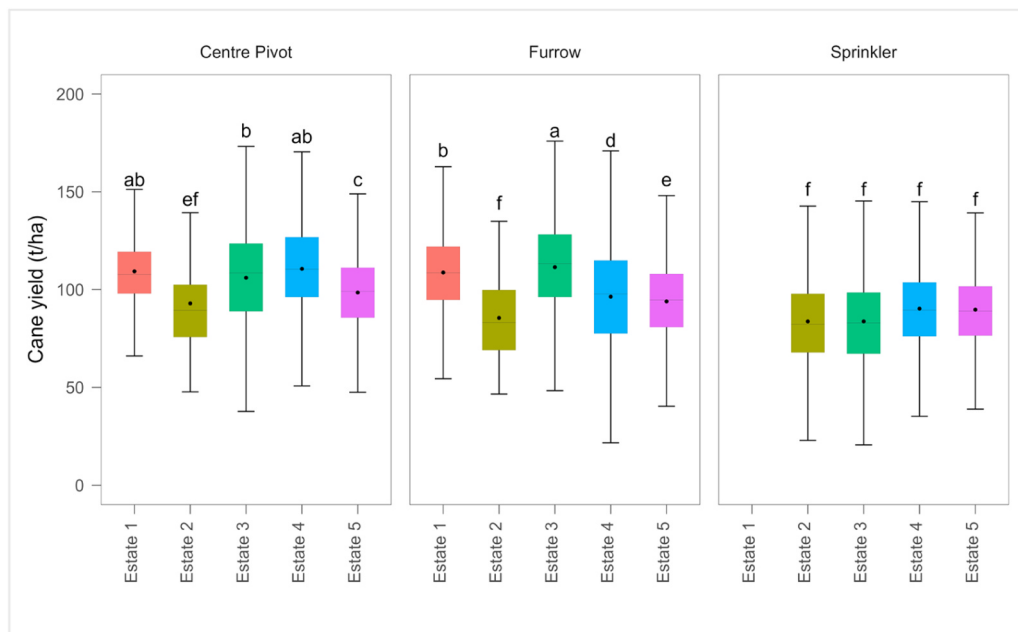


Fig. 2. Cane yield variation (t/ha) by irrigation system, by estate between 2009 and 2019. Letters on each boxplot denote significant differences between systems across the estates.

better than surface irrigation systems including furrow (Chauhdary et al., 2023; Xue and Ren, 2016). Differences in irrigation performance between different systems are generally attributable to design and management aspects (Hamid et al., 2024). The sprinkler systems used on the five estates in this study were a ‘dragline’ type where sprinklers mounted on tripod stands are connected by way of portable hoses to a pressurised water supply line (Zadrazil, 1990). Operation of the dragline system involves manually moving and fixing the sprinkler stands at predefined locations, but this process becomes more difficult as the cane crop height increases. Achieving maximum system performance (especially in fully grown cane) therefore requires careful in-field management to ensure the sprinkler risers are in the right location to achieve

correct overlapping. The low yields attributed to the sprinkler systems across the estates in this study could therefore be linked to the inherent challenges of their in-field irrigation management.

3.2. Water productivity

Fig. 3 shows the variations in water productivity at each estate between 2009 and 2019. The average water productivity ranged between 4.3 and 7.8 kg/m³. Estates 3 and 1 were the most and least water productive, respectively. The furrow system on estate 3 was the most water productive (7.8 kg/m³) whilst the sprinkler systems used on estates 2 and 4 were the least productive with average water productivities of



Fig. 3. Estimated variations in water productivity (kg/m^3) by estate between 2009 and 2019. Letters on each boxplot denote significant differences between systems across the estates.

4.3 kg/m^3 (Fig. 4).

