Experimental Agriculture (2024), vol. 60, e15, 1–17
doi:10.1017/S0014479724000127

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Impact of soil type and harvest season on the ratooning ability of sugarcane varieties

Njabulo Eugene Dlamini[1,2], Angelinus C. Franke[2] and Marvellous Zhou[3,4]

[1]Eswatini Sugar Association Technical Services, Simunye, Eswatini, [2]Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, South Africa, [3]South African Sugarcane Research Institute, Mount Edgecombe, South Africa and [4]Department of Plant Breeding, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, South Africa
Corresponding author: Njabulo Eugene Dlamini; Email: njabulod@esa.co.sz

(Received 05 September 2023; revised 29 April 2024; accepted 08 May 2024)

Summary
Sugarcane varieties differ in their ratooning ability (RA), and it is hypothesized that soil types and harvest seasons impact varieties' RA. However, the effects of these factors on varieties' RA remain unclear. This study aimed to assess the RA of different commercial sugarcane varieties (NCo376, N19, N23, N25, and N36), and establish the effects of soils and seasons on ratoon yields of these varieties in Eswatini. Fifteen years data on tons cane per ha per annum (TCHA) and tons sucrose per ha per annum (TSHA) achieved by plant cane and seven ratoon crops were collected from four commercial growers and analysed using linear regression models. The varieties significantly differed in RA. Variety N25, which had the highest plant cane yields (121.3 TCHA and 16.7 TSHA), had the sharpest yield decline over ratoon crops (–2.74 TCHA and −0.33 TSHA), suggesting that this variety is more suitable for short crop cycles. Variety N36 had second highest plant cane yields (111.7 TCHA and 16.4 TSHA) and a lower ratoon yield decline (–1.38 TCHA and −0.16 TSHA) than N25, suggesting that it is suitable for longer ratoon crop cycles. While soil type and harvest season significantly affected the relative yields of varieties, they did not significantly impact their RA, indicating that differences in varieties' RA were driven by genotype and were relatively stable across environments. This suggests that tests to assess the adaptability of varieties should be conducted in multiple environments, while testing the RA of varieties may be conducted in fewer environments.

Keywords: sugarcane; ratooning ability; yield

Introduction

The profitability of sugarcane (*Saccharum* sp.) production depends on the availability of varieties that are adaptable and high yielding across multiple ratoon crops. In addition, these varieties must be resistant to pests and diseases of economic importance. The ability of a variety to sustain profitable yields over ratoon crops is termed ratooning ability (RA) (Chapman *et al.*, 1992; Ferraris *et al.*, 1993; Milligan *et al.*, 1996), and it is a desirable trait for improved economics in sugarcane production (Farrag *et al.*, 2019). In many sugarcane-growing countries, high RA is a prerequisite for commercializing a variety. Several definitions of RA have been offered in literature. Milligan *et al.* (1996) defined RA in absolute and relative terms. In absolute terms, a good ratooning variety is one that produces high ratoon crop yields and/or several economically rewarding ratoon crops. In relative terms, a good ratooning variety is defined as one whose ratoon crop yields provide a relatively high percentage of its plant cane or a younger crop's yields.

In practice, varieties with high plant cane yields are not necessarily varieties with high ratoon yields. Selection for RA necessitates variety testing over multiple crop-years (ratoon crops) in locations representative of conditions experienced by commercial growers. This has necessitated sugarcane industries, for instance in South Africa, Mauritius, and others, to establish post-release variety projects independent of the core plant breeding programme (Ramburan, 2018). These programmes are set up to evaluate the performance of released varieties in environments beyond those tested during selection and to test performance over several ratoon crops, whereas breeding trials are usually harvested over shorter ratoon cycles. Several studies have reported significant differences in RA of sugarcane varieties (Ramburan *et al.*, 2009; Zhou and Shoko, 2012; Masri and Amein, 2015), suggesting that RA is genetically dependent. Such knowledge presents sugarcane breeders and agronomists with an opportunity to simultaneously select for yield and RA.

In the sugarcane sector, it is widely accepted that sugarcane yields decline with successive ratoon crops (Milligan *et al.*, 1996), a phenomenon termed ratoon yield decline (RYD). To distinguish between RA and RYD, Ramburan *et al.* (2013b) intimated that RA is considered a genetic trait describing variety differences in RYD, while RYD describes the general decline in productivity with successive ratoons. Several factors have been cited as being responsible for RYD in sugarcane crops including soil hydraulic properties (Chapman *et al.*, 1992; Kingston, 2003), harvest season (time of harvest) (Lawes *et al.*, 2002; Di Bella *et al.*, 2009), pests (Carnegie, 1988; Stirling and Blair, 2001; Kingston, 2003), and diseases (Grisham, 1991; Irwin, 2019). It has been demonstrated that soils and harvest seasons significantly affect yields of sugarcane ratoon crops in Eswatini (Dlamini and Zhou, 2022). However, the findings of the study by Dlamini and Zhou (2022) did not take into consideration the interaction effects between varieties' yield and RA, and soils and harvest seasons. The general understanding is that soil and harvest season have significant effects on the performance of sugarcane varieties, and therefore, new varieties are tested across different soil types and seasons at representative trial sites prior to their release as commercial cultivars (Butler, 2001; Dlamini and Ramburan, 2016). However, no in-depth studies have been conducted to determine the relative contribution of these factors (soil, season, and varieties' RA) to RYD.

The objectives of this study were (i) to assess the RA of different commercial sugarcane varieties, (ii) to determine the relative contribution of soil types, harvest seasons, and variety to sugarcane RA, and (iii) to establish the effects of soil types and harvest seasons on varieties' ratoon yields.

Material and Methods

Datasets

Data used for this study were sourced from four large-scale sugarcane growers, and for purposes of the study, they are named G1, G2, G3, and G4. These growers together supply the three sugar mills (Big Bend, Mhlume, and Simunye) of Eswatini in southern Africa with approximately 62% of sugarcane annually. The growers plant large areas of sugarcane with diverse soil types. As such, they are able to supply cane to the mills throughout the milling season from April to December. Furthermore, these growers face comparable climatic conditions essential for sugarcane production (Dlamini and Zhou, 2022). They employ skilled personnel such as farm managers and agronomists. The assumption therefore is that the management of sugarcane is comparable across the four growers, and as such, any variation in crop yield can be attributed to factors such as soil type and harvest season. Furthermore, these growers were chosen for this investigation due to the availability of credible and comprehensive field data.

The dataset sourced from the four growers covers a 15-year period (2000 to 2014). Five sugarcane varieties (N19, N23, N25, N36, and NCo376) were chosen (Table 1). These varieties were all widely cultivated by growers in the industry during the test period. In addition, they were

Table 1. Parentage, origin, and year of release of the five varieties used in this study

Variety	Parentage	Origin	Year of release
NCo376	Co421 × Co312	Coimbatore, India (seed) & SASRI, South Africa	1955
N19	NCo376 × CB40/35	SASRI, South Africa	1986
N23	NCo376 × N52/219	SASRI, South Africa	1992
N25	Co62175 × N14	SASRI, South Africa	1994
N36	82F1225 × 78Z1635	SASRI, South Africa	2000

SASRI: South African Sugarcane Research Institute.

