FULL PAPER

INDICES FOR ESTIMATING THE RATOONING ABILITY OF SUGARCANE

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Abstract

The primary objective of sugarcane Variety Testing Programs (VTPs) is to identify cultivars that have high yields and ratooning ability (RA). The purpose of this study was to evaluate six RA indices with the intention of identifying one that is ideal for longer ratoon crop cycles. The six indices were: ratoon crop yield means (CM); second ratoon to plant cane (SP) yield ratio; final ratoon crop to plant cane (FP) yield ratio; average of all ratoon crops to plant cane (RP) yield ratios; linear regression (LR); and, quadratic regression (QR). Data from four variety trials, consisting of eight varieties plus a control, and harvested over six successive crops were used for this study. The combined data from these trials were subjected to a linear mixed model to evaluate the effects of the different terms on RA. Variety rankings on both the yield and RA were then conducted for each index. To identify indices that are appropriate for longer ratoon crop cycles, commercial data were used. For each index, RA results of eleven successive crops were regressed on those of the first six crops (representing trial crops). All six indices indicated that the varieties had significantly ($p<0.001$) different RAs. However, the indices ranked the varieties differently on their RAs, which emphasised the importance of using the most appropriate indices for different ratooning systems. The RP index was identified as the most relevant for longer ratoon crop cycles, with an R^2 of 0.92, followed by the commonly used CM method which had an R^2 of 0.85. The other indices had R^2 values below 0.60. The RP index identified M1176/77 as the most preferred variety on both yield and RA. The methodology and findings of this study will inform future VTPs on the practicability of simultaneously selecting for both yield and RA.

Keywords: variety, ratooning ability, yield, ratoon, crop cycles, indices

Introduction

The profitability of a sugarcane enterprise depends on the optimum use of its production resources, one of which is sugarcane ratooning. Ratooning, in this context, is the practice of allowing a regrowth of sugarcane plants from the stubble left in the soil from the previous harvest. This practice provides economic and environmental benefits for a sugarcane grower, including elimination of replanting costs (i.e., land preparation, seedcane and planting) and minimisation of erosion due to undisturbed soil. Furthermore, under comparable conditions, ratoon crops have a higher sucrose content than plant cane crops due to earlier maturation, which leads to improved sucrose extraction at the mill. Hence, the more economically rewarding ratoon crops kept, the more profitable the enterprise becomes.

The longevity of ratoon crops, among other factors (i.e., management and environment), depends on the variety that is grown. The ability of a sugarcane variety to sustain multiple profitable ratoon crops is termed ratooning ability (RA). RA is considered a genetic trait. Several studies (Chapman *et al*., 1992; Milligan *et al*., 1996; Ferraris *et al*., 1993; Ramburan *et al*., 2013; Chumphu *et al*., 2019) have reported significant differences in RA of sugarcane varieties. Therefore, the primary target of any sugarcane Variety Testing Program (VTP) is to identify varieties that have both high yields and high RAs. It is therefore important to identify the most accurate index or indices for measuring RA. This is especially critical for industries with longer ratoon crop cycles such as Eswatini, South Africa, Mauritius, Malawi, Zambia, Zimbabwe, and other countries, where there can be as many as twenty ratoon crops.

The practice of many VTPs in industries with longer ratoon cycles is to use the average yield of the test crops as a measure of RA. The variety with a higher average yield than the control is considered to be a good ratooning variety. At Eswatini, the testing cycle is normally five crops (i.e., plant crop and four ratoons), and at commercial level, far more ratoon crops are achieved than these. The lingering question is whether the testing period is sufficient to separate good ratooning varieties from the poor varieties, or not? It is argued that where such a method is used, the testing period should match the length of the commercial ratooning cycles. However, due to limited testing resources and the need to release new varieties more frequently, this is not feasible for industries with longer ratoon cycles. For purposes of this study, this measure of RA is abbreviated to CM (i.e., crop means).

Milligan *et al*. (1996) defined a good ratooning variety as one whose second ratoon crop yield is a higher percentage of its plant cane yield. These authors proposed the following index (SP) as a measure of RA:

Second ratoon (SR) yield/ plant cane (PC) yield x 100 (1)

The variety with a higher second ratoon to plant cane ratio than standard varieties is regarded as having a higher ratooning ability. Several studies (Olaoye, 2005; Masri and Amein, 2015; Mehareb *et al*., 2016; Saadan *et al*. 2018**;** Farrag *et al*., 2019) utilised this index to compare RA of different sugarcane varieties. Ramburan *et al*. (2013), however, argued that this approach is not applicable to industries where profitable sugarcane production is possible for as many as ten ratoons. These authors contended that the difference in economic and environmental conditions between farms makes it difficult to use a rigid number of ratoons to define RA. In other words, what may be considered as a profitable number of ratoons in one farm may not be profitable in another. To accommodate longer ratoon cycles, the index of Milligan *et al*. (1996) may be modified to the following index (FP):

