REFEREED PAPER

CULTIVAR GENETIC GAINS FOR SUGARCANE YIELD, SUCROSE CONTENT AND SUGAR YIELD IN THE MIDLANDS REGION BREEDING PROGRAMMES

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Abstract

Analysis of genetic gains provides a measure of performance of plant breeding programmes. Previous studies have shown low gains among several sugarcane breeding programmes. The objectives of this study were to determine the trends in genetic gains for cane yield, sucrose content and sugar yield of cultivars grown in the humic and sandy soils of the Midlands region, and to determine cultivar characteristics for the soil types. Data derived from the final stage of variety testing were analysed using the mixed procedure of SAS to estimate cultivar least square means. Trends in yield and quality over time were tested using simple linear regression. There were consistent and significant cane and sugar yield increases with year of release, indicating significant genetic gains have been achieved. Recently released cultivars produced significantly higher cane and sugar yield than older cultivars, indicating adoption of new cultivars would significantly increase profitability. There were limited gains in sucrose content, indicating the need to enhance breeding for sucrose content. Principal component analysis indicated the negative association between cane yield and sucrose content, the main variables that grouped the cultivars. Generally, cultivars producing low sucrose content (for example N31) were unsuitable for humic soils, whereas cultivars producing low cane yield (for example N37) were unsuitable for sandy soils. Breeding cultivars producing high sucrose content for the humic soils and high cane yield for the sandy soils will increase genetic gains for sugar yield. Increasing area planted to new cultivars is expected to increase sugar yield by 7-20%.

Keywords: Cultivars, genetic gains, humic and sandy soils, principal component analysis

Introduction

Regular evaluation of the performance of cultivars is important for assessing their value. Such analysis also determines the efficiency of breeding programmes and aligns grower needs with plant breeding strategies. The cultivar genetic gains refer to the increase in yield and quality to be derived from the continuous release of varieties over time, and are a measure of the continual genetic improvement that benefits the growers (Burnquist, 2013). The evaluation of genetic gains of commercial cultivars also measures the influence of several cycles of recurrent selection in producing genetic material that produces benefits for the growers (Lingle *et al*., 2010).

Gains from sugarcane breeding are lower than other crops, such as maize, rapeseed, soybeans and sugar beet (Burnquist, 2013). The low gains in sugarcane are largely associated with limited resources invested in sugarcane breeding compared to other crops and the complex genetic make-up of sugarcane. Sugarcane breeding complexity is further confounded by the difficulty of creating genetic recombination especially in subtropical countries such as South Africa, where sugarcane does not produce fertile pollen outside controlled temperature conditions. When comparing gains from sugarcane breeding programmes, South Africa and the USA rank lower than Australia, India, Brazil, Thailand and Colombia (Burnquist, 2013). Generally, the countries that have achieved larger gains than South Africa are tropical countries where there is prolific flowering, resulting in better cross-combinations and wider crossing for introgressing genes from the ancestral species.

Previous studies to quantify the performance of sugarcane cultivars in Australia (Cox *et al*., 2005; Cox and Stringer, 2007) used complex computations and 30-year moving averages of commercial variety yield data. The trends of the 30-year moving averages were used to estimate genetic gains from the cultivars over time. While this approach has provided a good indication of the value of the Australian sugarcane cultivars, the scenario could be different for South Africa. Variety adoption in South Africa is slow, largely because of the longer ratoon cycles. Studies by Burnquist *et al*. (2010) also attempted to quantify the benefits from cultivars, while studies by Donovan (1998, 1999) demonstrated the contribution of varieties to productivity. While the analysis of Burnquist *et al*. (2010) included data from South Africa, the analysis did not evaluate specific breeding programmes, confounding progress from regional breeding programmes. Evaluation of realised gains in yield and quality among SASRI advanced selection populations produced differences among the breeding programmes (Zhou, 2013a,b). Trends in gains from advanced populations are expected to lead to similar trends in gains among cultivars from their respective programmes. Evaluation of the performance of cultivars from the different breeding programmes is required. Such an evaluation will highlight the gains achieved from cultivars and their adaptability over time.

The South African Sugarcane Research Institute (SASRI) operates seven regional breeding and selection programmes (Nuss, 1998). These programmes were established to develop varieties suited to each of the agro-ecological zones characterised by different environmental, soil, rainfall, age at harvest, pests and diseases. The Midlands zone is characterised by high altitude and longer winters, and therefore sugarcane is harvested at 24 months (Table 1). The two breeding programmes in the Midlands are aimed at producing cultivars adapted to two major soil types, humic and sandy soils. The humic soils are deep and rich while the sandy soils are poorer (Ramburan *et al*., 2012).

The objectives of this study were to determine the trends in genetic gains for cane yield, sucrose content and sugar yield of cultivars grown in the humic and sandy soils of the Midlands region, to determine differences in cultivar adaptability and to evaluate potential future variety trends that would enhance profitability.

Table 1. South African Sugarcane Research Institute regional selection research stations (Nuss, 2003).

