APPENDIX D
(Form 1050)

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PART 1: PROJECT IDENTIFICATION INFORMATION

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Mauritius Sugarcane Industry Research Institute
Mauritius Cane Industry Authority
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5. Project Title

Evaluation of high biomass sugarcane varieties in marginal areas for energy production

Mauritius Research Council

Evaluation of high biomass sugarcane varieties in marginal areas for energy production

EXECUTIVE SUMMARY

Background

Introduced in Mauritius in 1639, sugarcane was identified as the only major crop to resist the cyclonic conditions prevailing in the region. In spite of various attempts to diversify the agricultural sector, sugarcane stood the test of time and became the sole major cash crop and the backbone of the Mauritian economy for decades. Currently, sugarcane is still cultivated in over 80% of agricultural land and sugar represents around 14% of the value of total domestic exports. However, the Mauritius sugar industry is now faced with unprecedented challenges which arise as a result of trade liberalization world-wide, the EU sugar reform, the opening of the EU market to other non-ACP economies and the EU's decision to abolish production quotas by September 2017. The implementation of the new EU regime is having a far-reaching impact on ACP suppliers, with the threat of closure and wiping out of the whole sugar industry in those countries.

The risks of confining to a mono-product, raw sugar, and the short and long term diversification scenarios within the sugarcane industry were known for long but '*timing and pricing'* were not. Sugarcane is now recognized worldwide as a potential renewable and environment-friendly bioenergy crop capable of replacing the limiting oil reserve in all energy markets and mitigating the adverse effects of burning fossil fuels on the environment. Various government-funded reports and blueprints put emphasis on increased diversification through the use of "high biomass canes" to sustain the industry and as an internal source of environment-friendly renewable energy. All those reports expect great promises from the novel type of varieties that generally have higher fibre content in the cane stem. However, the long term focus of breeders has been to improve sugar yield and current varieties have not been optimized to achieve the required high biomass yield under a range of environments that will be necessary for an extensive production of biofuels. In order not to compete with sugar, high fibre energy canes have a greater potential in marginal and abandoned lands and outside the harvest season to ensure continuous generation of biomass year-round. Those high biomass varieties are yet to be identified and the quantum gains in terms of fibre and total dry matter yields compared to existing commercial varieties in different agro-climatic conditions still need to be established.

Breeding and selection of a new variety currently takes around 12-15 years worldwide. Populations derived from crosses between sugarcane and related wild species provide a good source of variation from which various types of canes with high fibre and total biomass can be identified. Foreseeing the threats on sugar price, the Mauritius Sugarcane Industry Research Institute (MSIRI) started breeding for higher fibre varieties involving sugarcane wild relatives as parents since 1980's. A pool of early generation hybrids with variable

sucrose to fibre ratios was gradually built and maintained in the MSIRI germplasm collection. Objective selection trials with potentially high biomass varieties were established in the last decade. The findings resulted in the definition of four types of economically exploitable varieties and the creation of a selection model that can simultaneously screen the different types from a population of test varieties. The four types of canes (varieties) have varying proportions of sucrose and fibre in the cane stem and are high total cane aboveground biomass yielders, as follows:

Models	**Cane types**	**Categorization**	**Cane components**
Sugar-model	*Type 1*	Existing commercial type	High sucrose, low fibre
Sugar-model	*Type 2*	Enhanced fibre type	High sucrose, high fibre
Fibre-model	*Type 3*	Multi-purpose type	Low sucrose, higher fibre
Fibre-model	*Type 4*	Pure fibre type	Negligible sucrose, very high fibre

They can be grouped into the sugar-model or the fibre-model where the major output is sugar or fibre, respectively. Twenty two selected best biomass varieties were planted in several environments in 2009-2010 for evaluation of their performance over four years in the middle period of the harvest season (mid-August - mid-October).

Evaluations in marginal lands

This study was conducted with the implementation of trials in two sub-optimal environments (super-humid upland and dry non-irrigated northern plain) and for harvest at two contrasting dates (June and December). Twelve highly selected varieties were concurrently planted in each of the four trials. The main objectives were to assess the performance of the biomass varieties in marginal areas, evaluate their stability across environments and successive harvests, and determine the possibilities of harvesting year-round fast growing high biomass clones. The physiological aspects of above-ground biomass accumulation across time were a prerequisite to determine the best time for data collection and harvest. The most appropriate harvesting method of the higher fibre energy canes was considered essential in the successful exploitation of the novel type of varieties in Mauritius.

Various cane quality, cane morphology and aboveground biomass parameters were measured at two months interval as from 8-months old crops. The cane quality traits referred to the cane stalk components in terms of Brix (soluble solids), sucrose content, fibre content and juice purity obtainable from laboratory analyses of cane samples. The morphological attributes measured were cane stalk diameter, height, number per unit area (cane density), growth habit and flowering behaviour. The constituents of aboveground biomass were cane yield, sugar yield, fibre yield, sugarcane field residues (consisting of cane tops and green and dry leaves) yield and total biomass yield. The measurements were made in both fresh and dry weights.

Additional measurements involved calculation of energy equivalences of selected best biomass varieties, determination of the net biomass balances (NBBs) with shorter crop cycles, creation of an economic selection index (ESI) and evaluation of the difficulties in harvesting the higher fibre energy canes. The gross calorific values in terms of kilojoules per kilogram (KJ kg^{-1}) of different cane components dry weight were obtained using a boom calorimeter. The values were used to estimate the net energy output of the different varieties in terms of gigajoules per hectare per year (GJ ha^{-1} yr^{-1}). The NBB was a method devised to measure the gain in yield by harvesting the varieties at younger crop ages. The ESI for each variety was based on the products of economic weights of sugar and bagasse with their corresponding yields obtainable from the different varieties. Economic weights were the actual price per tonne paid to sugarcane growers for the different components. The ease of manual harvesting the different varieties with variable fibre content was measured using a five-point-scale-index.