Final ratoon (FR) yield/ PC yield x 100 (2)

This index eliminates the use of a fixed ratoon number. However, it may be argued that this revised formula ignores the effects of the ratoon crops between the plant crop and the final ratoon crop, thereby not giving a good indication of varieties' RA. To circumvent this shortcoming of the revised Milligan *et al*. (1996) index (FP), the method of Dunckelman (1982) can be adopted, which is:

$$\left(\frac{R_1}{PC}+\frac{R_2}{PC}+\frac{R_3}{PC}+\cdots\frac{R_f}{PC}\right)/n_r \quad (3)$$

where R_1, R_2, R_3… R_f are the first, second, third and up to final ratoon crop yields; *PC* is the plant cane yield; and, n_r is the number of ratoon crops. Mehareb and Galal (2017) and Ebid *et al*. (2022) utilised this index to identify promising varieties with good RA. In this study, the index is abbreviated as RP, which represents the average of all ratoons to the plant cane yield ratios.

Most researchers, including crop breeders and agronomists, utilize the linear function to separate varieties according to their RA. The linear regression (LR) is as follows:

$$Y = Ax + B, \qquad (4)$$

where, Y (the dependent variable) is the cane yield at ratoon crop x (the explanatory variable); A is the linear coefficient (the slope of the line, measuring RA); and B is the intercept (the y-intercept, which is the value of Y when $x = 0$). Chapman *et al*. (1992), Zhou and Shoko (2012) and Ramburan *et al*. (2013) used the LR index to estimate the RAs of different test varieties.

The shortcoming of the linear regression as a model for determining RA is that the cane yield across successive ratoons is often non-linear. For example, irrigated cane is highly sensitive to water stress; hence, in years of drought or water stress, the yield is greatly reduced, but when normal irrigation or rainfall is restored, the yield recovers well. When the linear function is fitted on such data, the coefficient of determination (R^2) is often very low indicating that the model did not explain most of the variability within the dataset.

To overcome the weakness of the linear model, the quadratic function was proposed by Ramburan *et al*. (2013). Unlike the linear model, the quadratic function explains most of the variability in non-linear data. For data that are not described by the linear function, Brown (2001) opined that it is necessary to implement a protocol that will fit a non-linear function to the data. In polynomial functions, the better the fit, the more accurately the function describes the data. The quadratic function (QR) is of the form:

$$Y = Ax^2 + Bx + C, \qquad A \neq 0 \qquad (5)$$

where, Y is the cane yield at ratoon crop x; A is the quadratic coefficient (it indicates whether the curve opens upward or downward. When it is positive, the curve is opened upward, and when it is negative, the curve is opened downward. The absolute value of the coefficient also indicates whether the curve is narrow or wide); B is the linear coefficient (it indicates the slope of the curve; an estimate RA); and, C is the intercept (which is the yield of the first crop). While the quadratic function gives a better fit than the linear model, it is difficult to interpret the quadratic coefficients as simple and practical parameters to describe the RA of the varieties (Ramburan *et al*., 2013). Therefore, it may be a challenge for growers to use it for evaluating the RA of the varieties on their farms.

While so many indices are used to measure the RA, there is no evidence of any study that was dedicated to compare them, with the aim of identifying and recommending an index (or indices) that is most appropriate for longer ratoon cycles. It is also important to identify an index that can be used by growers to compare the RA of sugarcane varieties at farm level. The objectives of this study were: (i) to estimate the RA of sugarcane varieties using the six RA indices (CM, SP, FP, RP, LR and QR), (ii) to compare and contrast these RA indices, and (iii) to identify the most appropriate index for measuring the RA for longer ratoon cycles.

Materials and Methods

Datasets

The data used for this study were sourced from four variety trials that were established in 2005 at two representative sites (Mhlume and Simunye) of the Eswatini sugar industry. These trials were harvested over six successive crops (plant *plus* five ratoons). The Simunye site represents well-structured and well draining soils, while the Mhlume site represents poorly draining and weakly-structured/duplex soils. In Eswatini, sugarcane is harvested at 12 months, and the harvesting period normally occurs over nine months (April to December) in any milling year. The harvesting period is segregated into three seasons, namely, early season (April to June), mid-season (July to September), and late season (September to December). Two trials were established on each site. At the Mhlume site, one trial was planted in April and the other in September. At the Simunye site, one trial was planted in April and the other in November. All four trials were established as randomised complete block designs, each with eight replications. For each trial, eight test varieties (R570, M1176/77, M1186/86, M1246/84, M1400/86, M1551/80, M695/69 and M96/82) were planted alongside a commercial control, NCo376.