Research station	Code	Altitude (m)	Latitude	Harvest age	Conditions represented
Bruyns Hill	B	1012	29°25’	24 months	Midlands humic soils
Glenside	S	997	29°25’	24 months	Midlands sandy soils

Materials and Methods

Experimental materials and data collection

Data were collected from advanced variety trial series planted from 1997 (establishment of new research stations) to 2011, and harvested from 1999 to 2013. Data were collected from six trial locations in the Midlands region. The six trial locations in the Midlands were three for sandy soils at Glenside research station (SV), Cool Air site (S1V) and van Breda farm (S2V), and Bruyns Hill research station (BV), Conrad Klip farm 1 (B1V) and Conrad Klip farm 2 (B2V). Plot sizes were 5 rows by 8 m and spaced 1.0 m between rows for all trials. The number of genotypes in each trial ranged from 24 to 36. The trials were harvested in the plant, first and second ratoon crops at 20-24 months crop age.

At harvest, all millable stalks in the plots were cut by hand and weighed using a digital scale. From each plot, 12 stalks were randomly picked to provide a sample for estimating sucrose content. The sucrose content was measured using standard laboratory procedures (Shoonees-Muir *et al*., 2009) and expressed as estimated recoverable crystal (ERC % cane), using an empirical formula that accounts for losses via bagasse and molasses (waste products). The plot weights were divided by the plot area to estimate cane yield (t/ha). Sugar yield (ERC t/ha) was the product of cane yield by ERC % cane.

Data analysis

Data for cane yield, sucrose content and sugar yield from all trials were merged. Only the data for the cultivars was filtered and analysed for this study to establish the trends for cultivars over time. The data from unreleased genotypes was not used. The year of release of each cultivar was also added to the data to determine the trends over time. The data were analysed using SAS mixed models (SAS institute, 2013) to estimate the least square means of each cultivar for each of the humic and sandy soils. The data were analysed using the linear mixed model,

$$Y_{ijkl} = \mu + T_i + R(T)_{j(i)} + V_k + VT_{ik} + VR(T)_{jk(i)} + C_l + CR(T)_{jl(i)} + E_{ijkl} \qquad \text{Equation 1}$$

where, Y_{ijkl} is observation from cultivar k (k = 1, 2, …., v) in replication j (j = 1, 2, …, r) nested in trial i (i = 1, 2, …, t) harvested in crop-year l (l = 1, 2, …, c); μ is the overall mean; T_i is the random effect of the ith trials; $R(T)_{j(i)}$ is the random effect of the jth replication nested within the ith location; V_k is the fixed effect of the kth cultivar; VT_{ik} is the random interaction effect of the ith trial by the kth cultivar; $VR(T)_{ik(i)}$ is the random interaction effect of the jth replication by the kth cultivar nested with the ith trial; C_l is the random effect of the lth crop-year; $CR(T)_{jl(i)}$ is the random interaction effect of the jth replication by the lth crop-year nested within the ith trial; E_{ijkl} is the residual error.

The least square means were subjected to simple linear regression using SAS PROC REG to determine the strength of the association between cane yield, sucrose content and sugar yield against year of release. The least square means of the cultivars were plotted against year of release to determine the trends over time. The regression model used was,

$$Y_i = a + bx_i + e_i \qquad \text{Equation 2}$$

where, Y_i was the cultivar means for cane yield, sucrose content or sugar yield; a was the intercept; b was the slope; x_i was the ith year of release of a cultivar and also the predictor variable; e_i was the residual error.

A grouping of the data based on the years of release created a new design variable. Cultivars released before 1970 were in group I, 1970 to 2000, group II and after 2000, group 3. The grouping was done to create historical cultivars (before 1970), those released within a 30 year period (1970-2000) and recently released cultivars (released after 2000). The data were analysed using mixed procedure of SAS and the linear mixed model used was,

$$Y_{ijkl} = \mu + T_i + R(T)_{j(i)} + G_k + GT_{ik} + GR(T)_{jk(i)} + C_l + CR(T)_{jl(i)} + E_{ijkl} \qquad \text{Equation 3}$$

where G_k was the fixed effect of the *k*th group of cultivars; GT_{ik} is the random interaction effect of the *i*th trial by the *k*th group of cultivars; $GR(T)_{jk(i)}$ is the random interaction effect of the *j*th replication by the *k*th group of cultivars nested with the *i*th trial. The other effects are as described in equation 1.

The least square means of the cultivars generated by equation 1 were subjected to principal component analysis (PCA) using SAS Proc PRIN to determine the groupings of the cultivars as well as the major influencing variables. When the clusters of cultivars were determined, the clusters were defined as class variables and subjected to analysis of variance using equation 3, where grouping was replaced with cluster. This analysis was used to describe the traits defining each cluster for each of sandy and humic soils.