Main findings and discussion

The results could be summarised and discussed as below:

- There were significant differences among the varieties evaluated for all the measured biomass related variables.
- Harvest date (June vs. December) affected the sucrose accumulation pattern among the varieties. Top-ranking high sucrose varieties in June were superseded by others in December. Fibre content, however, remained more stable across time. It was also most heritable.
- Location had a greater impact than harvest date on the performance of the varieties in terms of cane and total biomass yields.
- High fibre varieties were found to adapt better in the super-humid environment. In the dry zone, high sucrose commercial type varieties produced the highest total biomass.
- The best high fibre varieties maintained good performance across successive annual harvests (ratoons). Results obtained in ratoon crops were found more reliable than those obtained from plant cane (first harvest).
- One candidate was identified as a sugar-model high biomass variety with sugar as the main feedstock and high total biomass. The quantum gain was +20% superior total biomass yield to the average of three commercial varieties widely cultivated in Mauritius. Sugar yield was not compromised.
- Three high fibre energy canes were identified mainly for exploitation in the super-humid environment for their total fibre yield. The highest quantum gains achieved compared to commercial varieties in terms of total biomass and fibre yields were +50% and +90%, respectively.
- The high fibre varieties (energy canes) produced high density of thin and tall canes that were lighter than those of the commercial varieties. They were also highly vigorous during the vegetative phase and could be harvested year-round and at younger crop ages. One genotype showed the aptitude for three harvests in two years.
- The energy equivalences in GJ ha^{-1} yr^{-}1 of the best biomass varieties were comparable with their total biomass yields in tonnes ha^{-1} yr^{-1}. However, the ESI model favoured varieties with high sucrose at the expense of high fibre ones.
- The main limitations for industrial exploitation of high fibre varieties in marginal environments were identified as harvest, transport, milling and sharing of benefits. They represent the future research focus areas.

- *Environmental effects on best biomass varieties*

In this study, the main effect, variety, was highly significant for all the variables measured. Location and harvest period main effects were generally significant except for a few morphological traits. For a given measured variable, significant interactions of varieties with location or harvest date meant that varieties showed differential performance across the environments. The cane quality traits showed higher interactions across harvest dates than across locations. Conversely, the cane biomass traits showed higher differential performance across locations than across harvest dates. These results confirmed that top ranking varieties in terms of cane quality traits in June were not the same in December. Also, ranking of varieties for biomass yield changed significantly between the super-humid and dry environments.

The significant genotype by environment interaction (GEI) for cane biomass parameters validated formal investigations using statistical tools designed for the purpose, namely of **A**dditive **M**ain effects and **M**ultiplicative **I**nteraction (AMMI) and **G**enotype x **E**nvironment **E**ffects (GGE) multivariate models. Both techniques include good visualization tools that show major response patterns. In this study, the trials with biomass varieties established in five different environments in 2009 and 2010 and evaluated over three successive annual harvests (crop cycles) were found appropriate to establish the stability and adaptation of the energy canes across locations and years. The study provided preliminary indications of the presence of two mega-environments in the island of Mauritius: the low-altitude dry low-lands and the more humid central environments. Environments that were highly discriminating and those that were most representative for wide adaptation were defined. In the super-humid environment, high fibre, low sucrose energy canes were best biomass yielders. In the dry low-lands, clones with relatively high sucrose were more productive across both harvest dates. These observations were confirmed by the trends obtained from the trials established in marginal areas in 2014.

The variety by crop cycle interaction was significant only within locations. In consequence analyses on interactions involving crop cycle were done separately within two trials established in 2009 in two contrasting locations. Plant cane results were found least representative of the performance of varieties across ratoons. Since sugarcane is planted once and harvested over several years in Mauritius, the biomass yields of varieties in ratoons were considered more representative and precise than those obtained at plant cane. The best high fibre energy canes were found stable across ratoons and responded similarly as the commercial varieties included in the trials. The trials implemented in 2014 confirmed the trends. Plant cane harvest data were obtained in 2015. Particularly for trials planted in the super-humid upland, the relative differences of individual best biomass varieties with the commercial controls for cane yield were >125%. Those differences were drastically reduced to around +50% in the first ratoon crop in 2016 and reflected closely the differences observed from previous trials. Preliminary raw data obtained from second ratoon harvests, taken in June-July 2017 (early harvest), concurred well with the first ratoon results. Full-fledged GEI analysis of the trials implemented in marginal areas will be possible only after the third harvest of two remaining late trials scheduled for December 2017. Nevertheless, the findings obtained so far point to the higher predictive power obtainable from ratoon results.

– *Commercially exploitable best biomass varieties*

From the plant cane results (year 2015) of the four trials established in the sub-optimal areas, six biomass varieties (M 1334/84, M 196/07, M 1395/87, R 585, WI 79461 and WI 81456) were found selectable for multiple end-uses. At the first ratoon crop, four test genotypes, M 196/07, M 1334/84, M 1395/87 and WI 81456, maintained high green biomass yields. Genotypes M 196/07 and WI 81456 significantly surpassed the commercial varieties by +20%. Given the significant genotype-location interactions, in the super-humid uplands, WI 81456 was superior with +51% higher dry biomass yields than those of the commercial controls across the two harvest dates. In the dry zone, M 1334/84 and M 196/07 ranked top in June and December, respectively. Their dry biomass yields were +21% and +31% superior to the average of the commercial varieties.