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/m^3 , respectively. The estimated water productivities for all five estates were below these reported values for each corresponding country. Low water productivity is potentially an indication of inadequate irrigation management practices including irrigation scheduling (incorrect amounts and/or timings of water

application), inefficient irrigation systems (excess non-beneficial water use) and lower yields as a result of high non-beneficial water use and crop stress. Hess et al. (2016) reported that irrigated sugarcane productivity is almost threefold higher than that from rain-fed cropping. However, the impact of irrigation can only be maximised if it is applied where it is required at the right time and in the right amount. Proper irrigation management practices including correct irrigation scheduling have potential to improve water productivity (Birendra et al., 2021;

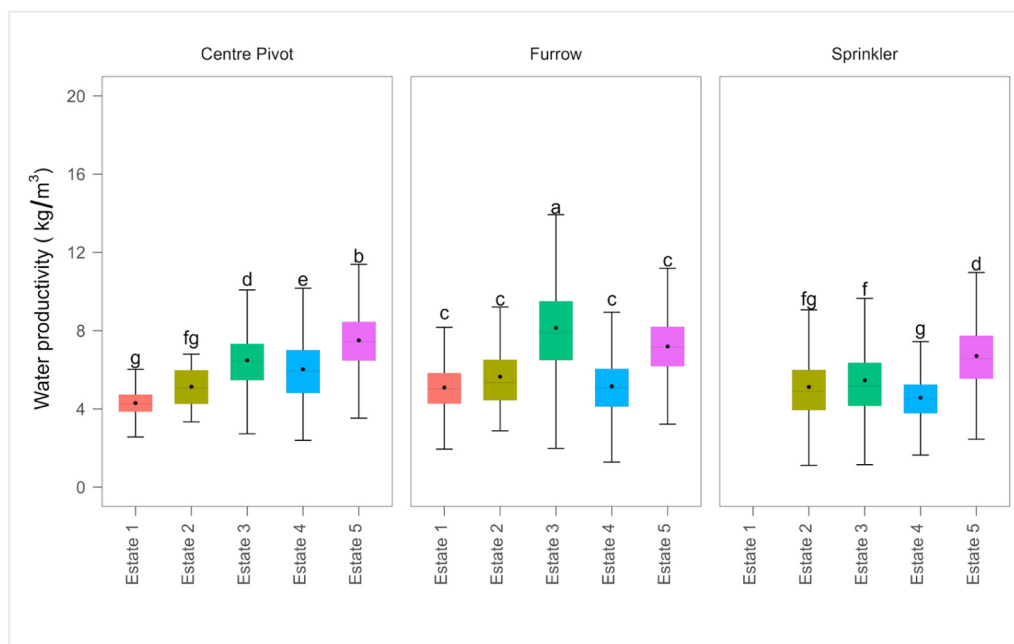


Fig. 4. Seasonal water productivity (kg/m^3) variation across estates grouped by irrigation system between 2009 and 2019. Letters on each boxplot denote significant differences between systems across the estates.

Jones, 2004; Li et al., 2024; Song et al., 2022). 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 this area. Water productivity can be improved when the yield benefits attributable to irrigation (through scheduling) are maximised. This not only helps to reduce water waste, but also ensures that the water applied contributes to productive use and minimises crop stress and non-beneficial losses.

3.3. Relative water supply (RWS)

The estimated RWS values across the five estates between 2009 and 2019 showed significant variations (Fig. 5). Estate 1 showed a consistent over-supply of water (34% on average each year) with a RWS > 1. On average, estate 4 had 13% over-supply each year while estates 2, 3 and 5 had average water supply deficits of 13%, 25% and 1%, respectively. Estates 4 and 5 showed variable water supply situations with the total supply exceeding crop water requirements in some years but inadequate in other years, while estates 2 and 3 showed supplies consistently inadequate to meet crop water requirements (Fig. 6).

3.4. Relative irrigation supply (RIS)

The range in estimated RIS values showed significant variation both between individual estates (Fig. 7) and across different cropping years (Fig. 8). While RIS values of < 1.0 indicate inadequate irrigation, any divergence (positive or negative) could also imply shortcomings in irrigation management. For example, estates 1 and 4 showed values > 1.0 in most years, in contrast to estates 2 and 3 which had values < 1.0 in most years. In cane production, irrigation is meant to supplement rainfall to support crop production and should only be applied when soil moisture contribution from rainfall is insufficient to meet crop water requirements. Inconsistencies in RIS imply that estates 2 and 3 potentially suffered yield losses due to water stress (RIS < 1) through inadequate irrigation scheduling and/or in-field system management. The gap

between actual and target RIS values highlights the opportunity for improved irrigation management practices including scheduling and water supply planning. While high yields are often associated with adequate water supplies, it is also dependent on appropriate on-farm water management practices. This determines the level of consistency in crop productivity and limits excessive non-beneficial water losses, reduces pumping costs and improves both crop yield and quality. Although rainfall and irrigation constitute the main inputs to support production, emphasis needs to be focussed on irrigation as it provides the greatest opportunity to be managed and controlled to attain maximum crop benefit.