Results

Results showed highly significant differences ($P<0.0001$) among cultivars for cane yield, sucrose content and sugar yield for the humic and sandy soils (data not shown). To evaluate the trends for time of release, cane yield, sucrose content and sugar yield were plotted against year of release (Figures 1 to 3). The humic soils generally produced higher cane yield than the sandy soils. There was consistent increase in cane and sugar yield with year of release. For the humic soils (Figure 1), cane yield increased by a non-significant ($r=0.59$, $P=0.0564$) 0.40 tons per hectare per year. In sandy soils, cane yield increased by a non-significant ($r=0.56$, $P=0.074$) 0.35 tons per hectare per year. However, cultivar N37 for the sandy soils produced very low cane yield, indicating its poor adaptability. In further analysis of the data from sandy soils, N37 was excluded. The cane yield of the cultivars grown the in sandy soils increased by a significant ($r=0.82$, $P=0.0037$) and 0.38 tons per hectare per year. The magnitude of the increases was greater in recently released cultivars. Cultivars produced higher sucrose content when grown in sandy soils than when grown in humic soils. Sucrose content (Figure 2) showed non-significant trends for the humic ($r=0.09$, $P=0.7952$) and sandy ($r=0.02$, $P=0.9523$) soils. Sucrose content was largely stable across years of release. The trends for sandy soils remained largely unchanged over time, and that for the humic soils showed marginal increases with years of release.

The cultivars produced higher sugar yield when grown in humic soils than when grown in sandy soils. Sugar yield (Figure 3) had significant ($r=0.81$, $P=0.0024$) trends over years for the humic soils. The trend resulted in 0.05 t/ha/year sugar yield gains over time. The sandy soils had a significant ($r=0.65$, $P=0.0313$) and 0.05 t/ha/year increase in sugar yield including N37. Cultivar N37 (Figures 1 and 3) was poorly adapted to sandy soils. Another analysis was done excluding

N37. The trend was significant (r=0.88, P=0.0008) and 0.052 tons per hectare per year sugar yield gains. The magnitude of the increase was larger in recently released cultivars.

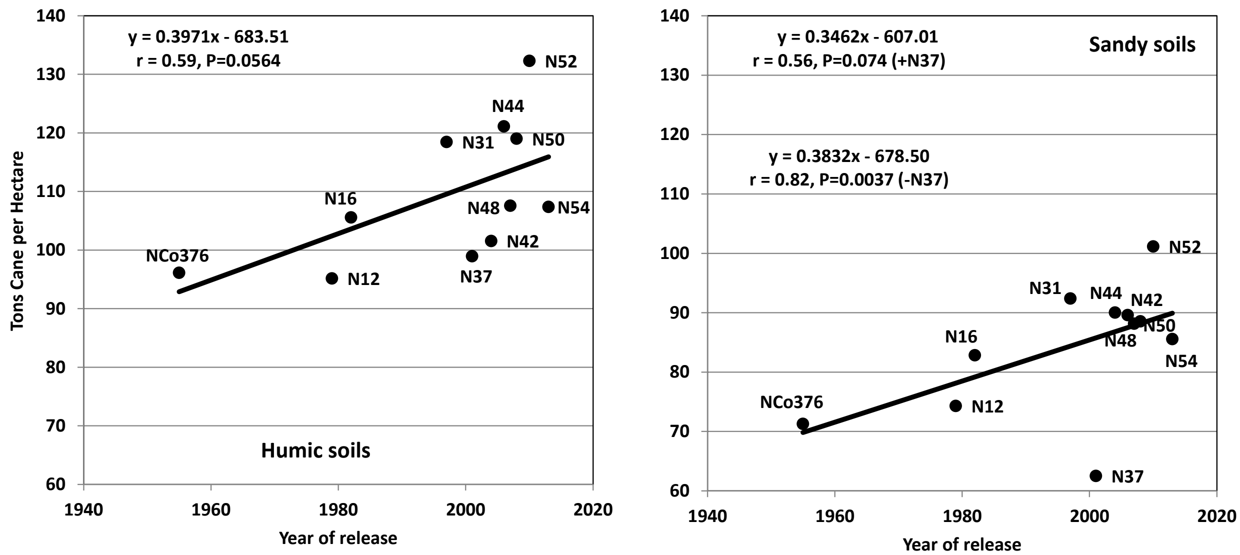

Figure 1. Sugarcane yield (tons cane per hectare) plotted against year of release of a cultivar for humic and sandy soils in the Midlands region of South Africa.