M 1334/84 suited the sugar-model high biomass cane. It had 1.2 units lower sucrose content than the commercial varieties but ensured significantly higher aboveground dry biomass yield (+20%) and sugar yield (+11%) than those of the commercial varieties in the dry zone. The morphological attributes of the genotype are very interesting with non-flowering erect canes of good diameter and height, which are highly appreciated characteristics by growers. Overall, M 1334/84 represents a good candidate in the dry zone for increasing the total biomass without jeopardizing sugar yield. It should be harvested when it sucrose accumulation peaks, which is around November-December.

Genotypes M 196/07, M 1395/87 and WI 81456 fitted the fibre model with relatively high fibre (~20%) and low sucrose content (~10%) while those of the commercial controls averaged 15% and 13%, respectively. WI 81456 was the overall best ranking fibre-model variety. It performed best in the super-humid environment where the gain in biomass and fibre yields were +50% and +90% to those of the commercial controls, respectively. The three energy canes were generally highly vigorous with fast canopy cover. This feature is highly desirable for more efficient weed control. The three varieties were good candidates of *Type 3* cane type for exploitation for their fibre in marginal and abandoned lands. The extracted juice can be used for ethanol or other high value products.

– *Year-round generation of sugarcane biomass*

Contrary to sucrose accumulation pattern, that showed a sharp rise at the pre-harvest season (May-June) and a tendency to flatten thereafter, with some profusely flowering varieties expressing a decline by the end of the harvest season, fibre accumulation was linear and progressive. The genotypes were already markedly different for fibre content at the pre-harvest season and they did not show significant differential performance across time. The results validate that fibre accumulation occurs mainly during the growth phase and sucrose accumulates mainly during the ripening phase (pre-harvest to harvest season). These results confirmed that fibre-model varieties can be harvested at any time during the year provided that the overall biomass yield is appreciable. Sugar-model varieties should be harvested when sucrose accumulation peaks.

Data collected from 8-, 10- and 12-months old crops ascertained that the three energy canes identified earlier could be cultivated in marginal and abandoned uplands for harvest as from 10-months aged crops with fibre as the main product. WI 81456 also ensured the fastest growth rate in the super-humid region and by 8-months age, its biomass yield doubled those of the commercial varieties. The genotype may be harvested at a younger stage, thereby ensuring three harvests in two years compared to two annual harvests.

– *Further investigations*

In this study, Gross Calorific Values (GCVs) of bagasse and cane trash were comparable and nearly the same for the different varieties, while those for cane juice were more variable. The net energy outputs in GJ ha^{-1} yr^{-1} of the different varieties generally showed nearly the same relative differences from the commercial varieties as those of total aboveground dry matter yields in tonnes ha^{-1} yr^{-1}. However, ranking changed drastically with the ESI, which favored varieties rich in sucrose content at the expense of high fibre canes. Those high fibre energy canes were also found most difficult to harvest manually, due to their high density of tough rind stalks per unit area. Further research strategies on mechanized whole cane harvesting were investigated.

Concluding remarks

Overall, the study established the gains in yield in marginal environments and at extreme harvest periods with the currently available best biomass varieties. Good results were obtained from few high fibre energy canes in the super-humid environment, where the gains in green biomass and fibre yields were +50% and +90% of the existing commercial varieties. With their fast growth habit, the varieties can be cultivated in marginal humid lands for year-round harvest and possibly for three harvests in two years. In the dry zone, mainly high sucrose commercial type varieties were best biomass yielders. One sugar-model high biomass variety, M 1334/84, had 1.2 units lower sucrose content than the commercial varieties but produced significantly higher aboveground dry biomass (+20%) and sugar yield (+11%) than those of the commercial varieties.

The selected best biomass varieties also showed stable yields across years. The high fibre energy canes produced high number of cane stalks per unit area that were generally thinner, taller and around 40% lighter (per unit length) than those of the commercial varieties. These attributes rendered manual harvest difficult and are accordingly expected to impact upon the harvest, transport and milling efficiency of energy canes. Moreover, the current cane payment system favours high sucrose varieties at the expense of higher fibre energy canes.

In the short term, in a small country like Mauritius, where land is limited, sugar-model varieties that comprise *Type 1* (high sucrose low fibre) and *Type 2* (high sucrose high fibre) canes can bring immediate success by maximizing on biomass without impacting on sugar yield. The sugar-model biomass varieties can be adopted immediately and cultivated in fertile

lands as well to increase the total biomass yield without jeopardizing sugar yield. By being less stringent on the sucrose content, many more candidates can become exploitable without loss in total sugar. M 1334/84 is a typical example where, by relaxing the stringency on sucrose level, the total biomass and sugar yields exceed those of existing commercial varieties in the dry zone. The fibre-model *Type 3* (low sucrose high fibre) and *Type 4* (pure fibre) energy canes can be cultivated in the marginal environments for the generation of biomass year-round. Successful exploitation of high fibre varieties requires further investigations on the economic aspects of cane biomass payment to growers, the best alternative for mechanized harvest, bulk density improvement for transport and processing efficiency of the harder canes at the mill.

Keywords: energy canes, bioenergy, marginal lands, adaptation, year-round harvest

I certify to the best of my knowledge (1) the statement herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to MRC is a criminal offense.

Principal Investigator Signature:	Date:

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This project falls under the Mauritius Sugarcane Industry Research Institute (MSIRI) main Research Focus Area in breeding and selection of high biomass varieties to sustain the local sugarcane industry and the national energy strategy. We are most grateful to the Mauritius Cane Industry Board and the Research and Development Committee for approving the research project. We thank the Mauritius Research Council and the MSIRI for jointly funding the evaluations of biomass varieties in marginal areas.