The trials were managed as per estates' standard practices, including fertiliser application, irrigation and weed control. The plots consisted of six rows that were 13 m long at Simunye and 17 m long at Mhlume. The inter-row spacing was 1.5 m. Yield data were collected on a per-plot basis at harvesting, for each of the six successive crops. A one metre end-row effect was provided for in all the experimental plots, and the two outer plot rows were regarded as guard rows. At harvesting, the end rows and the guard rows were cut and removed from the net rows. Thereafter, the cane from the net rows was also cut, topped (i.e., the removal of the top leafy part of the sugarcane stalk) and placed in heaps, in preparation for weighing.
The cane yield was determined by weighing the bundles of cane from the net plots using a tractor-fitted hydraulic weighing apparatus. The weight of the cane from the net plots was then transformed and expressed as tonnes of cane per hectare (TCH), using the formula:

$$\text{TCH} = \text{Weighed cane (kg)}/(\text{net row length [m]} \times \text{interrow spacing [m]} \times 10 \qquad (6)$$

Data analysis

The TCH data from the four trials were combined and the values for each of the RA indices (CM, SP, FP, RP, LR and QR) were calculated for each experiment plot (that is, the RA was calculated at plot level). To establish the relative effect of variety, season and location (representing soil type) as well as their interactions on sugarcane RA, as measured by each index, the following linear mixed model was fitted:

$$Y_{ijkl} = \mu + L_i + S(L)_{ij} + R(SL)_{ijk} + V_l + VL_{il} + VS(L)_{ijl} + VR(SL)_{ijkl} + E_{ijkl} \qquad (7)$$

Where, Y_{ijkl} is the observation for l^{th} variety, in the i^{th} location nesting j^{th} season, k^{th} replication nested within the i^{th} location nesting j^{th} season; μ is the overall mean; L_i is the effect of the i^{th} location; $S(L)_{ij}$ is j^{th} season nested in i^{th} location; $R(SL)_{ijk}$ is the random effect of the k^{th} replication nested within the i^{th} location and j^{th} season (Error 1); V_l is the effect of the l^{th} variety; VL_{il} is the interaction effect of the l^{th} variety and i^{th} location; $VS(L)_{ijl}$ is the interaction effect of the l^{th} variety with the j^{th} season nested within the i^{th} location; $VR(SL)_{ijkl}$ is the random interaction effect of the l^{th} variety and the k^{th} replication nested within the i^{th} location and the j^{th} season (Error 2); and E_{ijkl} is the residual term (Error 3). In addition to the RA indices, the plant cane (PC) yields were also subjected to this analysis. The PC yields represent the yield potential for each variety. Statistical analyses for this study were conducted using GenStat® 22nd Edition statistical software (VSN International, 2022).

The varieties were first ranked (Rk1) according to their PC yields, with the highest yielding variety ranked 1 and the lowest ranked 9. Secondly, the varieties were then ranked (Rk2) according to their RA for each index, with the variety having the highest RA being ranked 1 and the lowest ranked 9. Since a preferred variety is one that has both a high yield and a high RA, a third ranking (Rk3) was performed, which integrated both the yield potential (PC) and RA rankings:

$$Rk3 = (Rk1 + Rk2)/2 \qquad (8)$$

Recommended varieties are those with lower Rk3 values (high ranking) than the control variety. The Rk3 was also performed for all six indices, to compare how they rank the varieties.

A Pearson correlation analysis was conducted at plot level to establish the relationship between the indices. To identify the index that provides better RA estimates for longer ratoon cycles (i.e., ten ratoons or more), commercial field yield data (tonnes cane per ha per annum, TCHA) were used. For this purpose, 111 commercial fields planted in the year 2000 and harvested over eleven consecutive crops (i.e., plant and ten ratoons) were selected from data obtained from four large growers within the Eswatini sugar industry. Values for each index were calculated on a per field basis, using the first six crops (i.e., plant and five ratoons) to mirror the variety testing period. Similar calculations were also performed per field over the eleven crops for each index. The strength of the relationship between these two datasets (i.e., six crops vs. eleven crops) was tested by using a regression analysis for each index. The index that had the highest coefficient of determination (R^2) was interpreted to be the most accurate for estimating RA for longer ratoon crop cycles.

Results

Analysis of variance components

The random term, block (location x season), was significant ($p<0.05$) for the plant cane (PC) yield and CM, SP and QR indices (Table 1). However, it was not significant ($p>0.05$) for the FP, RP and LR indices. The block x variety (location x season) term, representing the residual effect, was highly significant ($p<0.001$) for the PC and all RA indices, suggesting that the random terms did not account for all the variations in the dataset.