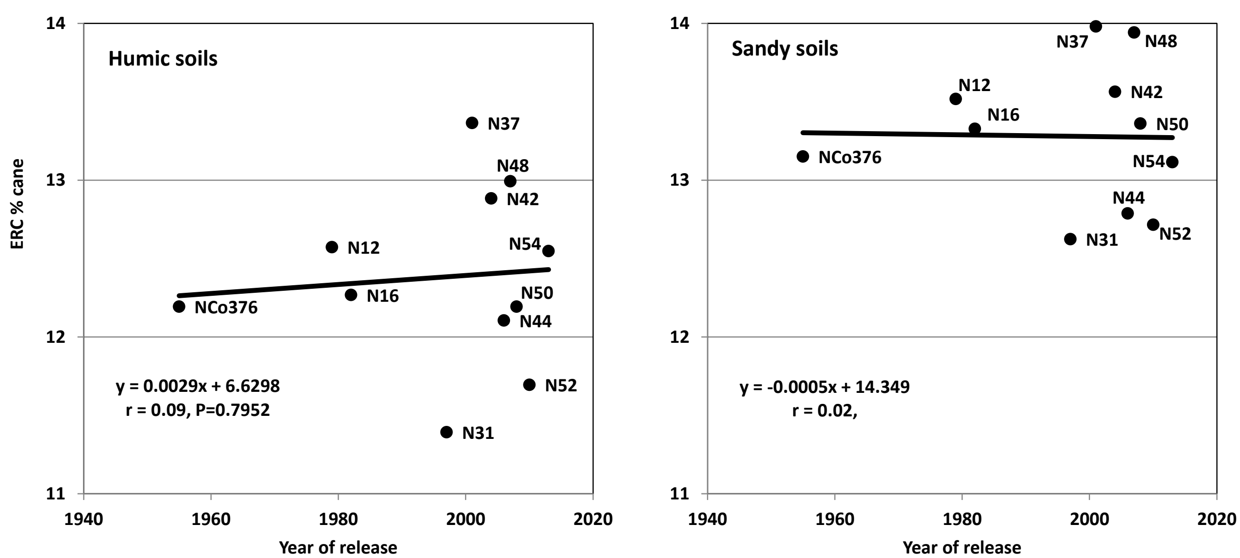

Figure 2. Sucrose content (ERC % cane) plotted against year of release of a cultivar for humic and sandy soils in the Midlands region of South Africa.

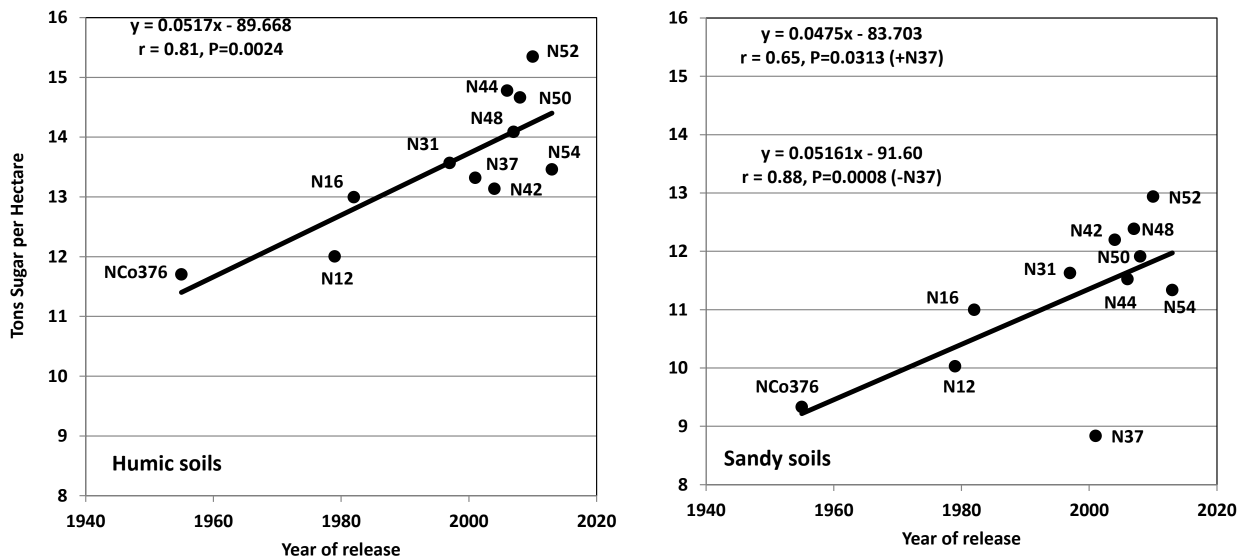

Figure 3. Sugar yield (tons sugar per hectare) plotted against year of release of a cultivar for humic and sandy soils in the Midlands region of South Africa.

To further understand the improvement in yield and quality over time, the cultivars were divided into three groups by year of release. Cultivars released prior to 1970 were categorised as group 1, those released between 1970 and 2000 were categorised as group 2, and cultivars released after 2000 were in group 3. For the sandy soils, N37 was excluded from the analysis because of poor adaptability shown in Figures 1 and 3. The data was subjected to analysis of variance with the groups as fixed effects and mean separation using Tukey adjustment (Freund and Wilson, 2003).