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List of acronyms

1G	First generation
1R	First ratoon
2G	Second generation
2R	Second ratoon
ACP	African-Caribbean-Pacific (sugar producing countries)
AMMI	Additive Main effect and Multiplicative Interaction
ANOVA	Analysis of Variance
BC1	First backcross between F1 and noble or commercial hybrids
BC2	Second backcross between BC1 and noble or commercial hybrids
BC3	Third backcross between BC2 and noble or commercial hybrids
BIG-CC	Bagasse Integrated Gasification-Combine Cycle
BIOEN	Brazil Bioenergy Research Programme (Brazil)
BRIT	Britannia
BVUE	Belle Vue
BXY	Brix Yield
BY	Biomass Yield
CBS	Cane Breeding Station (West Indies)
CEST	Condensing Extraction Steam Turbine
CTC	Centro de Tecnología Canavieira
CTL	Cane Tops and Leaves
CV	Coefficient of Variance
CY	Cane Yield
DMY	Dry Matter Yield
DW	Dry Weight
EJ	Exajoule
ESI	Economic Selection Index
EU	European Union
EW	Economic Weight
F1	Crosses involving noble or commercial hybrids x wild relatives
FORIP	Field Operations, Regrouping and Irrigation Project
FUEL	Flacq Union of Estates Ltd.
FW	Fresh Weight
FY	Fibre Yield
GCV	Genetic Coefficient of Variance or Gross Calorific Value
GEI	Genotype by Environment Interaction
GGE	Genotype main effects and Genotype by Environment effects
GHG	Green House Gas
GJ	Gigajoule
H	Heritability (broad sense)
IAC	Instituto Agronómico de Campiñas
IEA	International Energy Agency
IMY	Impurity Yield
IPCA	Interaction Principal Component Analysis
IRSC	Industrial Recoverable Sucrose Content
LMC	Landell Mills Consultancy
LMM	Linear Mixed Model

LSD	Least Significant Difference
LSU	Louisiana State University
LTES	Long Term Energy Strategy
MAAS	Multi-Annual Adaptation Strategy
MAIF	Ministry of Agro-Industry and Fisheries (Road Map for the Mauritian Sugarcane Industry
MCIA	Mauritius Cane Industry Authority
MDA	Mon Desert Alma
MJ	Mega Joules
MLOI	Mon Loisir
MSIRI	Mauritius Sugarcane Industry Research Institute
MY	Molasses Yield
NBB	Net Biomass Balance
NBR	Net Biomass Ratio
NEB	Net Energy Balance
NER	Net Energy Ratio
PC	Principal Component or Plant Cane
PCA	Principal Component Analysis
PF index	Pol to Fibre Index
REML	Residual Maximum Likelihood
RIDESA	Brazilian Interuniversity network for the Development of the Sugar/Energy Sector
RIGES	Renewable Intensive Global Energy Scenario
SCAR	Sugarcane Agricultural Residues
SD	Standard Deviation
SE	Standard Error
SED	Standard Error of Difference
SIFB	Sugar Industry Fund Board
SNO	Stalk Number
SY	Sugar Yield
TCH	Tonne Cane per Hectare
TY	Trash Yield
USDA -ARS	United States Department of Agriculture – Agricultural Research Service
WICSCBS	West Indies Central Sugar Cane Breeding Station

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Chapter 1

Introduction

1 Introduction

Energy security is of paramount importance in the overall socio-economic development in a global context. The fluctuating prices of petroleum, its dwindling worldwide stocks and the adverse environmental effects of fossil fuel usage have collectively renewed interest in alternative sources of energy. There has been a global research surge in recent years aimed at developing alternative sources of energy that can decrease or replace the use of fossil fuel (Waclawovsky *et al.*, 2010). Plant biomass provides a viable alternative to fossil fuels in view of their renewable nature and long term sustainability. Several crops are being evaluated for their bioenergy potential. At present, the crop that has most successfully met the energy crop attributes is sugarcane (Matsuoka *et al.*, 2014). However, the long term focus of breeders has been to improve for sugar yield and current varieties have not been optimized to achieve the required high biomass yield under a range of environments that will be necessary for an extensive production of biofuels. Therefore, the genetic improvement of the crop is essential and the sugar industry worldwide is at a crossroad as the traditional approach of sugar production is being reshaped by the biomass potential of the crop. Various sugarcane producing countries are investing in the creation of sugarcane varieties for multipurpose use in anticipation of upcoming technologies that may allow for efficient energy production from cellulosic residues (Tew and Cobill, 2008; Rao and Weerathaworn, 2009; Govindaraj and Nair, 2014; Rao *et al.*, 2007; Ramdoyal and Badaloo, 2007; Goldemberg, 2008). To many breeders, biomass breeding closely parallels increasing fibre content in the cane stem. Significant genetic diversity for sucrose and fibre percentages exists in the sugarcane wild relatives that served as the foundation of present day sugarcane cultivars. The presence of genetic variation for biomass related variables in the sugarcane germplasm collections suggests that if these parameters become breeding objectives, then significant progress can be made in achieving net gains in gigajoules per hectare per year (Botha and Moore, 2014).

Sugarcane was introduced in Mauritius in 1639 and was identified as the only major crop to resist the cyclonic conditions prevailing in the region. In spite of various attempts to diversify the agricultural sector, the crop stood the test of time and became the sole major cash crop and the backbone of the Mauritian economy for decades. Throughout its long life, the sugar industry has shaped the history and culture of the island. Since the mid-1970s, in order to diversify its national economic base, Mauritius embarked on vigorous development programmes that have seen manufacturing, tourism, Information and Communication Technologies and service sectors become major foreign exchange earners. The country today has successfully changed from a mono-culture economy to that of an industrialized one. Nevertheless, sugarcane crop is still cultivated over 85% of agricultural land and sugar represents 14% of the value of total domestic exports (Statistics-Mauritius, 2015). The sugar industry, thus, remains one of the pillars of the Mauritian economy.