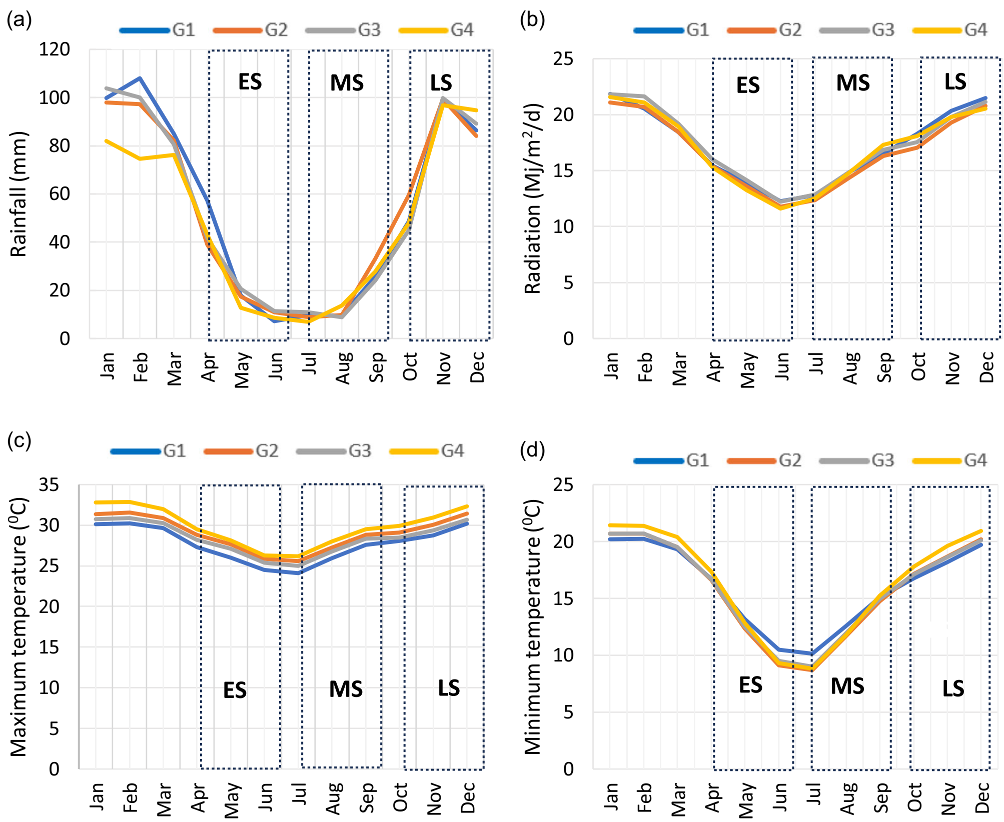

Figure 1. Mean monthly weather patterns (a): rainfall; (b): radiation; (c): maximum temperature; and D: minimum temperature for the four sugarcane growers (G1, G2, G3, and G4) recorded and averaged over the 2000–2014 period, retrieved from meteorological stations situated within each growing area. The three harvest seasons (early season, ES; mid-season, MS; late season, LS) are shown in columns with dotted outlines.

harvested across the different harvest seasons and grown on all soil types prevalent in the sector. Sugarcane harvesting in Eswatini typically occurs over a nine-month period (April-December). This period is segregated into three seasons: early (April to June), mid (July to September), and late (October to December), and the segregation is primarily driven by climatic conditions (Figure 1). Soils used for sugarcane production are broadly categorized into three types based on their hydraulic properties: well-draining, moderately draining, and poorly draining soils (Nixon *et al.*, 1986) as shown in Table 2.

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

Table 2. Land classes and soil types in the Eswatini sugar industry (sourced from Nixon *et al.* 1986)

Land class	Sets/Series	Description	Soil type
I	R, N, L sets	• Deep, red, well structured • Medium to heavy textured • Free draining	Good draining
II	W, B, F sets, Daputi series	• Moderate to weak structure • Deep, light textured • Excessively draining • Mainly of alluvial origin	Good draining
III	S set	• Shallow, well structured • Medium to heavy texture • Freely draining	Good draining
IV	T, D sets (excluding Daputi series)	• Moderate structure • Medium to heavy texture • Imperfectly draining • Moderately deep	Moderate draining
V	K, C, V sets	• Deep • Blocky or cracking clays • Moderate to poor drainage	Moderate draining
VI	Z set, Homestead series	• Thin topsoil (often absent) • Coarsely structured subsoil • Inherent salinity/sodicity problems • Poorly draining	Poor draining
VII	E, O, P, J, G, H sets (excluding Homestead series)	1. Coarsely structured topsoil 2. Abrupt change to heavy, poorly drained subsoil 3. High salinity/sodicity risk	Poor draining

Crop husbandry practices such as planting, irrigation, fertilizer application, pests and disease control, and harvesting are standard across estates in the Eswatini sugar industry. The timing and amount of water applied at irrigation depended on water holding capacity of the soil, effective rainfall, evapotranspiration, and crop age. The type and amount of fertilizing material applied are determined by a laboratory soil test. Essential nutrients' critical values for optimum sugarcane yields for the different soil types and harvest seasons were determined experimentally over many years and soil types. These are therefore important in formulating fertilizer recommendations.

For each field, the following variables were available: year of harvest, start date (planting date for plant cane and previous harvest date for ratoons), harvest date, soil set, variety, ratoon crop number, yield (tons cane and tons sucrose), and productivity (tons cane per hectare, TCH; tons sucrose per hectare, TSH; and sucrose content, SUC%). Sugarcane in the Eswatini sugar industry is harvested 12 months after planting or previous harvest for ratoon crops. For meaningful comparison across years, the productivity data (TCH and TSH) were annualized, that is they were extrapolated to represent yield at 12 months. The annualized TCH and TSH were expressed as tons cane per hectare per annum (TCHA) and tons sucrose per hectare per annum (TSHA), respectively.

Data analysis

The data were analysed using the generalized linear model procedure of GenStat® 21st Edition statistical software (VSN International, 2020), and only the first eight crops (plant cane and seven ratoons) were considered. The analyses were conducted for the three yield traits: TCHA, SUC%, and TSHA. Each variety, season, and soil type had entries of the eight crops. This approach addressed the confounding of ratoon crop and crop year experienced in variety trials (Kang *et al.*, 1987; Zhou and Shoko, 2012). Chapman *et al.* (1992) suggested that to address the confounding effect of ratoon crop and crop year, variety plantings should be repeated every year. However, this was not feasible given the additional land, labour, funds, equipment, and other resources that would be required.

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

The linear model equation used for this analysis was:

$$Y_{ijkl} = S_i + D_k + SD_{ik} + V_j + SV_{ij} + VD_{jk} + SVD_{ijk} + C_l + SC_{il} + DC_{kl} + VC_{jl} + SDC_{ikl} + SVC_{ijl} + VDC_{jkl} + E_{ijkl} \quad (1)$$

where Y_{ijkl} is the yield of variety j in ratoon crop l, grown in soil type k and harvested in season i; S_i, D_k, V_j, and C_l are the main effects of season i, soil type k, variety j, and crop l, respectively, and their interactions (SD_{ik}, SV_{ij}, VD_{jk}, SVD_{ijk}, SC_{il}, VC_{jl}, SDC_{ikl}, SVC_{ijl}, and VDC_{jkl}); and, E_{ijkl} is the residual. All factors were treated as fixed.

To compare and visualize the impact of main factors (i.e., season, soil, and variety) on the evaluated traits, figures with column charts were created. To evaluate the interaction effects of season by variety (SV) and variety by soil (VD) on the three traits, variety by environment-trait biplots were created using the GGE biplots software (Yan, 2001). These biplots allow the graphical display of the two-way data and visualization of the interrelationship among varieties, environment traits, and their interactions (variety by environment trait). The GGE biplots were constructed by plotting the first principal component (PC1) scores of the varieties and environment traits against their respective scores of the second principal component (PC2) that result from singular value decomposition (SVD) of environment-centred genotype by environmental interaction data (Yan *et al.*, 2007). A polygon was then drawn on varieties located farthest away from the biplot origin such that all varieties were contained within the polygon. A perpendicular line was then drawn from each side of the polygon through the biplot origin such that the biplot was divided into vertices. Varieties located on the vertices of the polygon were the best in the environment traits contained within the same vertices.

If any of the variance components (i.e., VC, SVC, and VDC) affecting RA in Equation 1 were significant, a simple linear regression was conducted to estimate intercepts and slopes of the different yield traits across ratoon numbers:

$$Y_{im} = \alpha_i + \beta_j C_m + \varepsilon_{im} \quad (2)$$

where Y_{im} is the yield of variety i in ratoon crop m; α_i is the intercept predicting plant cane yield of variety i; β_j is the slope of yield of variety i; C_m is ratoon crop number m; and ε_{im} is the random error. The results were presented in graphical form.