There were highly significant differences (P<0.0001) among the groups for cane yield for both humic and sandy soils (Table 2). Cultivars in group 3 for humic soils produced significantly (P<0.002) higher cane yield than cultivars in group 2, while cultivars in group 2 produced significantly (P<0.0001) higher cane yield than cultivars in group 1. There was a consistent increase in cane yield from groups 1 to 2 to 3. For sandy soils, cultivars in group 3 produced significantly (P<0.0004) higher cane yield than cultivars in group 2, while cultivars in group 2 produced significantly (P<0.0001) higher cane yield than cultivars in group 1. There was a consistent increase in cane yield from group 1 to 3. The data from sandy soils produced larger F-values than that from humic soils. The data from humic soils produced higher R^2 and lower coefficient of variation percent (CV%) values than the data from sandy soils. Cultivars generally produced higher cane yield in the humic soils than in the sandy soils.

The sucrose content of cultivars when grown in humic soils produced highly significant (P<0.0001) differences among groups (Table 2). Cultivars in group 3 produced significantly (P<0.0001) higher sucrose content than cultivars in both groups 1 and 2. Groups 1 and 2 produced no significant differences (P=0.874) in sucrose content. In the sandy soils, there were no significant (P=0.931) differences in sucrose content among cultivar groups. The data from humic soils had higher F-values than that of sandy soils. There was higher CV% from humic than sandy soils data. Generally, the cultivars consistently produced higher sucrose content when grown in sandy soils than when grown in humic soils.

There were highly significant differences (P<0.0001) among cultivars for sugar yield when grown in Humic soils (Table 2). Cultivars in group 3 produced significantly (P<0.0001) higher sugar yield than cultivars in group 2 while cultivars in group 2 cultivars produced significantly (P<0.0001) higher sugar yield than cultivars group 1. There was a consistent increase in the sugar yield of cultivars from group 1 to 2 to 3. In sandy soils, cultivars in group 3 produced significantly (P<0.0001) higher sugar yield than cultivars in group 2 while cultivars in group 2 produced significantly (P<0.0001) higher sugar yield than cultivars in group 1. Cultivars produced higher sugar yield when grown in humic than when grown in sandy soils. The F-value of data from humic soils was larger than that of data from the sandy soils. The data from the humic soils produce higher R^2 and lower CV% than data from sandy soils.

Table 2. The least square means for tons cane per hectare, sucrose content (ERC % cane) and sugar yield for the humic and sandy soils of the Midlands region of South Africa for cultivars released before 1970, between 1970-2000 and after 2000.

Year of release	Cane yield (t/ha)		ERC % cane		Sugar yield (t/ha)	
	Humic	Sandy	Humic	Sandy	Humic	Sandy
<1970	96.32[a]	71.33[a]	12.18[a]	13.15[a]	11.71[a]	9.34[a]
1970-2000	104.72[b]	83.40[b]	12.17[a]	13.11[a]	12.75[b]	10.87[b]
>2000	110.08[c]	91.61[c]	12.73[b]	13.15[a]	13.97[c]	12.05[c]
F-value	31.19	43.28	22.49	0.07	62.49	52.36
P-value	0.0001	0.0001	0.0001	0.931	0.0001	0.0001
R^2	0.79	0.77	0.70	0.70	0.81	0.78
CV%	15.71	19.96	8.90	7.57	16.57	19.63

To further visualise the performance of the cultivars in the Midlands humic and sandy soils, the data for yield and quality was subjected to principal component analysis. More than 90% of the variation in the data was explained by the first two principal components (data not shown). For both humic and sandy soils, principal component 1 was positively and strongly influenced by cane yield, followed by negative influence of sucrose content (Table 3). Principal component 2 was strongly and positively influenced by sucrose content. In humic soils, the influence of sugar yield was the same in both principal components 1 and 2. In sandy soils, sugar yield was more influential in principal component 1 than in principal component 2. Only results from principal components 1 and 2 were interpreted.

Table 3. The first three principal components (Prin) for cultivars grown in the humic and sandy soils of the Midlands region of South Africa.

Trait	Humic soils			Sandy soils		
	Prin 1	Prin 2	Prin 3	Prin 1	Prin 2	Prin 3
Cane yield (tons/ha)	0.66	0.08	0.74	0.65	0.16	0.74
ERC % cane	-0.48	0.81	0.33	-0.45	0.87	0.21
Sugar yield (tons/ha)	0.58	0.58	-0.58	0.61	0.47	-0.64

The principal component 1 (x-axis) was plotted against principal component 2 (y-axis) to produce bi-plots (Figure 4). When the cultivars were grown in humic and sandy soils, three clusters emerged. For the humic soils, cluster I was made up of N12 and N16, cluster II was made up of N37, N42, N48 and N54, while cluster III was made up of N44, N50 and N52. Cultivars NCo376 and N31 were separated from the three clusters. For sandy soils, cluster I was made up of N12 and N16, cluster II was made up of N31, N44, N52 and N54 and cluster III was made up of N42, N48 and N50. Cultivars NCo376 and N37 did not fit into any of the clusters. Using data from Table 2, for the humic soils, cultivars in clusters I and II were separated largely by sucrose content while cluster II cultivars were separated from clusters I and II by cane yield. Cluster III is made up of cultivars producing high cane yield and good sucrose content. Cluster I is made up of cultivars producing low cane yield and low sucrose content while cluster II is made up of cultivars producing low cane yield and high sucrose content. In sandy soils, cluster I is made up of cultivars that produce lower cane yield than cluster II. Cluster III is made up of cultivars that produce higher cane yield than cluster I and similar to cluster II, and higher sucrose content than both clusters I and II.