Mauritius also forms part of the ACP (African-Caribbean-Pacific) developing countries that have benefited from a preferential and guaranteed access to high prices of sugar in the European Union (EU) market under an agreed "Sugar Protocol". The success of the sugar industry in these countries has contributed greatly to economic progress and the welfare of the nations in generating funds for investment in other economic activities. Mauritius has benefited about 38% (the largest share) of the sugar export quotas that, to a large extent, has served to provide resources for diversification of the Mauritian economy, given its direct contribution to economic growth, rural stability, increased social welfare provision and the protection of the environment (MAIF, 2005). However, the Mauritian sugar industry and other ACP countries are now faced with unprecedented challenges which arise as a result of trade liberalization world-wide, the EU sugar reform and the opening of the EU market to other non-ACP economies. The implementation of the new EU regime is having a far-reaching impact on ACP suppliers, with the risk of closure, due to the significant fall in revenue resulting from the drastic sugar price cut, cumulating to 36% over a period of four years (2006-2009). The price fall will further be compounded following the EU's decision to abolish production quotas by end September 2017 (Gajadhur, 2015).

In view of the numerous challenges ahead, coherent and well-focused diversification approaches are imperative to ensure the long-term sustainability of the local sugarcane industry by reducing cost of production, increasing yield per unit area and time, and maximizing the use of the crop biomass for the production of renewable bioenergy and other high value products. For decades, the collaboration between the Mauritian Government and the private sector has been instrumental, particularly in the development of the bagasse (fibrous by-product left after juice extraction at the mill) cogeneration programme. Within the ACP group, the Mauritian sugarcane industry is considered to be extremely successful in the generation of electricity from sugarcane residues and is believed to be one of the most efficient at the world level (Wilson, 2006). Surplus electricity export to the national grid, using bagasse as fuel, reached its peak in 2008 with about 16.0% (366.4 GWh) of the total electricity produced. The quantum has gone down to 12.7% (334.5 GWh) in 2014, which is largely due to a decline in the production of bagasse (Statistics-Mauritius, 2015).

The achievements attained so far are still insufficient to sustain the sugar industry in the ever-changing market environment. Various recent government-funded reports and blue-prints (MAAS, 2006; LTES, 2009; LMC International Ltd., 2015) put emphasis on increased diversification through the use of new varieties with higher fibre and total biomass, commonly termed as "high biomass canes". All those reports expect great promises from the novel type of varieties and are quoted as an important lifeline of the Mauritian sugarcane industry and as an internal source of renewable energy. However, those high biomass canes are yet to be identified and the quantum gains in terms of fibre and total dry matter yields in contrast to existing commercial varieties in different agro-climatic conditions still need to be established.

Studies on energy canes at the Mauritius Sugarcane Industry Research Institute (MSIRI) started in the mid-1980s with the assessment of basic species and early generation interspecific crosses with wild canes. In the last decade, a hundred of locally bred and imported genotypes were evaluated at an intermediate selection stage in one environment. Few elite clones were retained for further evaluations in several contrasting environments and years during the period 2009-2014. The focus of this study is on the screening of the novel types of high biomass sugarcane varieties that will be exploitable in sub-optimal environments year-round to contribute to the sustainability of the Mauritian sugarcane industry and boost the energy security in the overall socio-economic development of the island. The objectives of this project are to:

a) Assess the performance of selected high biomass varieties in marginal areas,
b) Evaluate the stability of high fibre clones across environments and successive harvests,
c) Assess the physiological aspects of above-ground biomass accumulation,
d) Determine the possibilities of harvesting year-round fast growing high biomass clones
e) Determine the most appropriate harvesting method, and
f) Create an economic selection index for rapid screening of high biomass canes from MSIRI sugarcane breeding programme.

In order to attain the set targets, we focused on in-depth analysis of the five trials evaluated between 2009 and 2014 and on new trials established in 2014 in marginal environments to determine the magnitudes of the genetic gains with the selected high biomass varieties. The different objectives are elaborated in the following order:

- Literature review,
- Marginal environments and seasonal effects on yield, quality and morphological traits of high biomass sugarcane genotypes,
- Genotype x environment interaction, adaptability and stability of biomass sugarcane varieties in Mauritius,
- Physiological studies on biomass accumulation in different types of sugarcane varieties,
- Sugarcane yield estimation at different crop age in marginal environments for the generation of biomass year-round,
- Further investigations on selected high biomass varieties
    - Energy equivalence,
    - Economic selection index,
    - Best harvesting method
- General discussion, and
- General conclusion.

Chapter 2

Literature review

2 Literature review

2.1 Plant biomass – a source of renewable energy

Plant biomass, also known as lignocellulosic biomass, can be defined as all organic material derived from living or recently living plants (including algae), that represent a potential source of bioenergy. Mankind has been burning plant biomass since prehistoric times to produce heat. Discoveries about the conversion of heat into other forms of energy led to the development of machineries that became the basis of the industrial revolution. The innovations created such a massive demand on energy that mankind switched from burning renewable energy to burning fossil fuels (coal, gas and petroleum). These fuels are, however, finite and energy consumption worldwide has increased 13 fold in the twentieth century and has tripled since 1960 (Hein, 2005). Hodgson (2008) stipulated that the world energy use is doubling every 14 years and the need is increasing faster still and that the world oil production, currently accounting for 80% of total world energy supply, is expected to peak by 2018 and thereafter fall. At this rate, oil reserves are projected to last for about five more decades and coal for around 150 years (British-Petroleum, 2012). Furthermore, burning fossil fuels that were buried for millions of years generates noxious greenhouse gases (GHGs). Those gases (CO_2 being the most important) cause climate change and global warming, the dangers of which have been recognized for many years. The search for alternative, renewable and environment-friendly energy sources is imperative.