Results

Analysis of variance

Table 3 shows the analysis of variance for the three traits of interest: TCHA, SUC%, and TSHA. The main effects of harvest season (season), soil type (soil), variety, and ratoon crop (crop) significantly ($p \leq 0.001$) affected TCHA. Varieties had a larger influence (27.8%) on cane yield than soil, season, and crop (19.8, 18.8 and 17.8%, respectively). The two-way interactions of season × variety and soil × variety were highly significant ($p < 0.001$) indicating that season and soil affected the relative TCHA of varieties. The interactions of season × crop and variety × crop were also highly significant ($p < 0.001$) signifying considerable effects of seasons and varieties on RYD. Significant variety × crop interactions suggested that RYD differed between varieties. The interaction of soil × crop was not significant ($p > 0.05$) suggesting that soil type did not affect RYD. The highly significant ($p < 0.001$) three-way interaction of season × soil × variety indicated that the relative TCHA of varieties was affected by environments, defined by season × soil. However, the three-way interactions of season × soil × crop, season × variety × crop and soil × variety × crop were all not significant indicating that harvest seasons and soil types had no clear influence on differences in RA between varieties.

Table 3. Analysis of variance of cane yield per annum (TCHA), sucrose content (SUC%), and sucrose yield per annum (TSHA). Season (Se): [harvest season; soil (so): soil types; crop (C): ratoon crop]

		TCHA		SUC%		TSHA	
Variance components	NDF:DDF	p-value	%SS expl.	p-value	%SS expl.	p-value	%SS expl.
Season (Se)	2:112	<0.001	18.8	<0.001	42.2	<0.001	33.3
Soil (So)	2:112	<0.001	19.8	<0.001	7.0	<0.001	14.5
Se × So	4:112	0.001	0.4	<0.001	3.2	0.006	0.5
Variety (V)	4:112	<0.001	27. 8	<0.001	29.8	<0.001	17.4
Se × V	8:112	<0.001	0.6	<0.001	2.0	<0.001	1.3
So × V	8:112	<0.001	2.5	<0.001	2.6	<0.001	3.5
Se × So × V	16:112	<0.001	1.3	0.001	1.4	<0.001	2.2
Crop (C)	7:112	<0.001	17.8	<0.001	3.4	<0.001	14.1
Se × C	14:112	<0.001	4. 7	<0.001	1.4	<0.001	4.2
So × C	14:112	0.116	0.5	0.023	0.9	0.006	1.2
V × C	28:112	<0.001	1.9	0.667	0.8	0.01	1.9
Se × So × C	28:112	0.237	0.7	0.104	1.30	0.378	1.1
Se × V × C	56:112	0.059	1.7	0.074	2.6	0.102	2.6
So × V × C	56:112	0.101	1.6	0.730	1.6	0.158	2.4
Mean (Trait)		101.45		14.44		14.61	
SE		3.32		0.25		0.57	
CV%		3.30		1.70		3.90	

NDF: numerator degrees of freedom; DDF: denominator degrees of freedom; *p*-value: probability value; SE: standard error; CV%: coefficient of variation; %SS expl.: per cent sum of squares explained.

Harvest season, soil type, variety and ratoon crop had significant ($p < 0.001$) impacts on SUC% (Table 3). Season accounted for a larger portion (42.2%) of the variation in SUC% than variety (30.0%), soil (7.0%), and ratoon crop (3.4%). Significant ($p < 0.001$) season × variety and soil × variety interactions suggested that seasons and soils influenced the relative performance of varieties. Significant season × crop and soil × crop interactions indicated notable effects of seasons and soils on ratoon crops' SUC%. Unlike with TCHA, variety × crop interaction effects on SUC% were not significant, suggesting that differences in SUC% between varieties were not affected by ratoon crops. The highly significant ($p = 0.001$) three-way interaction of season × soil × variety suggested that the environment (season × soil) contributed to the differences in SUC% between varieties.

TSHA was significantly affected by harvest season, soil type, variety, and ratoon crop (Table 3). The order of importance of these main effects was season (33.3%), variety (17.4%), soil (14.5%), and crop (14.1%). Significant season × variety and soil × variety interactions indicated that seasons and soils affected the relative TSHA of varieties. The interactions of season × crop and soil × crop were highly significant, indicating that the decline in sucrose yield over ratoons differed between harvest seasons and between soil types. Variety × crop interaction was significant ($p = 0.006$) suggesting that TSHA decline with increasing ratoon crops differed between varieties. The three-way interaction of season × soil × variety was highly significant ($p < 0.001$) implying significant effect of environments on the relative performance of varieties. Similar to TCHA, the interactions of season × soil × crop, season × variety × crop and soil × variety × crop were not significant for TSHA.

For all three yield traits, the interaction of soil × variety accounted for a larger proportion of variation than the interaction of season × variety. This suggests that soil type had a greater effect on the differences in variety performance than harvest season. The interaction of season × crop explained a larger percentage of variation in all traits than the interaction of soil × crop. This indicates that harvest season had a greater influence on RYD than soil type.

Early and mid-season harvests gave higher TCHA than late harvests (Figure 2a). Mid-season harvests gave higher SUC% and TSHA than early and late-season harvests, and early-season

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

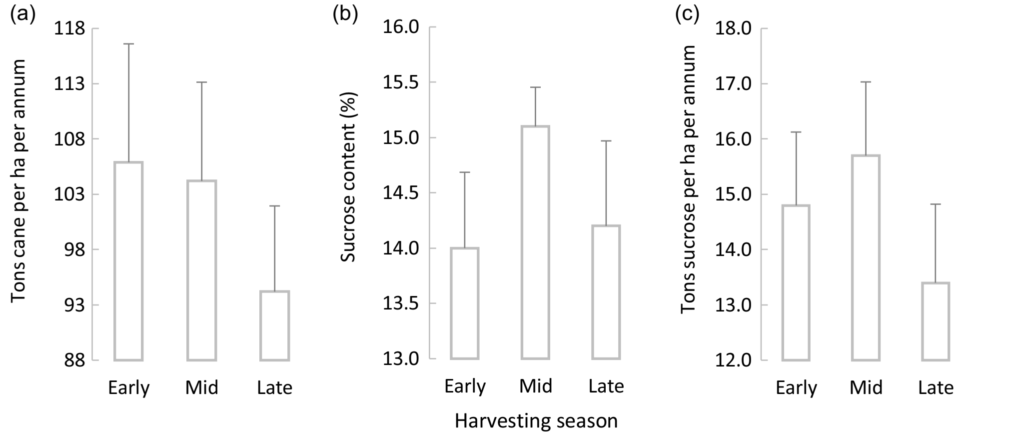

Figure 2. Comparison of averages of sugarcane yield – tons per ha per annum (a), sucrose content – % (b), and sucrose yield – tons per ha per annum (c) for three harvesting seasons – early, mid, and late. The vertical error bars represent standard errors. [Total number of observations is 360].

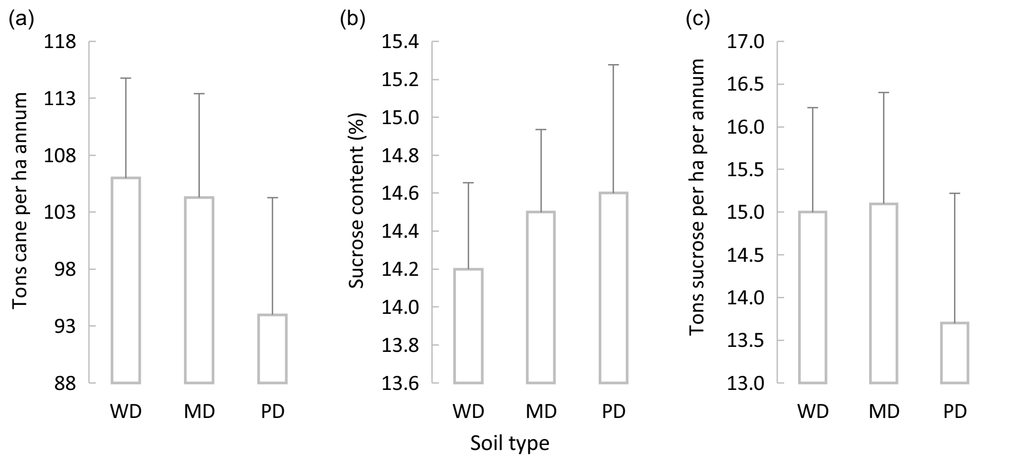

Figure 3. Comparison of averages of sugarcane yield – tons per ha per annum (a), sucrose content – % (b), and sucrose yield _ tons per ha per annum (c) for three soil types – well-draining (WD), moderately draining (MD), and poorly draining (PD) soils. The vertical error bars represent standard errors. [Total number of observations is 360].

harvests were greater than late season on both traits (Figures 2b and 2c). Well and moderately draining soils had higher TCHA and TSHA than poorly draining soils (Figures 3a and 3c). Poor and moderately draining soils had higher SUC% than well-draining soils (Figure 3b).