Table 1. Random effects for the ratooning ability indices for tonnes cane per ha (TCH). [*PC*: plant cane yield representing yield potential; *CM*: ratoon crops yield means; *SP*: second ratoon yield/plant cane yield ratio; *FP*: final ratoon yield/plant cane yield ratio; *RP*: average of all ratoon to plant cane yield ratios; *LR*: linear regression; *QR*: quadratic regression].

Random Term	PC	*CM*	*SP*	*FP*	*RP*	*LR*	*QR*
				Variances			
B (L x S)	19.5^{*}	56.6^{**}	0.003^{*}	0.001^{ns}	0.001^{ns}	0.120^{ns}	19.8^{*}
B x V (L x S)	210.6^{***}	120.7^{***}	0.020^{***}	0.024^{***}	0.016^{***}	11.000^{***}	118.6^{***}

B (L x S): blocks nested within locations interacting with seasons; B x V (L x S): blocks interacting with varieties nested within locations interacting with seasons; ns: not significant ($p>0.05$); * significant at $p<0.05$; ** significant at $p<0.01$*;* *** significant at $p<0.001$

The fixed term effects of location, season and variety were highly significant ($p<0.001$) for the PC, suggesting the existence of considerable differences in yield potential (i.e., cane) for these factors (Table 2). The effects of location x variety and variety x season were not significant ($p>0.05$) for the PC, indicating that the varieties' yield potential was not dependent on location and season. The F-values of the fixed terms showed that seasons had a larger effect on PC yield than locations and varieties, and locations had a larger effect than varieties.

On RA, only the LR and QR indices were significant ($p<0.01$) for the fixed term effect of location (Table 2). All RA indices were significant for the fixed terms of season and variety, indicating larger effects of seasons and varieties on RA. The two-way interaction effect of location x variety was not significant ($p>0.05$) for all indices suggesting that RA of the different varieties was not influenced by location. For the variety x season interaction, four of the six indices (CM, FP, RP and LR) were significant ($p<0.05$), which indicated that seasons influenced the RA of the varieties.

Variety rankings

Table 3 shows PC and RA values, as well as the rankings of the different varieties on PC yield (Rk1), RA (Rk2) and combined PC and RA (Rk3). The combined ranking (Rk3) of PC yield and RA is critical in sugarcane production because variety recommendations are based on the combined effects of these two parameters. Preferred varieties are those with high PC yield and RA.

Table 2. Fixed effects for the ratooning ability indices for tonnes cane per ha (TCH). [PC: plant cane yield representing yield potential; *CM*: ratoon crops yield means; *SP*: second ratoon yield/plant cane yield ratio; *FP*: final ratoon yield/plant cane yield ratio; *RP*: average of all ratoon to plant cane yield ratios; *LR*: linear regression; *QR*: quadratic regression].

Fixed Term	ndf:ddf	*PC*	*CM*	*SP*	*FP*	*RP*	*LR*	*QR*
					F-values			
L	1:28	13.73***	2.89 ns	0.58 ns	2.64 ns	0.46 ns	9.99**	8.30**
S (L)	2:28	20.79***	4.84*	15.86***	27.45***	42.93***	19.56***	30.98***
V	8:224	8.53***	22.67***	5.34***	8.67***	5.45***	7.55***	3.01**
L x V	8:224	0.81ns	1.39 ns	1.75 ns	1.33 ns	1.31 ns	0.59 ns	0.92 ns
V x S (L)	16:224	1.59 ns	1.82*	1.06 ns	1.77*	1.73*	1.71*	1.33 ns

L: location; S(L): seasons nested within locations; V: variety; L x V: location by variety interaction; V x S (L): variety by season interaction nested within locations; ndf: numerator degrees of freedom; ddf: denominator degrees of freedom; F-values: F distribution statistics; ns: not significant ($p>0.05$); * significant at $p<0.05$; ** significant at $p<0.01$; *** significant at $p<0.001$

Four varieties, namely M1176/77, M1400/86, M1551/80 and M96/82 had higher PC yields than the control variety (NCo376). The six indices ranked the varieties differently on RA. The CM index identified M1179/77 and M96/82 as the only varieties that had RAs above the control. The SP and RP indices identified M1246/84 as the only variety that had a larger RA than the control. According to the FP and LR indices, none of the test varieties had a larger RA than the control. The QR index, on the other hand, indicated that varieties M1246/84, M695/69 and M96/82 had a larger RA than the control variety.