3.5. Methodological limitations

Due to data constraints, the study was limited to considering only agronomic and water productivity related KPIs, and excluded those relating to financial, environmental and energy factors. For example, these could have included, crop water benefits (£ per m³ water applied), the blue water footprint (m³ water per ton of cane), a carbon footprint per volume (kg CO₂/m³), the energy efficiency of irrigation (kWh/m³) and the energy consumption per unit irrigated area (KWh/ha). There was also a scale issue, with the RWS and RIS indicators being estimated at the estate level, rather than at a field by field level. This would have provided valuable insights into how in-field irrigation management and system application practices impacted on performance (water and energy) and crop productivity (yield and value).

4. Conclusions

Using a benchmarking approach, this study identified key areas where improvements in irrigated sugarcane production might be required across a sample of estates in southern and eastern Africa. Improving irrigation scheduling practices appears to be a key opportunity for improving yields, reducing irrigation use and increasing water productivity. The sugarcane industry in SSA employs various irrigation

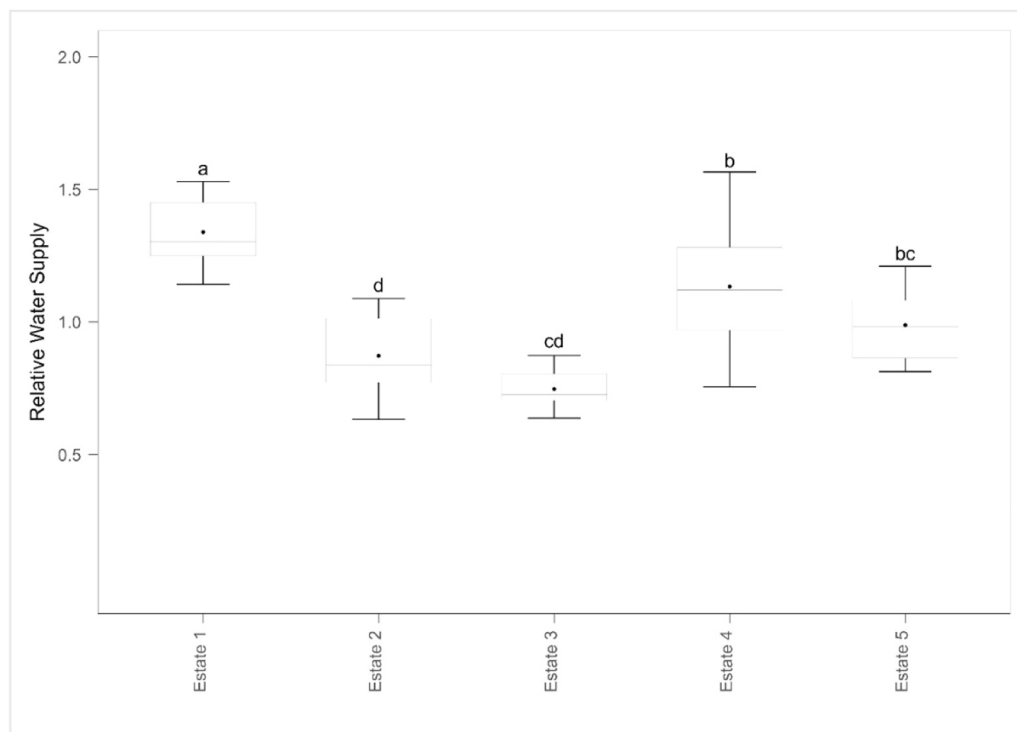


Fig. 5. Differences in relative water supply (RWS) between estates (2009–2019). Letters on each boxplot denote significant differences between systems across the estates.