Variety N25 produced higher TCHA than the other varieties, followed by N36 and N23 (Figure 4a). Variety N19 produced higher SUC% than the other varieties, followed by N36 (Figure 4b). Variety N19 was the lowest on TCHA and variety N25, which produced the highest TCHA, was the lowest on SUC% suggesting a negative correlation between TCHA and SUC% for these varieties. Variety N36, which was second on both TCHA and SUC%, produced the highest TSHA than all the other varieties, followed by N25 and N23 (Figure 4c).

The older varieties, NCo376 and N19, produced lower TCHA and TSHA than the 'newer' varieties (N23, N25, and N36), suggesting genetic improvement on cane and sucrose yield.

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

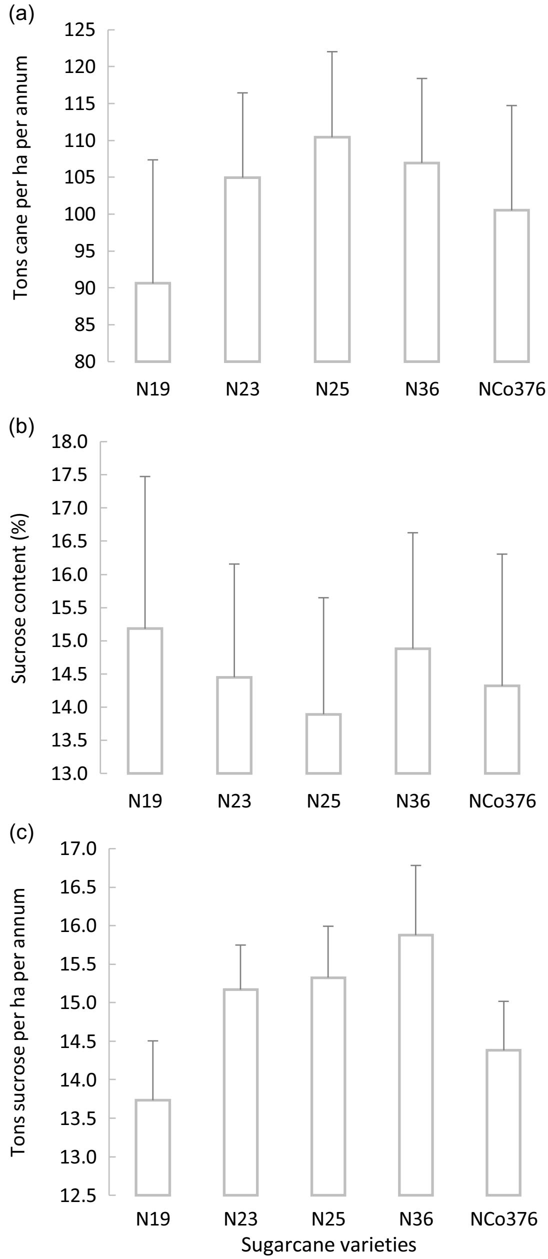

Figure 4. Comparison of averages of sugarcane yield – tons per ha per annum (a), sucrose content – % (b), and sucrose yield – tons per ha per annum (c) for five sugarcane varieties. The vertical error bars represent standard errors. [Total number of observations is 360].

Variety N25 produced the highest TCHA on well-draining and moderately draining soils (Figure 5a). There were no significant differences between N25 and N36 on TCHA on poorly draining soils. Variety N25 produced the highest TSHA on well-draining soils, while N36 was the highest under poorly draining and moderately draining soils. Variety N19 produced the highest SUC% on poorly and moderately draining soils, whereas N36 was the highest on SUC% on well-draining soils. Similar to harvest seasons, variety N23 showed an average performance on the three

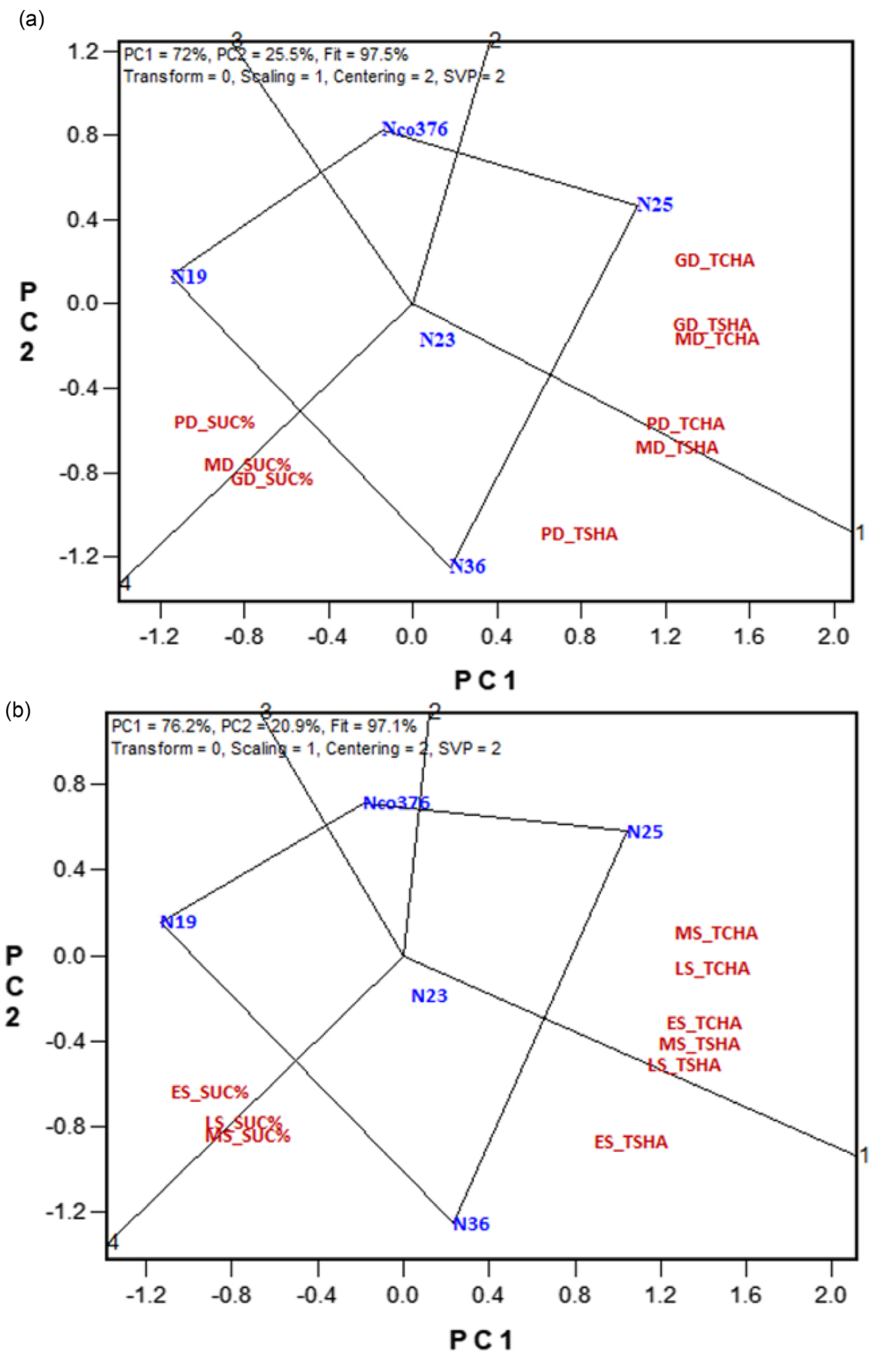

Figure 5. Variety by environment-trait biplots for five sugarcane varieties (NCo376, N19, N23, N25, and N36) planted on three soil types (well draining, WD; moderately draining, MD; poorly draining, PD) (a) and harvested across three seasons (early season, EL; mid-season, MS; late season, LS) (B) over eight successive crops (plant cane and seven ratoons) evaluated on cane yield (TCHA), sucrose content (SUC%), and sucrose yield (TSHA). The environment trait shows the relative yield of the trait in an environment. For example, MD_TCHA (a) and MS_TCHA (b) show the relative performance of the varieties on cane yield (TCHA) under moderately draining (MD) soil and mid-season (MS), respectively.