On the combined ranking (Rk3), four indices, namely CM, SP, FP and RP, ranked variety M1176/77 higher than the control. In addition, CM, SP and RP also ranked variety M96/82 either equal to, or higher, than the control. The LR index showed that none of the varieties had a combined ranking higher than the control. The QR index identified four varieties, namely

M96/82, M1176/77, M1246/84 and M1551/80, as being higher than the control. Indices SP and RP ranked the nine varieties similarly.

Correlation analyses

A correlation analysis was conducted to establish the relationship between the six RA indices (Table 4). The results indicated that there was a strong (CM vs. LR) to very strong (RP vs. SP) positive correlation between the indices, with the RP index showing relatively stronger correlations with most of the indices. The stronger correlation between RP and SP supports the previous observation that these two indices frequently ranked the varieties similarly.

Table 4. **Pearson correlation of the ratooning ability indices on cane yield (TCH). [PC: plant cane yield representing yield potential; CM: ratoon crops yield means; SP: second ratoon yield/plant cane yield ratio; FP: final ratoon yield/plant cane yield ratio; RP: average of all ratoon to plant cane yield ratios; LR: linear regression; QR: quadratic regression]**

	CM	FP	LR	QR	RP	SP
CM	-					
FP	0.5378***	-				
LR	0.3692***	0.8577***	-			
QR	0.4029***	0.4541***	0.5463***	-		
RP	0.6007***	0.8506***	0.7642***	0.8266***	-	
SP	0.5258***	0.7210***	0.5735***	0.7700***	0.8769***	-

Tests of accuracy

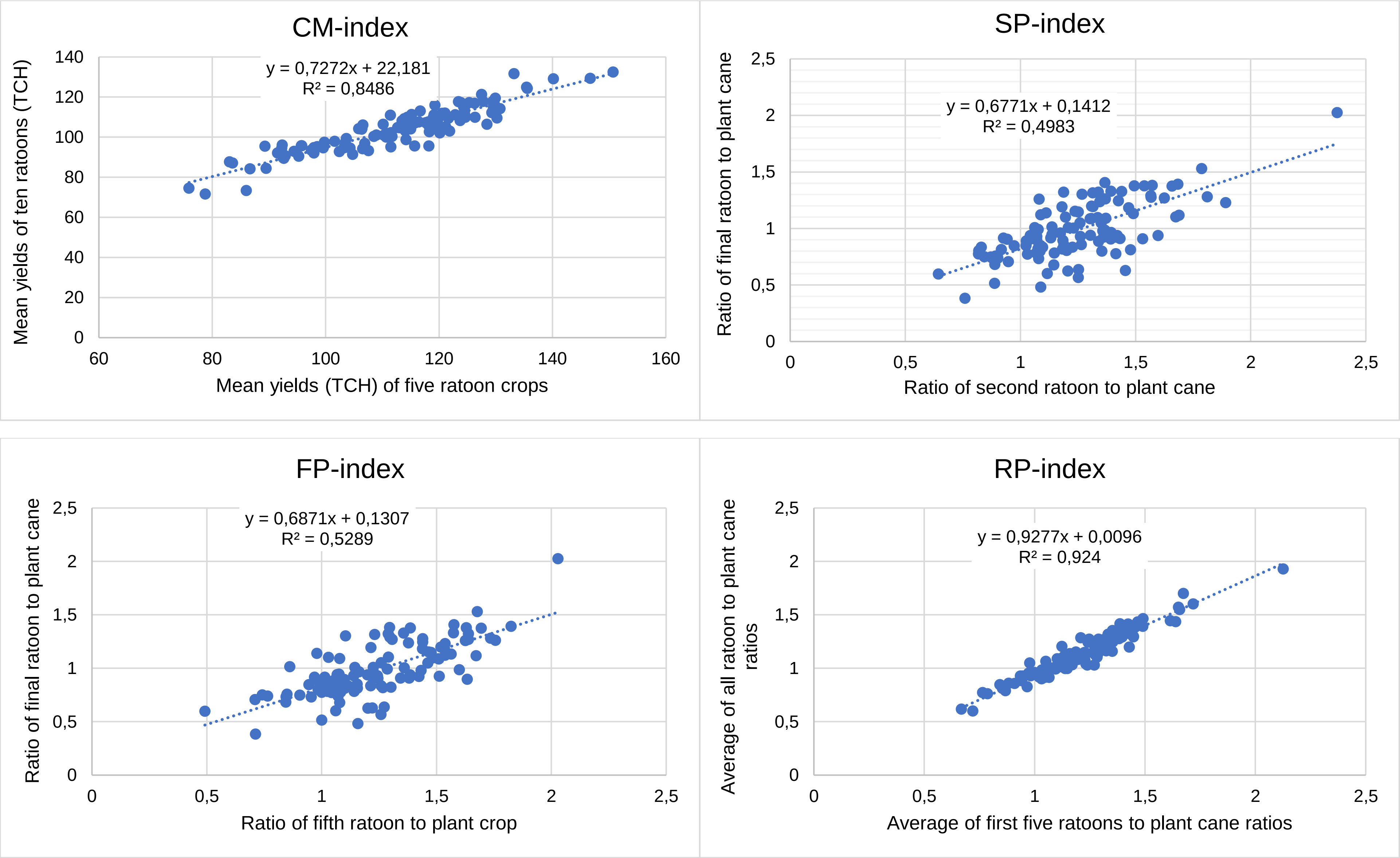
An analysis to identify the most accurate index (or indices) for measuring RA in longer ratoon crop cycles was conducted using commercial data. Figure 1 shows that the RP index had the largest R^2 value of 0.9240, which suggested that it was the most accurate index for estimating the RA for longer ratoon crop cycles. It was followed by the CM index, which had an R^2 of 0.8486, authenticating the current practice of recommending varieties based on the average yields of the test crops (i.e., plant and ratoon crops). Ranked in terms of accuracy in this analysis, the indices were in the order: RP (0.9240) > CM (0.8486) > FP (0.5289) > SP (0.4983) > LR (0.4178) > QR (0.2218).