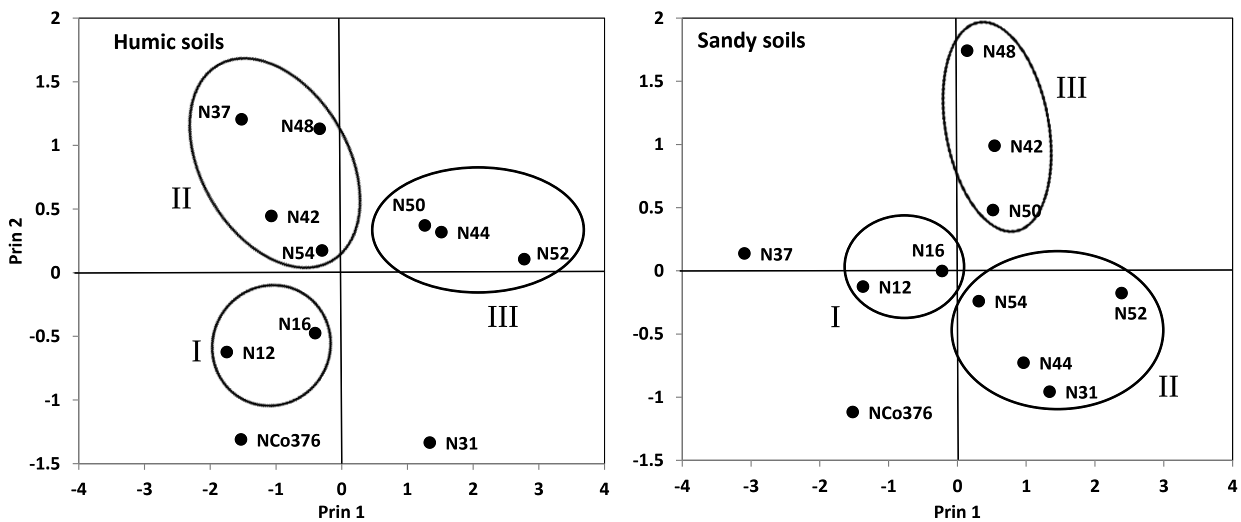

Figure 4. Bi-plot of principal component 1 (Prin 1) on the x-axis versus principal component 2 (Prin 2) on the y-axis for cultivars grown in humic and sandy soils of the Midlands region of South Africa.

To further characterise the cultivars in the clusters, a data set was created for both humic and sandy soils with the clusters of varieties as fixed effect. The data was subjected to analysis of variance to determine the characteristics of the different clusters. When cultivars were grown in humic soils, there were no significant differences (P=0.9155) in cane yield between clusters I and II, while cultivars in cluster III produced significantly (P<0.0001) higher cane yield than cultivars in both clusters I and II, a results inferred from Figure 4. Cultivars in cluster II produced significantly (P<0.0001) higher sucrose content than cultivars in cluster I while cultivars in cluster I produced significantly (P=0.0002) higher sucrose content than cultivars in cluster III. Cultivars in cluster II produced significantly (P<0.0001) higher sugar yield than cultivars in cluster II while cultivars in cluster II produced significantly (P<0.0001) higher sugar yield than cultivars in cluster I. The order of magnitude of F-values and R^2 values was cane yield > sugar yield > sucrose content. The order of magnitude of CV% was sugar yield = cane yield > sucrose content. Cultivars in cluster I were characterised by low cane yield, intermediate sucrose content and low sugar yield. Cultivars in cluster II were characterised by marginally higher cane yield, highest sucrose content resulting in intermediate sugar yield. Cultivars in cluster III were characterised by the highest cane yield (at least 24% higher than the other clusters) but lowest sucrose content and the highest sugar yield.

For the sandy soils, cluster I cultivars produced significantly ($P<0.0001$) lower cane yield than clusters II and III. There were no significant differences ($P=0.2522$) in cane yield between clusters II and III, a result inferred from Figure 4. There were no significant differences ($P=0.2841$) in sucrose content between the cultivars in clusters I and III. Cultivars in both clusters I and III produced significantly higher ($P<0.0001$) sucrose content than cultivars in cluster II. The sugar yield of cultivars in cluster I was significantly ($P<0.0001$) lower than that of cultivars clusters II and III. Cultivars in cluster II and III produced non-significant differences ($P=0.1422$) in sugar yield. Cultivars in cluster I were characterised by low cane yield, high sucrose content and low sugar yield. Cultivars in cluster 2 were characterised by high cane yield and low sucrose content and produced intermediate sugar yield. Cultivars in cluster 3 produced high cane yield and high sucrose content and the highest sugar yield. The order of magnitude of F-values was cane yield > sugar yield > sucrose content. The order of magnitude of CV% was sugar yield > cane yield > sucrose content. The order of magnitude of R^2 values was sugar yield > cane yield > sucrose content (Table 4).