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

traits across soil types. The biplot (Figure 5a) captured 97.5% of the variation in the data, indicating a good model fit.

Variety N25 produced the highest TCHA across all harvest seasons (Figure 5b). Variety N36 produced the highest TSHA early season, while N25 was the highest mid-season. TSHA values for N25 and N36 were comparable late season as demonstrated by its location on the perpendicular line between the two varieties. Variety N19 produced the highest SUC% early season, while at mid-season and late season it was comparable to N36. Variety N23 had an average performance on all three traits. This is suggested by its proximity to the centre of origin of the biplot. The first two PCs (PC1 and PC2) of the biplot explained 97.1% of the variation within the data (Figure 5b), indicating a good fit.

Variety yield trends

The regression lines predicted TCHA (Figure 6a) and TSHA (Figure 6b) as a function of ratoon crop number. Ratoon number 0 referred to the plant crop, ratoon number 1 to the first ratoon crop, and so forth. SUC% was excluded from this analysis because the slopes of four of the five varieties were not significant, indicating that SUC% was hardly influenced by ratoon crop number as confirmed by non-significant variety × crop interaction. The results clearly showed the variability in intercepts and slopes of lines predicting TCHA and TSHA indicating differences in yield potential and RA between the varieties. The predicted TCHA of N25, a high-yielding variety, intersected with that of N36 in the seventh ratoon crop due to a larger cane yield decline in the former (−2.74 TCHA vs. −1.38 TCHA) (Figure 6a). The trendline predicting TCHA of variety N36 was slightly and consistently above that of N23. The rates of TCHA decline for N36 and N23 were comparable (–1.38 TCHA vs. −1.40 TCHA). Varieties N23 and NCo376 had comparable intercepts (110.8 TCHA vs. 109.6 TCHA); however, NCo376 had a larger negative slope (–2.18 TCHA) than N23 (–1.56 TCHA). TCHA of variety N19 was consistently lower than that of the other varieties across the ratoon crops.

The intercept of the trendline predicting TSHA of variety N25 (16.7 TSHA) was greater than those of the other varieties, followed by N36 (16.4 TSHA) (Figure 6b). However, the N25 regression line crossed the trendlines of N36 and N23 between the first and second ratoon crops and fourth and fifth ratoon crops, respectively, since TSHA of N25 declined faster (–0.33 TSHA) than that of the other varieties. While variety N36 had higher TSHA than N25 in the last six ratoon crops, it had consistently higher sucrose yield than N23, NCo376, and N19 across all crops (i.e., plant cane and ratoons). Similar to TCHA, the gap between the TSHA trendlines of N23 and NCo376 widened with increase in ratoon crop numbers due to the larger decline of NCo376 (−0.24 TSHA) than N23 (–0.14 TSHA). Variety N19 had the lowest TSHA than all the other varieties across all crops even though it had a smaller decline than N25 and NCo376.

Harvest seasons yield trends

Since the season × crop interaction was significant for all three traits, regression lines predicting the traits were drawn for each harvesting season against ratoon crops (Figure 7).

Early season gave the greatest initial harvest (119.3 TCHA), but also showed the greatest cane yield decline over ratoon crops (–3.72 TCHA) (Figure 7a). Mid-season harvests gave the second highest TCHA intercept (115.0 TCHA) and had the lowest decline over ratoon crops (–2.61 TCHA). Late-season harvests provided lower TCHA across all ratoon crops and had a higher yield decline (–3.28 TCHA) than mid-season harvests.

SUC% did not change across ratoon crops in the late-season harvest (Figure 7b). In the early and mid-season harvests, the SUC% trendlines were positive indicating an increase over ratoon crops. Mid-season harvests had consistently higher SUC% than the other harvest seasons. Early-

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

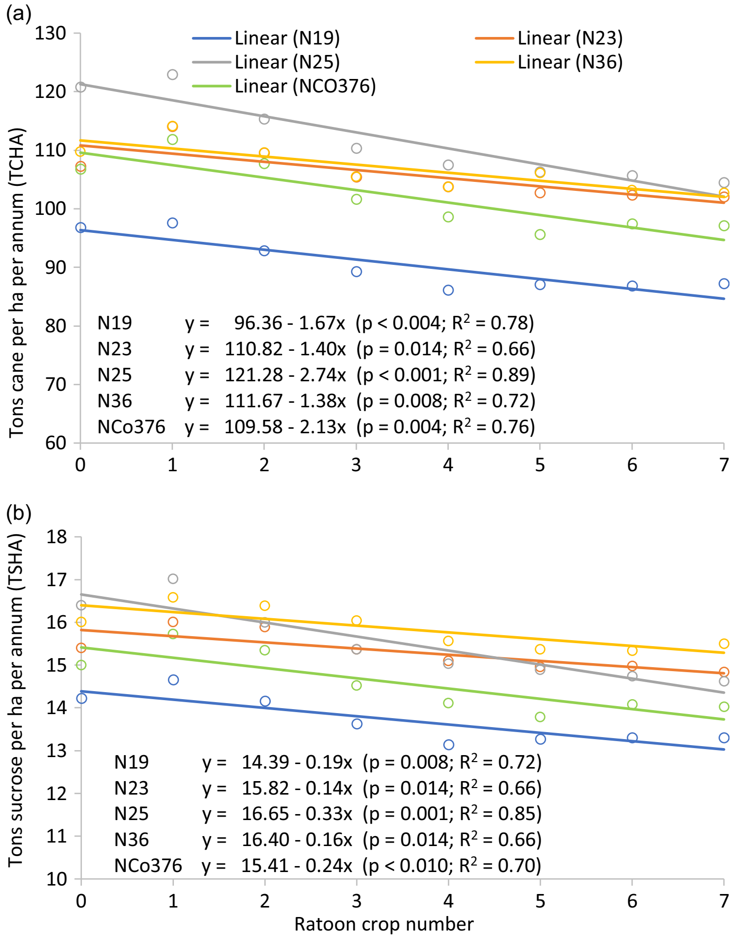

Figure 6. Predicted averages of cane (a) and sucrose (b) yields of sugarcane varieties as a function of ratoon crop numbers (y is the estimated yield at the x^{th} ratoon crop). (p-values and coefficient of determination [R^2] values for the linear regressions are shown in parentheses). [Total number of observations is 360].

season harvests gave the lowest intercept (13.7%) and had the most positive slope (0.12%) crossing the late-season harvest trendline between the second and third ratoon crops.

Mid-season harvests gave TSHA that was consistently higher than those of the other two seasons (Figure 7c). Early-season harvests had consistently higher TSHA than late-season harvests, and the rate of TSHA decline across ratoon crops was comparable between the two seasons (−0.35 TSHA vs. −0.36 TSHA). Mid-season harvests had slightly lower TSHA decline (−0.30 TSHA) across ratoon crops compared to the other seasons.