Discussion

Identifying the most accurate method of measuring RA is essential in sugarcane VTPs. This study identified the RP method as the most accurate index for estimating RA in longer sugarcane ratoon crop cycles. The RP method considers yields of all the ratoon crops, as it entails averaging all ratoon crop to plant cane ratios. Assuming that there are no significant differences in plant cane yields, recommended varieties are those with higher average ratios than the control variety. In this analysis, variety M1246/84 was identified by the RP index as the only variety with a higher ratio than the control. However, since a variety that is eventually advanced for commercial propagation is one that combines high plant cane yield and RA, the RP index ranked variety M1176/77 above the control. This suggested that M1176/77 was the preferred variety with respect to cane yield for longer ratoon cycles. The success of this study

Table 3. **Plant cane (PC) yields (tonnes cane per ha, TCH) of nine sugarcane varieties and their rankings according to six ratooning ability indices [*CM*, ratoon crops yield means (TCH); *SP*, second ratoon yield/plant cane yield; *FP*, final ratoon yield/plant cane yield; *RP*, average of all ratoon to plant cane yield ratios; *LR*, linear regression; *QR*, quadratic regression]. Rk1: PC yield ranking; Rk2: ranking according to ratooning ability; Rk3: ranking according to PC yield and RA ((Rk1 + Rk2)/2) for cane yield.**

Variety	PC	Rk1	CM	Rk2	Rk3	SP	Rk2	Rk3	FP	Rk2	Rk3	RP	Rk2	Rk3	LR	Rk2	Rk3	QR	Rk2	Rk3
M1176/77	137.0	1	113.4	1	1.0	0.872	4	2.5	0.881	2	1.5	0.850	4	2.5	-5.183	7	4.0	-18.49	7	4.0
M1186/86	115.8	8	80.6	9	8.5	0.716	9	8.5	0.624	9	8.5	0.701	9	8.5	-9.076	9	8.5	-19.99	8	8.0
M1246/84	119.8	7	101.3	5	6.0	0.904	1	4.0	0.873	3	5.0	0.869	1	4.0	-4.019	2	4.5	-11.37	1	4.0
M1400/86	131.0	2	101.0	6	4.0	0.805	8	5.0	0.794	8	5.0	0.783	8	5.0	-5.924	8	5.0	-20.01	9	5.5
M1551/80	124.8	3	101.8	4	3.5	0.858	6	4.5	0.821	5	4.0	0.824	5	4.0	-4.852	6	4.5	-14.41	5	4.0
M695/69	112.2	9	91.0	8	8.5	0.871	5	7.0	0.809	7	8.0	0.819	6	7.5	-4.519	3	6.0	-12.43	2	5.5
M96/82	124.0	4	104.2	2	3.0	0.872	3	3.5	0.845	4	4.0	0.853	3	3.5	-4.827	4	4.0	-12.67	3	3.5
R570	120.8	6	96.3	7	6.5	0.827	7	6.5	0.812	6	6.0	0.810	7	6.5	-4.838	5	5.5	-15.03	6	6.0
NCo376	122.7	5	103.7	3	4.0	0.896	2	3.5	0.893	1	3.0	0.856	2	3.5	-3.477	1	3.0	-13.44	4	4.5