Table 4. The least square means for the clusters for cane yield, sucrose content (ERC % cane) and sugar yield for the humic and sandy soils of the Midlands region of South Africa.

Cluster	Humic soils			Sandy soils		
	Cane yield (t/ha)	ERC % cane	Sugar yield (t/ha)	Cane yield (t/ha)	ERC % cane	Sugar yield (t/ha)
I	100.60a	12.41b	12.50a	76.70a	13.42b	10.27a
II	100.77a	13.23c	13.39b	93.15b	12.66a	11.77b
III	124.83b	11.98a	14.97c	89.94b	13.59b	12.29b
F-value	90.33	61.22	61.29	43.84	33.76	31.02
P-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
R^2	0.86	0.77	0.86	0.82	0.78	0.80
CV%	13.53	7.98	15.15	17.76	7.25	19.09

Discussion

The results showed consistent differences in cane yield, sucrose content and sugar yield between the humic and sandy soils. The humic soils breeding programme is based at Bruyns Hill research station while the sandy soils breeding programme is based at Glenside research station. The Bruyns Hill programme was set up for the development of varieties adapted to the humic soils. Humic soils are deep soils with high water holding capacity and high inherent soil nutrition. The sandy soils are generally low clay, low water holding capacity and low inherent nutrient holding capacity. While the soil types are different, other growing conditions such as rainfall and temperature are largely similar (Ramburan *et al*., 2011). The large yield and quality differences bring into question the validity of merging the two programmes at final testing stages. While the benefits of identifying broadly adapted genotypes exist, it appears that there are potential disadvantages to the strategy. Principal component analysis (PCA) plots also highlighted that the most ideal cultivars were largely different between the two agro-ecological zones. Further data analysis of breeding populations is required in this regard.

The trends for sucrose content in cultivars released for the humic and sandy soils showed marginal and non-significant increases over time. The result may indicate the narrow genetic variability for sucrose content that exist among the breeding populations. Further, the sandy soils produced higher levels of sucrose content that were associated with even small or no gains over time. The lack of gains may indicate the narrow genetic variability in the populations. The good maturity conditions in the sandy soils, which are associated with moisture stress would require larger variability for sucrose content to detect differences as well as make genetic gains at selection. For the humic soils, small but non-significant gains appear, indicating potential for improvement. The favourable growing conditions in the humic soils results in lower sucrose content compared to sandy soils indicating the need to enhance breeding for high sucrose content. The low gains may be associated with the high cane yield cultivars that have emerged in these programmes and some that have been released. It has been established that cane yield and sucrose content are negatively correlated (Zhou, 2013a) and the negative correlation could be manifesting in our cultivars.

There were significant gains in cane yield and sugar yield, and non-significant or no gains for sucrose content. The trends in gains observed in this study match the realised gains from the study of advanced breeding populations by Zhou (2013b). In the study of Zhou (2013b), the realised gains were larger for cane and sugar yield and lower for sucrose content. The significant gains in cane and sugar yield therefore reflect the gains observed in advanced breeding populations. The gains for the cultivars are however lower than the realised gains from Zhou (2013b). The lower gains reflect the fewer cultivars involved in this study. Only 11 cultivars have currently been released in the Midlands region of South Africa. The other explanation could be associated with the shorter lifespan of the breeding programmes. The Midlands breeding programmes are the youngest of the South African regional programmes, therefore fewer cycle of recurrent selection have occurred (Nuss, 1998). The benefits from the cycles of recurrent selection are expected to be realised in future cultivars. The third explanation could be associated with variety release decision. During variety release, genotypes would only be recommended if they possess in addition to high yield and quality, high disease and pest resistance. The analysis of the realised gains included some high yield and quality genotypes that were not released because of insufficient resistance to pests and diseases.

Trends in yield increases were larger in newer cultivars than older cultivars, indicating the potential effectiveness of recurrent selection particularly for cane and sugar yield. This trend is also similar to the trends observed in advanced breeding populations by Zhou (2013b). Parent selection generally targets high yield genotypes and these trends probably reflect that strategy. Additionally, the Midlands region experiences less pest and disease pressure than other regional breeding programmes in South Africa. Rust, a seasonal disease, is predominant in the Midlands. Smut disease and the stalk borer eldana, although present, are at low levels. As a result of low selection pressure, a larger number of higher yielding genotypes get advanced to later stages for future selection as parents than in other regional programmes. This trend has resulted in a more efficient recurrent selection for yield with limited negative confounding effects from pests and diseases.