Discussion

The variance components of season × variety × ratoon crop and soil × variety × ratoon crop were critical in explaining the effect of seasons and soil types on sugarcane varieties RA. These three-way interactions were not significant for all three yield traits (TCHA, SUC%, and TSHA) suggesting that seasons and soil types did not have major impacts on the differences in RA between the five varieties studied. This suggests that RA tests conducted in fewer harvest seasons and soil types (i.e., environments) are sufficient to assess the RA of varieties, hence reducing

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

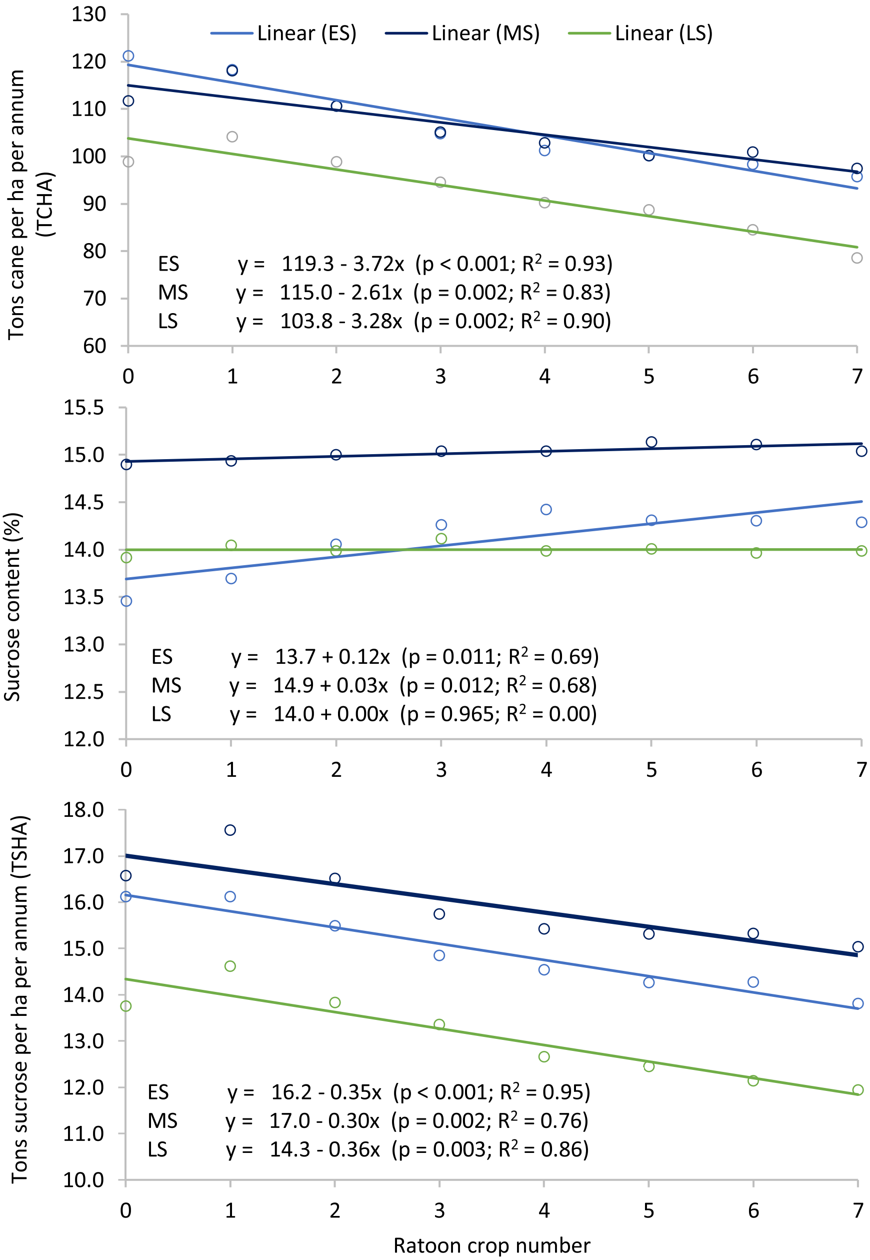

Figure 7. Predicted averages of cane yields (a), sucrose content (b), and sucrose yields (c) as a function of ratoon crop numbers (y is the estimated yield at the x^{th} ratoon crop). ES: early season; MS: mid-season; LS: late season. (p-values and coefficient of determination [R^2] values for the linear regressions are shown in parentheses). [Total number of observations is 360].

testing costs. At present, sugarcane variety trials in the Eswatini sugar industry are conducted across nine environments (three soil types × three harvest seasons). Similar results were reported by Zhou (2015) for irrigated sugar cane in South Africa. Milligan *et al.* (1990) and Kimbeng *et al.* (2009) emphasized that these higher-order interactions (season × variety × ratoon crop and soil × variety × ratoon crop) contribute little to explaining overall yield variance.

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

The significant variety × crop interaction effect for cane and sucrose yield indicated differences in RA between varieties for these traits. This is consistent with the findings by others (Chapman *et al.*, 1992; Zhou and Shoko, 2012; Chumphu *et al.*, 2019). Studies defined RA as a genetic trait (Chapman *et al.* 1992; Ramburan *et al.*, 2013a, 2013b), and as such sugarcane breeding and selection programmes place priority on it when developing varieties (Shanthi *et al.*, 2011; Gravois *et al.*, 2019). The differences in varieties' RA arise from the relative contributions to the genetic makeup of the variety from the different sugarcane ancestors (Ramburan *et al.*, 2013a).

These differences in varieties' RA emphasize the need to test sugarcane varieties for longer ratoon cycles prior to recommendations for commercial cultivation. Testing over longer ratoon crops increases discriminating ability for yield and ratooning among the varieties (Zhou, 2015). This is important for irrigated sugarcane where profitable ratoon crops from a single planting can be as many as 20 (Ellis and Merry, 2004; Ramburan *et al.*, 2013b). Under ideal environmental conditions, management practices, and variety of choice, the ratoon cycles can be extended to over 30 crops in the Eswatini industry (Meyer and Clowes, 2013).

Compared to other varieties, variety N25 produced higher cane and sucrose yield at the first planting, but showed a steeper yield decline with increasing ratoon crop number, suggesting that this variety is suitable for short ratoon cycles. On the other hand, varieties N36 and N23 produced lower yields at the first planting but showed a slower yield decline with increasing ratoon crops than N25, indicating suitability for longer ratoon cycles. Future studies should develop a variety recommendation model that takes into consideration economic benefit of test varieties over the standard ratoon crop cycles for different environmental conditions. Varieties NCo376 and N19 had consistently lower cane and sucrose yields than N25, N36, and N23 across ratoon crops, confirming the superiority of newer varieties over older varieties. Ramburan *et al.* (2013a) and Rae (2018) noted that many growers are not adopting new varieties because of the perception that they possess a lower RA than older varieties. The finding of this study should help address this grower concern.

The variety × ratoon crop interaction did not significantly affect sucrose concentration indicating that there were no clear differences in RA between varieties for this trait. Past sugarcane studies also reported non-significant interaction effect of variety by ratoon crop on sucrose content (Milligan *et al.*, 1990; Kang and Miller, 1984; Masri and Amein, 2015). Unlike cane and sucrose yield, sucrose content is more strongly influenced by genetic composition than variety × environment interactions (Nayamuth *et al.*, 1999, 2005; Ramburan and Zhou, 2011; Sandhu *et al.*, 2012). This suggests that fewer ratoon crops are necessary to segregate varieties on sucrose content compared to cane and sucrose yields. Jackson (2005), Kimbeng *et al.* (2009) and Ramburan *et al.* (2013b) also confirmed that selection for sucrose content in sugarcane breeding programmes is relatively quick.

The highly significant two-way interaction of season × variety for all three yield traits indicated that harvest seasons had a large influence on the differences in varieties' performance. Other studies reported significant variety × season interactions as well (Di Bella *et al.*, 2009; Dlamini and Ramburan, 2016; Farrag *et al.*, 2019), emphasizing the importance of selecting varieties for seasonal adaptation. Hence, varieties in sugarcane industries are classified according to the seasons of their adaption (early, mid, and late). For example in this study, variety N36 produced the largest sucrose yield in an early-season harvest, while N25 produced the largest yields during mid- and late-season harvests.