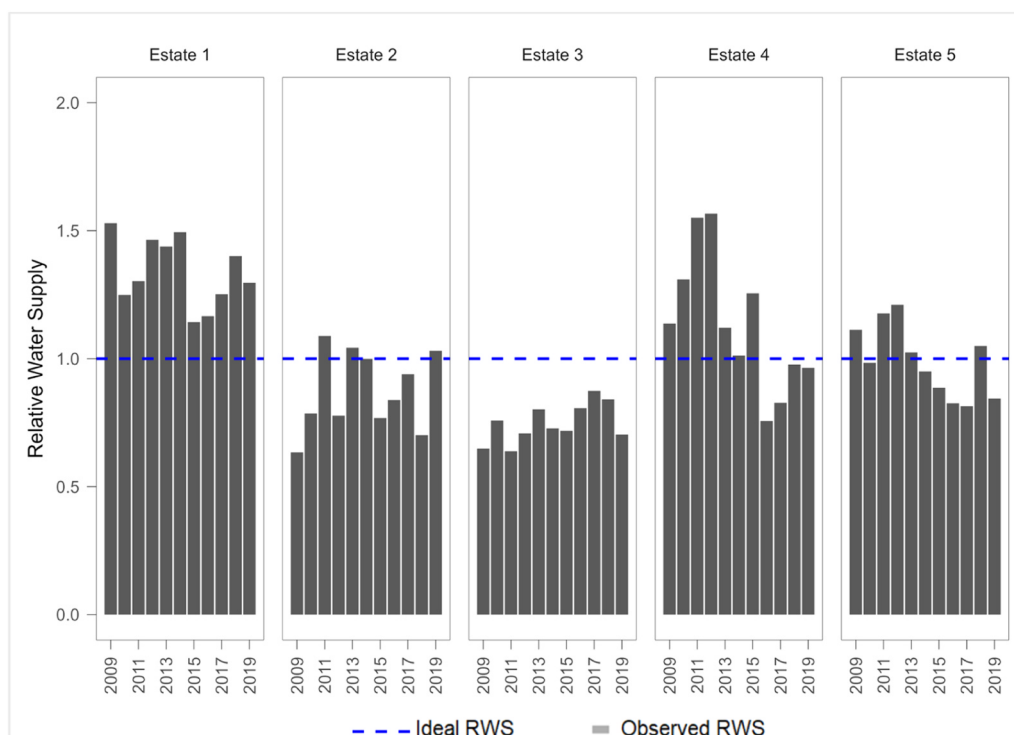


Fig. 6. Relative water supply (RWS) for each estate between 2009 and 2019.