In 1992 at the Rio United Nations Conference on environment and development, the renewable intensive global energy scenario (RIGES) suggested that, by 2050, approximately half of the world’s current primary consumption of about 400 exajoules per year (EJ yr^{-1}), could be met by biomass and that 60% of the world’s electricity market could be supplied by renewables, of which biomass is a significant component (Price, 1998). More recently, Bauen *et al.* (2009) from the International Energy Agency (IEA) estimated bioenergy to sustainably contribute between a quarter and a third of global primary energy supply in 2050. It is the only renewable source that can replace fossil fuels in all energy markets – in the production of heat, electricity, and fuels for transport. Ming *et al.* (2006) summarised the important realities that contribute to the endeavour for biomass use:

- First, there is the growing desire on the part of most nations to have a dependable, renewable energy source of internal origin.
- Second, technological developments such as lignocellulose conversion promise the application of biomass at lower cost and with higher conversion efficiency than was previously possible. These technologies are in the scale-up phase and in the next few years will become commercial realities, changing the fate of cellulosic residues.
- Third, the potential threat posed by climate change, due to high emissions of greenhouse gases, has become a major stimulus for renewable energy sources, in general. The adoption of the Kyoto Protocol of the United Nations Framework Convention on Climate

Change is an important step to further stimulate the search for methods of reducing net CO_2 emissions to the atmosphere.

- Fourth, with reorientation of breeding objectives towards the generation of high biomass varieties and advances in biotechnology, there is the growing recognition that highly energy-efficient plants can be developed to provide a platform for the production of a vast array of high-value products, over and above the production of energy, *per se*.

Several crops have been targeted as biofuel crops, such as corn (*Zea mays*), sugarcane (*Saccharum officinarum*), sugar beet (*Beta vulgaris*), switchgrass (*Panicum virgatum*), sweet sorghum (*Sorghum bicolor*), Brachipodium (*Brachypodium distachyon*), Miscanthus (*Miscanthus giganteus*) and Giant reed (*Arundo donax*) (Goldemberg, 2008; Vega-Sanchez and Ronald, 2010; Christou, 2013). A major bottleneck with the next generation of biofuels currently is related to the gain in terms of net energy output to input ratio (NER- net energy input divided by net energy output). Matsuoka *et al.* (2014) described the general requirements energy crops should fulfil to be thoroughly and promptly adopted. These are:

- having feedstock that must be easily and reliably transformed in useful forms of energy;
- high density of energy;
- high spatial density;
- year round availability;
- well-developed agronomic practices;
- favourable cost of production and delivery;
- perennial plant (renewable);
- being amenable to be produced under stress conditions and so not to compete with land used for food production;
- high favourable life cycle balance both of energy and GHG emissions.

In an ideal situation, if the goal is to produce energy from plant lignocellulose breakdown, the crop should be a high yielding, fast growing, with a cell wall that is easy to break down and requiring relatively small energy inputs for its growth and harvest. The biomass also should have high energy density as this impacts several other factors, the lowest final cost of a unit of energy being the target; thus high productivity of dry matter per area is required. High spatial density implies the availability of land within a short radius from the processing or consuming facility. To be an economic alternative energy source in the long run, the feedstock must be available all year-round. One of the weak points of annual crops is the seasonality and consequently short lived availability. A favourable cost of production and delivery is obviously a factor for any feedstock, which is influenced by a well-established agronomic production system, from planting to harvesting and delivery. To achieve sustainability, energy crops should not require extensive use of prime agricultural lands, and they should have low cost of energy production from biomass. Basically, the crop energy output must be more than the fossil fuel energy equivalent used for its production (Matsuoka *et al.*, 2014).

At present, the crop that has most successfully met the biofuel crop attributes is sugarcane (Waclawovsky *et al.*, 2010). Heaton *et al.* (2008) found that sugarcane annual production per hectare compares favourably to other high-yield bioenergy crops such as Miscanthus, switchgrass and corn (total grain plus stover). Other authors (Renouf *et al.*, 2008; Goldemberg *et al.*, 2008; Reijnders, 2009) similarly reported that existing sugarcane varieties as such offer more potential of high biomass for renewable energy than the other crops and there are very few agronomic crops that rival sugarcane in energy conversion efficiency. Furthermore, sugarcane has a significant advantage over most other potential biomass crops because of its long history of industry research and development and the existing agronomic and processing infrastructures that is currently used for traditional sugar production (Botha and Moore, 2014). The authors further stated that "*energy canes"* require approximately twofold less land for the same final dry mass yield. The concept of energy cane, which mainly refers to sugarcane varieties with high fibre and total biomass, is described in section 2.4.

2.2 Sugarcane biomass and energy potential

2.2.1 Sugarcane production statistics

In 2013, sugarcane crop occupied 2% of agricultural area (26.5 million hectares) of the world (FAOSTAT, 2014). The land area devoted to sugarcane is small compared to those of the three major cereal crops (wheat: 18%, maize: 16% and rice: 14%), which collectively occupy 48% of the world's cropland (Table 2-1).

Table 2-1: Major crops grown globally and their productivity per hectare in 2013; in brackets: percentage to world's total

Crops	**Area harvested (x 10^6 ha)**	**Quantity (x 10^6 tonnes)**	**Yield (t ha^{-1})**
Wheat	218.5 (18%)	713.2 (11%)	3.3
Corn	184.2 (16%)	1016.7 (15%)	5.5
Rice, paddy	164.7 (14%)	745.7 (11%)	4.5
Soybeans	111.3 (9%)	276.4 (4%)	2.5
Barley	49.8 (4%)	144.8 (2%)	2.9
Sorghum	42.1 (4%)	61.4 (1%)	1.5
Sugarcane	26.5 (2%)	1877.1 (28%)	70.8
Cassava	20.7 (2%)	276.7 (4%)	13.3
Potatoes	19.5 (2%)	368.1 (5%)	18.9

Source: FAOSTAT (2014)

The area under sugarcane cultivation is witnessing a dramatic rise worldwide, representing a 34% increase between 2005 and 2013 (Figure 2-1). Major increases have occurred in Brazil, India, China (mainland) and Thailand. Brazil has created the highest impact by doubling its acreage harvested since year 2000 (year 2000: 4.845 x 10^6 ha; year 2013: 9.835 x 10^6 ha). Sugarcane can be considered a speciality crop because, of all food crops, sugarcane has the highest level of production worldwide (1877 mega tonnes), followed by the cereals, maize (1017 mega tonnes), rice (746 mega tonnes) and wheat (713 mega tonnes). This high level of production recorded for sugarcane is related to its productivity per unit area with the global average being at 70.8 t ha^{-1}. Apart from sugar, the crop produces a high proportion of bagasse and field residues that represent valuable low-cost feedstock for bioenergy production.