The highly significant season × crop interaction for cane yield, sucrose content, and sucrose yield suggested an influence of harvest seasons on RYD. Similar results were reported by Zhou (2015). Early and late-season harvests showed a stronger cane and sucrose yield decline over ratoon crops compared to mid-season harvests. This is largely attributed to harvesting operations in early and late seasons that coincide with heavy rains, while the mid-harvest season is relatively dry. Early-season harvesting happens during the summer/autumn rains, while late-season harvesting happens during the spring rains. Mid-season harvesting occurs predominantly during

https://doi.org/10.1017/S0014479724000127 Published online by Cambridge University Press

winter when rains are scarce (Figure 1). Movement of harvesting machinery infield when soils are wet leads to stool damage and compaction which creates anaerobic conditions (Kingston, 2003; Seeruttun *et al.*, 2014; Gravois *et al.*, 2019). Compacted soil restricts the growth and effectiveness of the root systems. This suggests that harvesting and milling operations should be maximized during the dry season. An additional advantage of harvesting mid-season is the high sucrose content realized.

Unlike cane and sucrose yields, sucrose content trendlines were either flat (late season) suggesting stability across ratoon crops or positive (early and mid-seasons) indicating an incline with increase in ratoon number. The negative correlation between cane yield and sucrose content is well documented (Milligan *et al.*, 1990; Jackson, 2005; Klomsa-ard *et al.*, 2013). Factors which promote higher cane yields often lead to lower accumulation of sucrose content. For example, early-season harvests which had the highest plant cane yield and largest decline across ratoon crops had the lowest plant cane sucrose content and largest sucrose content increase across ratoon crops. However, for late-season harvests, there was a trend for sucrose content to be stable across ratoon crops, yet they also experienced a large cane yield decline which suggests that the factors affecting cane yield are complex.

The two-way interaction of soil × variety was also highly significant for all three traits, indicating the importance of categorizing sugarcane varieties according to their adaptations to different soil types. Breeding varieties with specific adaptation to different soils could enhance adaptability and optimize genetic gains within distinct soil types (Zhou, 2015). Todd *et al.* (2014) and Dlamini and Ramburan (2016) also reported significant variety × soil interactions. Variety N36 with regard to sucrose yield performed better on moderately and poorly draining soils than the other varieties, while N25 performed better on well-draining soils. In Eswatini, new sugarcane varieties are tested across different soil types over multiple years before their release for commercial planting. Future studies will have to investigate the genetic and physiological responses of sugarcane varieties to these different soil conditions to inform breeding efforts. This is particularly important in view of the increased frequencies of flooding in sugarcane fields, which alternate with prolonged drought periods as a result of a changing climate.

The significant three-way interaction of season × soil × variety for the three traits demonstrated the influence of the environments on the differences between varieties' performances. The different combinations of harvest seasons and soil types constitute the environment in which the sugarcane crop is grown in Eswatini. Previous studies (Gilbert *et al.*, 2006; Rodriguez *et al.*, 2010; Dlamini and Ramburan, 2016) reported significant variety × environment interaction effects on yield. This highlights the presence of opportunities to identify varieties with greater adaptation to specific environments (Campbell and Jones, 2005). Variety × environment interactions can either be exploited by selecting superior varieties for each specific target environment (specific adaptation) or be avoided by selecting widely adapted (broad adaptation) varieties across a wide range of environments (Ceccarelli, 1989). Over the years, Eswatini and South African sugarcane growers have expressed interest in high-yielding and stable varieties that are adapted across a wide range of environments.

This study showed that harvest seasons and soil types had a significant impact on yields (Figures 2 and 3, respectively). Harvest seasons are largely characterized by the climatic factors: temperature, radiation, and rainfall. For early-season harvests, these factors are highly favourable during the period of rapid stalk elongation and maturation, hence the higher cane yield compared to the other seasons. The downside is that a large proportion of the photosynthates produced during this period are used for vegetative growth instead of being stored in the cane stalks, hence the lower sucrose content than mid and late seasons. For mid-season harvests, these factors are high during the period of rapid stalk elongation and low at maturation. Low levels of temperature and rainfall promote a higher rate of sucrose accumulation in the cane stalks. This gives mid-season harvests a good balance between cane yield and sucrose content hence the higher sucrose yields compared to the other harvest seasons. For late-season harvests, the critical stage of cane growth coincides with the period of low temperatures, radiation and rainfall leading to lower cane and sucrose yields during this season.

The different cane and sucrose yields between the soil types were expected. Well-draining soils have the highest cane-yielding potential while poorly draining soils have the lowest and moderately draining soils intermediate. The results of this study mirrored this assertion. However, the reverse was noted on sucrose content, with poor-draining soils having the highest sucrose content while the well-draining soils had the lowest. The gap between moderately draining and well-draining soils on cane yield was marginal. Similarly, the sucrose content of moderately draining and poorly draining soils was comparable. Consequently, the sucrose yields of moderately draining and well-draining soils were comparable. Poorly draining soils had the lowest sucrose yield, suggesting that more investment needs to be directed towards improving the productivity of this soil.

Conclusions

In this study, soil types and harvest seasons did not affect the relative performance of sugarcane varieties with regard to RA. The studied varieties had different RAs, which was attributed to the varieties' genetic makeup. This has considerable implications for variety of evaluations in future. New varieties should therefore be evaluated for RA over an extended period. However, this can be conducted in a limited number of testing environments. The strong effects of soil types and harvest seasons on the differences in yields of varieties emphasized the importance of continuing variety testing for adaptability across multiple environments. The methodology employed in this study demonstrated that data from commercial sugarcane growers can provide valuable insights that can supplement or complement on-station trial data in informing future crop production practices and answering research questions.

Acknowledgements. We thank the four growers who shared their field performance data.

Funding statement. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. The authors declare no competing interests.

References

Butler, D.W.F. (2001) The performance of sugarcane varieties N23 and N25 on low yield potential soils in Swaziland. *Proceedings of the South African Sugar Technologists Association* **75**, 165–170.

Campbell, B.T. and Jones, M.A. (2005) Assessment of genotype × environment interactions for yield and fiber quality in cotton performance trials. *Euphytica* **144**, 69–78.

Carnegie, A.J.M. (1988) White grubs (Scarabaeoidea) continue to cause sporadic damage to sugarcane in South Africa and Swaziland. *Proceedings of the South African Sugarcane Technologists Association* **62**, 161–163.

Ceccarelli, S. (1989) Wide adaptation: how wide? *Euphytica* **40**, 197–205.

Chapman, L.S., Ferraris, R. and Ludlow, M.M. (1992) Ratooning ability of cane varieties: variation in yield and yield components. *Proceedings of the Australian Society of Sugar Cane Technologists* **14**, 130–138.

Chumphu, S., Jongrungklang, N. and Songsri, P. (2019) Association of physiological responses and root distribution patterns of ratooning ability and yield of the second ratoon cane in sugarcane elite clones. *Agronomy Journal* **9**, 200–2018.

Di Bella, L.P., Stringer, J.K., Wood, A.W., Royle, A.R. and Holzberger, G.P. (2009) What impact does time of harvest have on sugarcane crops in the Herbert River district (in Australia)? *Sugar Cane International* **27**(4), 143–148.

Dlamini, N.E. and Ramburan, S. (2016) Investigating sugarcane genotype × environment interactions in the northern area of the Swaziland sugar industry using variance components and biplot analysis. *Proceedings of the South African Sugar Technologists Association* **89**, 234–257.

Dlamini, N.E. and Zhou, M. (2022) Soils and seasons effect on sugarcane ratoon yield. *Field Crops Research* **284**, 108588. https://doi.org/10.1016/j.fcr.2022.108588.

Ellis, R.D. and Merry, R.E. (2004) Sugarcane agriculture. In James, G. (ed.), *Sugarcane* (2nd edition). Oxford: Blackwell Publishing, pp. 101–142.

Farrag, F.B.A., Abd El-Azez, Y.M. and Bassiony, N.A. (2019) Assessment of ratooning ability and genetic variability of promising sugarcane varieties under middle Egypt conditions. *Electronic Journal of Plant Breeding* **10**, 143–154.

Ferraris, R., Chapman, L.S. and Ludlow, M.M. (1993) Ratooning ability of cane varieties: interception of light and efficiency of light use. *Proceedings of Australian Society of Sugarcane Technologists* **15**, 316–322.