CM-index
y = 0,7272x + 22,181
R² = 0,8486
Mean yields of ten ratoons (TCH)
Mean yields (TCH) of five ratoon crops
0
20
40
60
80
100
120
140
60
80
100
120
140
160
SP-index
y = 0,6771x + 0,1412
R² = 0,4983
Ratio of final ratoon to plant cane
Ratio of second ratoon to plant cane
0
0,5
1
1,5
2
2,5
FP-index
y = 0,6871x + 0,1307
R² = 0,5289
Ratio of final ratoon to plant cane
Ratio of fifth ratoon to plant crop
0
0,5
1
1,5
2
2,5
RP-index
y = 0,9277x + 0,0096
R² = 0,924
Average of all ratoon to plant cane ratios
Average of first five ratoons to plant cane ratios
0
0,5
1
1,5
2
2,5

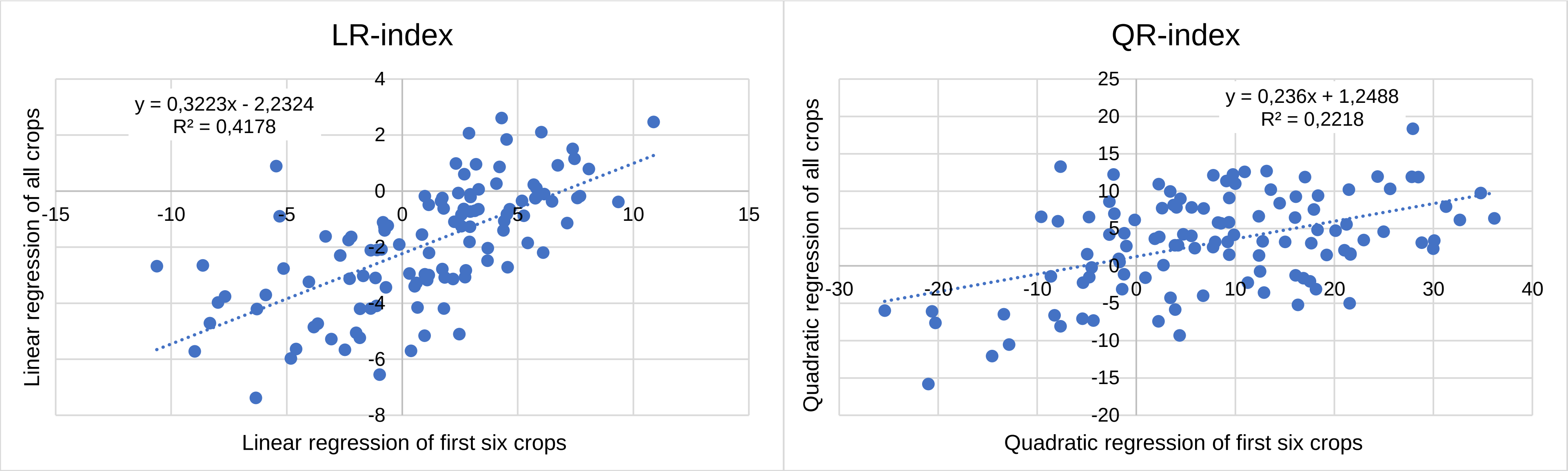


Figure 1. **Six ratooning ability (RA) indices (CM, SP, FP, RP, LR and QR) test, using commercial data. For CM, SP, FP and RP, the results of the first five ratoon crops were regressed against those of ten ratoon crops, while for LR and QR, the results of the first six crops (plant and five ratoons) were regressed against eleven crops (plant and crops ratoons). [*CM*, ratoon crops yield means; *SP*, second ratoon yield/plant cane yield; *FP*, final ratoon yield/plant cane yield; *RP*, average of all ratoon to plant cane yield ratios; *LR*, linear regression; *QR*, quadratic regression]**

was its ability to define a method that recommends a variety based on both yield and RA, the two important parameters in sugarcane VTPs.

This study also validated the current practice of advancing varieties based on crop yield means (CM). For this method, a variety that is advanced for commercial growing is one that has higher average yields over the test period than the control. The CM method identified varieties M1176/77 and M96/82 as being superior to the control with respect to cane yield. [The RP index ranked variety M96/82 as similar to the control]. For the CM method to effectively identify desirable varieties, the test period should be long enough to sufficiently segregate high yielding and ratooning varieties from poor varieties, such that the performance is well replicated under commercial scale. Previous studies conducted in separate areas recommended different test years to adequately discriminate variety performances. For example, Ramburan *et al*. (2018) recommended five crops for Eswatini, Kimbeng *et al*. (2009) and Zhou *et al*. (2012) recommended four crops for Rio Grande Valley Region of Texas (US) and Dwangwa Estate (Malawi), respectively, while Brown and Glaz (2001) reported that three crops were enough for Florida.