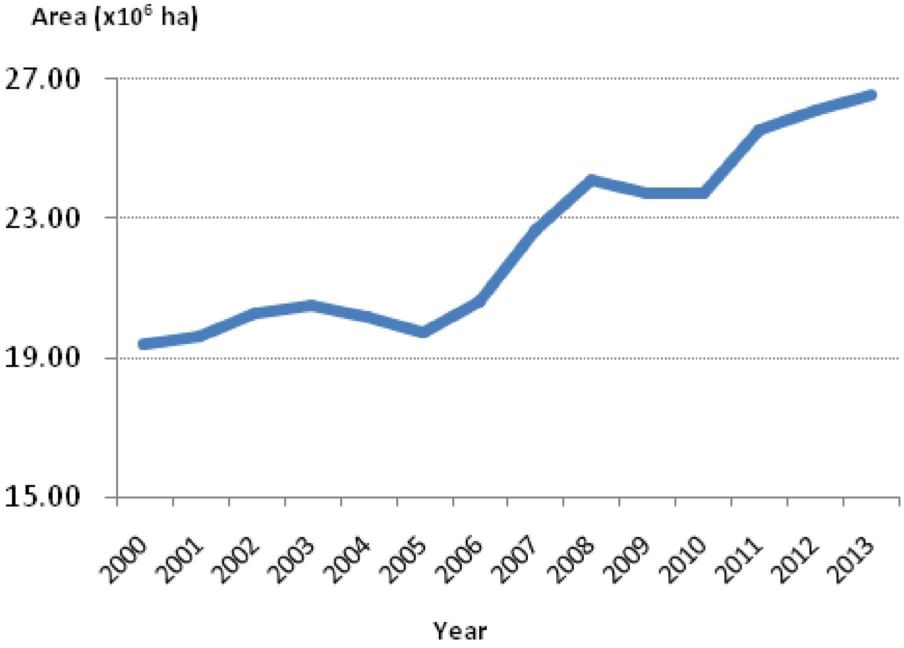
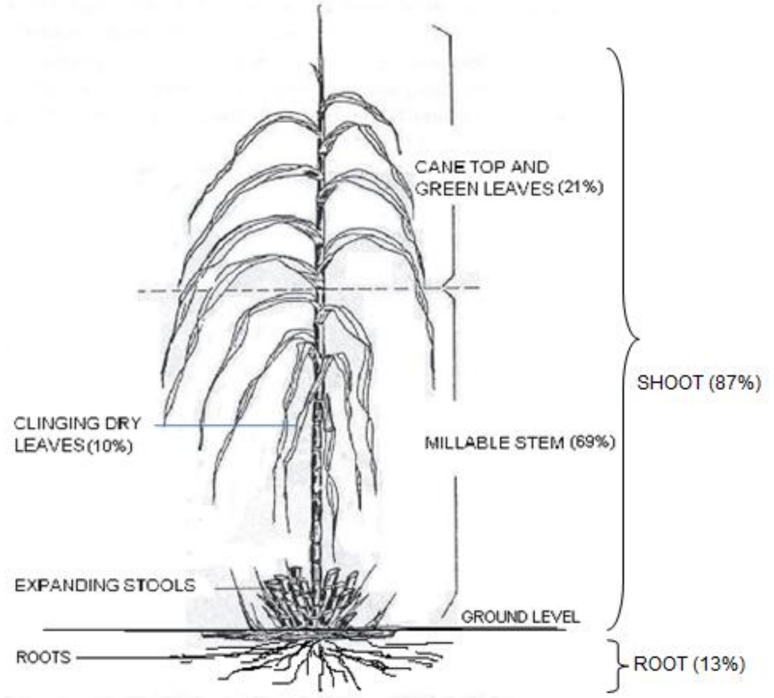


Figure 2-1: Sugarcane area harvested since year 2000 (FAO, 2014)

2.2.2 Sugarcane biomass components

Sugarcane biomass can be divided into four fractions (Figure 2-2), namely (a) the stubble and underground roots, (b) the cane stalk free of tops and leaves, i.e. millable cane, (c) green immature cane tops and leaves (CTL) removed from the cane during harvest, and (d) dead and dry leaves, known as trash. CTL and trash left in the field after harvest are collectively referred to as sugarcane agricultural residues (SCAR).

Under the local context, Beeharry (1996) reported that the millable canes of commercial varieties accounted for around 69% of aboveground biomass on a fresh weight basis, the CTL 21% and the trash for around 10% of the total aboveground biomass. The vegetative composition of cane plant is not uniform, but varies according to age, fertilization, variety and other factors. The effect of age was found to be dominant (Van Dillewijn, 1952).



Source: Adapted from Van Dillewijn (1952)

Figure 2-2: Schematic illustration of a sugarcane crop

Mature trash-free cane stalks are generally composed of approximately 73-76% water (Table 2-2) and the remainder is divided between fibre and soluble solids. Commercial varieties in Mauritius have been found to be composed of about 13.0% sucrose and 12.0% fibre in the cane stem (Paturau, 1989). The amount of each of these three components (water, fibre and soluble solids) is genetically determined and varietal differences are well known (Irvine, 1977).