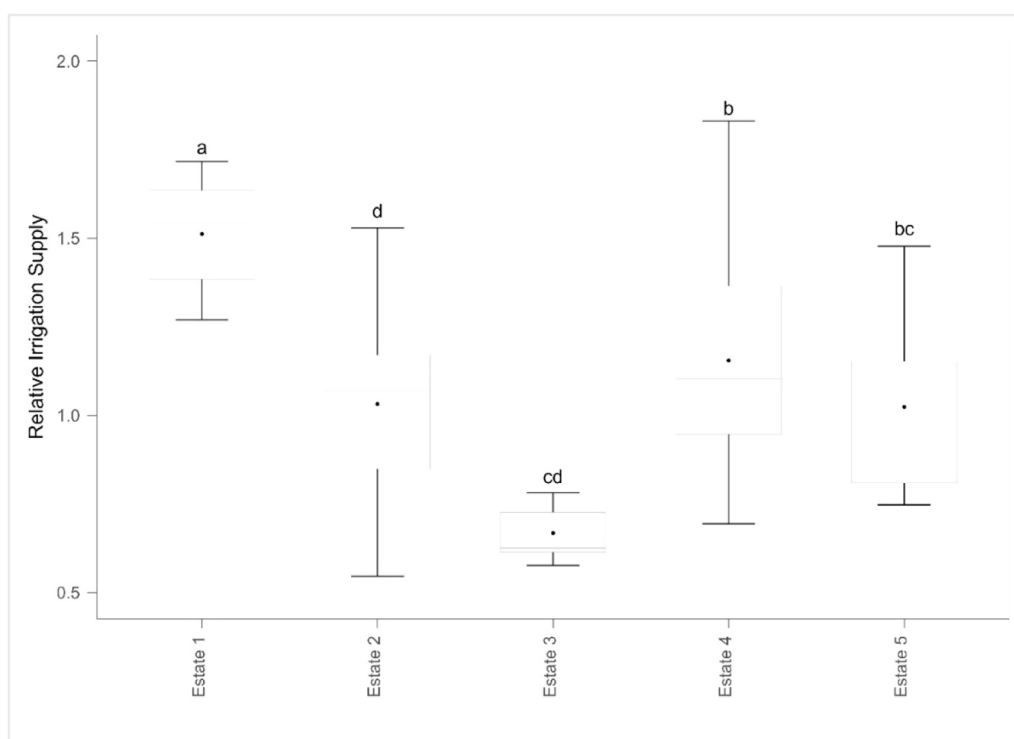


Fig. 7. Variation in relative irrigation supply (RIS) by estate between 2009 and 2019. Letters on each boxplot denote significant differences between estates.

methods including overhead (centre pivots and sprinklers), localised or micro (drip), and surface (furrow). However, crop yields and water productivities under each of these systems showed significant variability. Based on the study findings, the yield benefits associated with irrigation do not appear to be maximised across these regions in SSA, with evidence of highly variable yields, low water productivities and

mixed irrigation management practices leading to excessive irrigation use. Future research could focus on extending the benchmarking analysis across a wider network on cane estates and incorporating additional, financial, energy and environmental indicators to develop a more complete assessment of where the greatest opportunities for improvement lie in the cane industry.

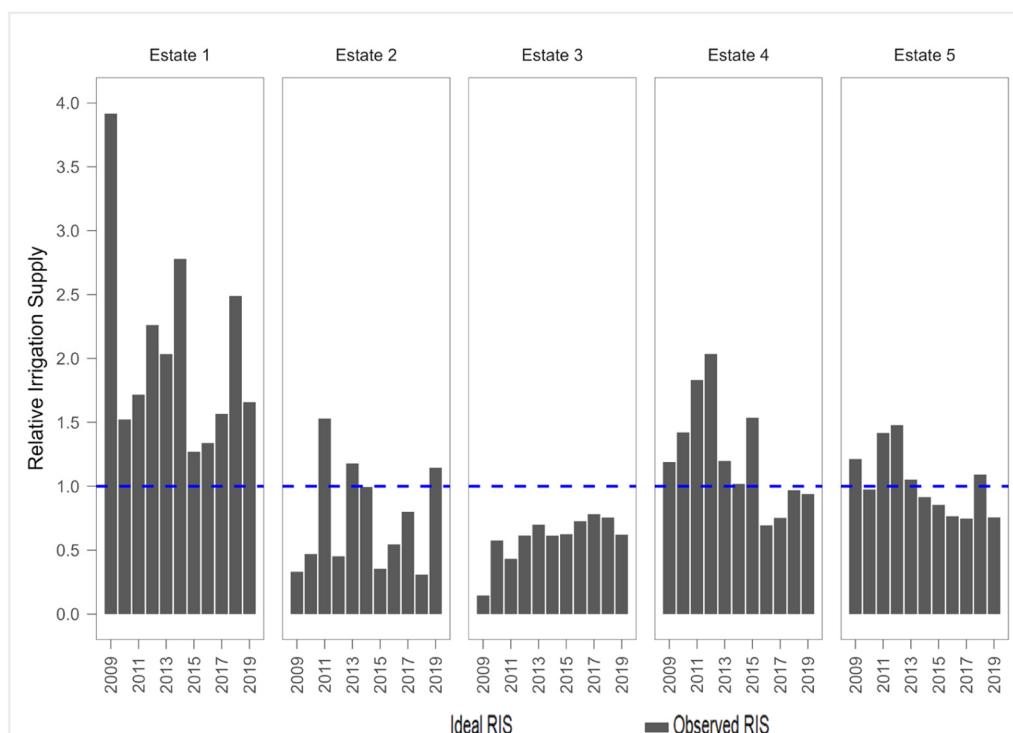


Fig. 8. Annual variation in relative irrigation supply (RIS) for each estate between 2009 and 2019.

CRedit authorship contribution statement

Tim Hess: Writing – review & editing, Supervision, Conceptualization. **Mavuto Banda:** Writing – original draft, Methodology, Formal analysis, Data curation. **Jerry Knox:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

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Data availability

Data supporting this study cannot be made publicly available due to its commercial sensitivity.

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