The ratio based indices of second ratoon to plant cane (SP) and the final ratoon to plant cane (FP), were not ideal for longer ratoon crop cycles. This is so because these indices do not take into consideration the effects of the other test ratoons, yet they are critical in identifying high ratooning varieties in such ratoon cropping systems. The yields of ratoon crops depend largely on the prevailing conditions under which they grow. Hence, the yield of one ratoon crop cannot be used to accurately predict the yield of another, unless the growing conditions and management practices are similar. When the growing conditions and management practices are similar for different ratoon crops, the differences in yields between them, is largely determined by the varieties involved. It is therefore important to take into consideration the effects of all ratoon crop when estimating varieties' RAs.

Similarly, the linear regression (LR) and quadratic regression (QR) indices showed to be less accurate compared to the RP and CM methods. The downside of the linear regression (LR) index is that ratoon yield trends are often not linear, especially for longer cycles. To side-step this weakness, Ramburan *et al*. (2013) treated plots with R^2 of less than 0.20 as missing values. However, for studies with relatively smaller datasets, eliminating certain experimental plots in the analysis may lead to incorrect conclusions. On the other hand, while the QR normally provides a good fit, the yield trends for the younger ratoon crops did not strongly reflect those of the longer crop cycles in the commercial data used for this study. This was indicated by the comparatively low R^2 (0.22) obtained for this index.

Apart from their accuracy in estimating RA, the RP and CM indices have the added advantage of ease to compute. By implication, they can therefore be used by growers to compare yield and RAs of released varieties under commercial conditions to inform on-farm decision-making. In addition to estimating RAs of varieties, these indices can also be used to segregate production factors such as soil types and harvesting seasons according to their rate of ratoon yield decline.

The highly significant effects of location (representing soil types), season and variety on plant cane yield (i.e., yield potential) indicated that these factors had a large impact on yield. This supports the segregation of soils, seasons and varieties according to their yielding abilities. The non-significant interactions of the variety x location and variety x season suggested that variety rankings on plant cane yield were not affected by soil type and season. In sugarcane VTPs, plant cane yields are not used to predict differences in varieties' ratoon yields, due to differences in RAs. The comparison of varieties for their yield potential, using plant cane, is valid when they have similar RAs. When the RAs are similar, varieties with higher plant cane yields produce overall higher yields, and vice versa. In this study, there was a wide range of values for plant cane yield and RA among the varieties, which suggested the existence of significant genotypic variability. This was supported by the highly significant differences in plant cane yields and RAs of the varieties. Effective variety selection depends largely on the magnitude of the genotypic variability within the population being tested. Therefore, the results indicated the existence of an opportunity to identify varieties that were both high-yielding and ratooning.

The non-significant variety x location interaction for RA indicated that the RAs of the varieties was not dependent on soil type. This therefore suggested that the testing of varieties for their RAs across different soil types was not essential, since the results obtained from one site were applicable to the other site. In the Eswatini sugar industry, soils under cane production are categorised into three, based on their hydraulic properties, and they are well draining, moderately draining and poorly draining soils. In this study, only two soil types (well draining and poorly draining soils) were considered. Future studies may need to consider including all three soil types to authenticate the findings of this study.

The variety x season interaction was significant, as shown by four of the six RA indices, including the recommended RP index. This highlighted the presence of seasonal effects on the RAs of the varieties. This therefore emphasises the importance of testing sugarcane varieties across different harvesting seasons. Matching varieties with their seasons of adaptability is the goal of multi-environment trials in the sugarcane industry (Dlamini, 2017). This is emphasised by the categorisation of sugarcane varieties according to their seasons of adaptation (i.e., early, mid and late) in most industries. This is particularly important in areas where the identification of broadly adapted varieties is not feasible, due to large genotype x environment interactions. Under such circumstances, identifying niche specific varieties becomes a viable option.

Conclusion

This study was the first to simultaneously estimate sugarcane yield and ratooning ability by using different ratooning ability indices. While there were strong correlations between the six indices, they ranked the eight test varieties and the control differently. This suggests the importance of identifying the most ideal RA index or indices for the different sugarcane ratooning systems. Where a wrong index is used, it will inadvertently lead to wrong conclusions. These conclusions may include recommending a poor ratooning variety in the long-term, or discarding a good ratooning variety which could have been advanced for commercial growing. This study identified the RP index as the most appropriate for estimating the RA for longer ratoon crop cycles of ten or more ratoons. The current practice of using crop yield means (CM) was also validated by this study. The methodology and findings of this study are anticipated to excite and stimulate more related investigations that are aimed at informing decision-making on sugarcane varieties' testing efforts, including on-farm testing.

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