Gilbert, R.A., Shine, J.M., Miller, J.D., Rice, R.W. and Rainbolt, C.R. (2006) The effect of genotype, environment and time of harvest on sugarcane yields in Florida, USA. *Field Crops Research* **95**, 156–170.

Gravois, K.A., Zhou, M.M., Hoffmann, H.P., Piperidis, G. and Badaloo, G. (2019) Breeding new sugarcane varieties with enhanced ratooning ability. *Proceedings of the International Society of Sugar Cane Technologists* **29**, 1683–1690.

Grisham, M.P. (1991) Effect of ratoon stunting disease on yield of sugarcane grown in multiple three-year plantings. *Phytopathology* **81**, 337–340.

Irwin, S. (2019) RSD Testing in Sugarcane. LSU AgCenter Media News Report, Sugarcane Diseases. Available at https://www.amscl.org/rsd-testing-in-sugarcane (accessed 22 August 2023).

Jackson, P.A. (2005) Breeding for improved sugar content in sugarcane. *Field Crops Research* **92**, 277–290.

Kang, M.S. and Miller, J.D. (1984) Genotype-environment interaction for cane and sugar yield and their implications in sugarcane breeding. *Crop Science* **24**, 435–440.

Kang, M.S., Miller, J.D., Tai, P.Y.P., Dean, J.D. and Glaz, B. (1987) Implications of confounding of genotype × year and genotype × crop effects in sugarcane. *Field Crops Research* **15**, 349–355.

Kimbeng, C.A., Zhou, M.M. and Da Silva, J.A. (2009) Genotype × environment interactions and resource allocation in sugarcane yield trials in the Rio Grande Valley Region of Texas. *Journal of the American Society of Sugarcane Technologists* **29**, 11–24.

Kingston, G. (2003) Ratooning and ratoon management in overseas cane-sugar industries. *Bureau of sugar experiment stations Queensland, Australia*. Final report – SRDC project BSS110. https://elibrary.sugarresearch.com.au/handle/11079/1038 (accessed 12 April 2021).

Klomsa-ard, P., Patanothai, A. and Jaisil, P. (2013) Efficient test sites for multi-environment evaluation of sugarcane genotypes in Thailand. *International Journal of Plant Production* **7**, 763–789.

Lawes, R.A., McDonald, L.M., Wegener, M.K., Basford, K.E. and Lawn, R.J. (2002) Factors affecting cane yield and commercial sugar in the Tully district. *Australian Journal of Experimental Agriculture* **42**, 473–480.

Masri, M.I. and Amein, M.M.M. (2015) Yield potential and ratooning ability of some sugar cane genotypes. *Journal of Plant Breeding and Crop Science* **7**, 262–274.

Meyer, J. and Clowes M. (2013) Sugarcane and its environment. In Meyer, J., Rein, P., Turner, P., Mathias, K. (eds.), *Good Management Practices for the Cane Sugar Industry*. Berlin, Germany: Bartens, pp. 73–113.

Milligan, S.B., Gravois, K.A., Birchoff, K.P. and Martin, F.A. (1990) Crop effects on broad-sense heritabilities and genetic variances of sugarcane yield components. *Crop Science* **30**, 344–349.

Milligan, S.B., Gravois, K.A. and Martin, F.A. (1996) Inheritance of sugarcane ratooning ability and the relationship of younger crop traits to older crop traits. *Crop Science* **36**, 45–50.

Nayamuth, A.R., Cheeroo-Nayamuth, B.F. and Soorpramanien, G.C. (1999) Agro-physiological characteritiscs underlying the sucrose accumulation pattern of early and late varieties. *Proceedings of the South African Sugar Technologists Association* **73**, 157–163.

Nayamuth, A.R., Mangar, M., Ramdoyal, K. and Badaloo, M.G.H. (2005) Early sucrose accumulation, a promising characteristic to use in sugarcane improvement programs. *Proceedings of the International Society of Sugarcane Cane Technologists* **25**, 421–429.

Nixon, D.J., Workman, M. and Glendinning, P.J. (1986) Soil and land classification in Swaziland. *Proceedings of the South African Sugarcane Technologists Association* **60**, 219–222.

Rae, A.L. (2018) *Impact of Stool Architecture on Ratooning Ability: Final Report 2015/004. Sugar Research Australia Limited.* Brisbane: Sugar Research Australia Limited.

Ramburan, S. (2018) Post-release variety testing: a key activity to ensure commercial value of genetic improvements. *Proceedings of the South African Sugarcane Technologists Association* **91**, 186–203.

Ramburan, S., Sewpersad, C. and Mcelligott, D. (2009) Effects of variety, harvest age and eldana on coastal sugarcane production in South Africa. *Proceedings of the South African Sugarcane Technologists Association* **82**, 580–588.

Ramburan, S. and Zhou, M. (2011) Investigating sugarcane genotype × environment interactions under rainfed conditions in South Africa using variance components and biplot analysis. *Proceedings of the South African Sugarcane Technologists Association* **84**, 245–362.

Ramburan, S., Wettergreen, T., Berry, S.D. and Shongwe, B. (2013a) Effects of variety, environment and management on sugarcane ratoon yield decline. *International Sugar Journal* **115**, 219–227.

Ramburan, S., Wettergreen, T., Berry, S.D. and Shongwe, B. (2013b) Genetic, environmental and management contributions to ratoon decline in sugarcane. *Field Crops Research* **146**, 105–112.

Rodriguez, R., Bernal, N., Jorge, H., García, H. and Puchades, Y. (2010) Genotypes by environment interaction for yield in sugarcane performance trials: a comparison of frequently used models. *Proceedings of the International Society of Sugarcane Technologists* **27**, 1–6.

Sandhu, S.K., Ram, B., Kumar, S., Singh, R.S., Uppal, S.K., Brar, K.S., Singh, P. and Nair, N.V. (2012) GGE biplot analysis for visualisation of performance rank and stability of sugarcane genotypes. *International Sugar Journal* **114**, 810–820.

Seeruttun, S., Ismael, F.M., Cheong, R.N.G, Rivière, V. and Umrit, G. (2014) Developing new cropping systems to mitigate sugarcane yield decline in Mauritius. *International Sugar Journal* **116**, 135–140.

Shanthi, R.M., Hemaprabha, G. and Alarmelu, S. (2011) An overview on the selection strategies in sugarcane breeding programmes. *Journal of Sugarcane Research* **1**, 27–37.

Stirling, G.R. and Blair, B. (2001) Nematodes are involved in the yield decline syndrome of sugarcane in Australia. *Proceedings of the International Society of Sugar Cane Technologists* **24**, 430–433.

Todd, J., Glaz, B., Irey, M.S., Zhao, D., Hu, C-J. and El-Hout, N. (2014) Sugarcane genotype selection on a sand soil with and without added mill mud. *Agronomy Journal* **106**, 315–323. https://doi.org/10.2134/agronj2013.0304.

VSN International (2020) GenStat for Windows, 21st Edn. https://genstat.kb.vsni.co.uk/knowledge-base/whats-new21st/ (accessed 04 April 2021).

Yan, W. (2001) GGE Biplot: a windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agronomy Journal* **93**, 1111–1118. https://doi.org/10.2134/agronj2001.9351111x.

Yan, W., Kang, M.S., Ma, B., Woods, S. and Cornelius, P.L. (2007) GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Science* **47**, 641–653.

Zhou, M.M. and Shoko, M.D. (2012) Simultaneous selection for yield and ratooning ability in sugarcane genotypes using analysis of covariance. *South African Journal of Plant and Soil* **29**, 93–100.

Zhou, M. (2015) Influence of locations and seasons and their implications on breeding for sugarcane yield and sucrose content in the irrigated region of South Africa. *Proceedings of the South African Sugarcane Technologists Association* **88**, 403–412.

Cite this article: Dlamini NE, Franke AC, and Zhou M. Impact of soil type and harvest season on the ratooning ability of sugarcane varieties. *Experimental Agriculture*. https://doi.org/10.1017/S0014479724000127