The humic soils cultivars showed a slightly higher marginal gain in sucrose content compared to sandy soils. The sandy soils produced higher sucrose content than the humic soils. Sandy soils experience fluctuating moisture stress conditions. Harvesting in the Midlands occurs during the winter months when rainfall is low to allow for ease of cane haulage from the fields. The sandy soils sugarcane crop will experience higher moisture stress conditions, forcing most cultivars to ripen naturally and thus create higher sucrose content. On the contrary, the humic soils have higher water holding capacity and the crop experiences less moisture stress, resulting in higher growth during winter than for the sandy soils. As a result, when cultivars are grown in sandy soils, they produce higher sucrose content than in humic soils. Additionally, in selection trials, the same effect prevails. Genotypes in sandy trials will all be forced to naturally ripen and all produce high sucrose content, thus showing less variability. In humic soils, the differences are larger and therefore higher sucrose content genotypes can be identified and selected. This possibly explains the marginal gains observed in cultivars grown in sandy soils. A dedicated recurrent selection for sucrose content is required particularly for the humic soils breeding programme.

Principal component analysis showed that cane yield and sucrose content were the two variables determining the grouping of the cultivars in the bi-plot. Generally, there was a wider range of values for cane yield (-4 to 4) along principal component 1 scale compared to sucrose content (-1.5 to 2) along principal component 2, indicating the large variability for cane yield among the Midlands cultivars compared to that for sucrose content. Generally, three groups of cultivars were determined: low cane yield and low sucrose, low cane yield and high sucrose and high cane yield and high sucrose content. Cultivars N50, N44 and N52 were the elite in the humic soils while N50, N42 and N48 were elite in sandy soils. Of particular interest is that N42 has shown to be less sensitive to moisture stress in sandy soils from field observations where it has maintained more green leaves and showed less wilting.

Cultivars NCo376 and N31 were both not adapted to humic soils. NCo376 was not adapted because it produced low cane yield and low sucrose content while N31 produced low sucrose content, a result commonly known in the Midlands. Cultivars NCo376 and N37 were not adapted to the sandy soils, as NCo376 produced low cane yield and low sucrose content, while N37 produced very low cane yield with good sucrose content.

The PCA groups were characterised to determine potential traits required for cultivars for the humic and sandy soils. Groups II and III were the cultivars most adapted to the humic and sandy soils. The humic soils cultivars were N44, N50 and N52 (group III) followed by N37, N42, N48 and N54 (group II). While N37 has low cane yield, its high sucrose content is an advantage in the humic soils. The most adaptable cultivars were dominated by the latest releases, indicating the high yield potential from newer cultivars. Higher sucrose content among the humic soils cultivars would increase the sugar yield. The newer cultivars appear to show average to low sucrose content. The most adaptable cultivars for the sandy soils were N42, N48 and N50 (Group III) followed by N31, N44, N52 and N54 (group II). Both sets of cultivars produced similar cane yield while group III produced higher sucrose content than group II. Cultivar N50 was adapted to both humic and sandy soils appearing in the elite group III of both.

The analysis methodology used in this study can be used to analyse gains in other traits such as pest and disease trends. The analysis can also be used in other regional breeding programmes. Future studies may need to focus on establishing yield gains trials. These trials would be planted using the old and new cultivars planted in the same trials and the data would be used to quantify the gains from new varieties as well as quantify the progress of plant breeding. Such trials would provide a more balanced comparison of the cultivars growing under similar conditions.

Generally, there were larger F-values and lower CV% for the humic than sandy soils data. This trend highlighted the large variability associated with trials in sandy soils compared to humic soils. The variability in moisture and associated stress is higher in sandy soils than humic soils. This implies that trial designs for sandy soils need to be reviewed and optimised to account for variability.

The PCA plots indicated the poor adaptability of cultivars NCo376, N31 and N37 in the Midlands. NCo376 produced low cane yield and low sucrose content, making it an unsuitable cultivar for the midlands environment. Cultivar N31 is known to be unsuitable for humic soils because of low sucrose content. Application of ripeners may increase sucrose content of N31. Cultivar N37 was not adaptable to the sandy soils because of very low cane yield. The results highlight the dynamic requirements for cultivar adaptability in the Midlands. High cane yield was important in sandy soils while sucrose content was important in humic soils.

The large gains associated with the newer cultivars indicated that potential increases in yield could be achieved with increased adoption of new cultivars. For example, currently, the largest cultivar by area in the Midlands is N12. The study showed N12 and N16 to be in group 1 for both humic and sandy soils. By increasing the area planted to newer cultivars (group II and III), the sugar yield increased by 7-20% for humic soils and 15-20% for sandy soils. The lower gains reported by Burnquist (2010, 2013) in South Africa will be increased by increasing variety adoption.

Conclusion

The high realised gains observed in Midlands breeding populations are being reflected in cultivars with significant gains in cane and sugar yield. The low gains for sucrose content need to be addressed using enhanced recurrent selection. Cultivar adaptability was clearly determined using PCA bi-plots. Cultivars NCo376 was not adapted to the Midlands while N31 was not adapted to humic soils, and N37 was not adapted to sandy soils. High cane yield appeared to be the most important trait for sandy soils while sucrose content needs to be high for humic soils. By significantly increasing the area planted to new cultivars in the Midlands (increased variety adoption), the sugar yield is expected to increase by 7-20% for humic soils and 15-20% for sandy soils.

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