Over the last two decades, two by-products have gained sizeable importance: *Bagasse* as a source of environment-friendly cane residue for the generation of electricity and *Molasses* for the production of ethanol as a gasoline mix in the transport sector. *Bagasse,* also termed as ‘bagasse proper’, is the fibrous material left after juice extraction from milled cane stalks. It is composed of moisture (46-52%), fibre (43-52%) and soluble solids (mostly sugar) (2-6%). The composition, however, varies according to the variety of cane, its maturity, the method of harvesting and finally the efficiency of the milling plants (Paturau, 1989). Bagasse represents about 21% of aboveground biomass. *Molasses* is the viscous residue (slurry) left after sugar crystals are centrifuged out. It represents around 2% of aboveground sugarcane biomass and can be relatively easily fermented into ethanol and other high-value products. It is also used for animal feed and the production of potable alcohol.

Table 2-2: Composition of sugarcane and juice solids

Millable cane	**Cane (%)**
Water	73-76
Solids	24-27
Soluble solids (Brix)	10-16
Fibre (dry)	11-16
Juice constituents	Soluble solids (%)
Sugars	75-92
Sucrose	70-88
Glucose	2-4
Fructose	2-4
Salts	3-4.5
Organic acids	1.5-5.5
Other organic non-sugars	
Protein	0.5-0.6
Starch	0.001-0.050
Gums	0.30-0.60
Waxes, fats, phosphatides	0.05-0.15
Other	3.0 – 5.0

Source: Meade et al. (1977)

2.2.3 Energy potential of sugarcane aboveground biomass

Sugarcane has long been recognized as one of the world’s most efficient crops in converting solar energy into chemical energy (Table 2-3) and together with certain of its tropical grass relatives, it is the most efficient crop in terms of biomass production (Klass, 2004; Brumbley *et al.*, 2007).

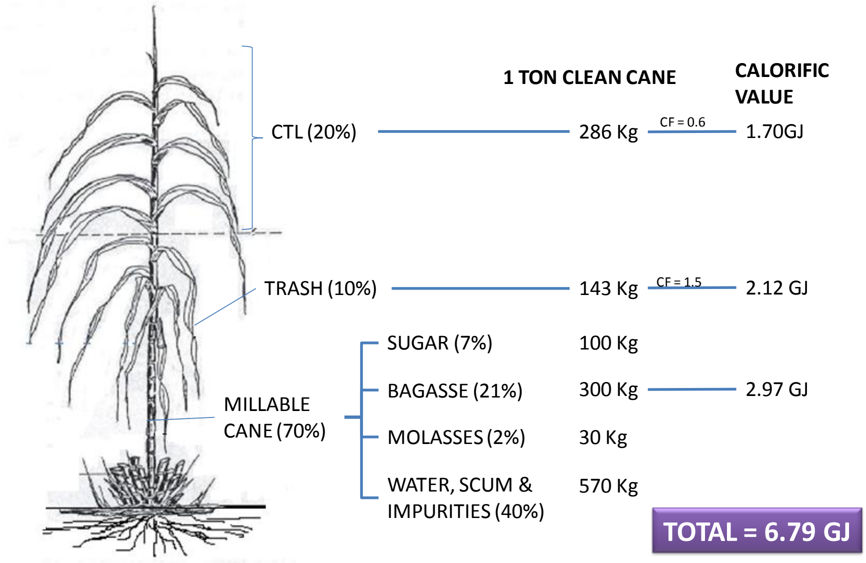
Table 2-3: Examples of estimated solar energy capture efficiency

Crop	**Location**	**Conversion efficiency %**
Switchgrass	Texas	0.22 – 0.56
Maize	Minnesota	0.79
Rice	New South Wales	1.04
Napier grass	Puerto Rico	2.78
Tropical forest	West Indies	1.55
Sugar cane	**Hawaii; Java**	**2.24 and 2.59**
Temperate grassland	New Zealand	1.02
Willow and Hybrid poplar	Minnesota	0.30 - 0.41

Source: Klass (2004)

The energy derived from sugarcane aboveground biomass entails an integrated use of bagasse, CTL, and trash. The energy potential of the three components has been described in Mauritius by Deepchand (1984), Beharry (1996), Seebaluck *et al.* (2008) and others. Assuming roughly a ratio of 70:20:10 for cane stalk:CTL:trash, then, for every 1000 kg of cane sent to the factory, 286 kg of CTL (with 70% moisture), 143 kg of trash (with 25% moisture) and 300 kg of bagasse proper (50% moisture) are obtainable for energy production (Figure 2-3).

Bagasse containing 50% moisture has a gross calorific value of 9.7-9.9 MJ kg^{-1} (Beeharry, 1996; Deepchand, 2000; Lau Ah Wing, 2008). A tonne of bagasse (on a 50% mill-wet basis) is equal to 0.17 tonnes (1.6 barrels) of fuel oil and 0.26 tonnes of coal (Statistics-Mauritius, 2015). Beeharry (1996) worked out the correction factors for CTL and trash as well as the total energy potential of sugarcane (Figure 2-3). In general, for every tonne of clean cane sent to the mill, a total of 696 kg of bagasse equivalent (at 50% moisture), corresponding to 6.79 Gigajoules (GJ) of electricity, are potentially available. Sugar manufacture requires a certain amount of bagasse for raising steam needed to provide motive power for cane crushing as well as for juice heating. Beeharry (1996) concluded that almost 565 kg of bagasse equivalent per tonne of millable cane could be made available for exportable electricity production. The extreme case where 100% of the fibrous material (all bagasse, CTL and trash produced by the plant) is utilized has the potential of producing up to 678 kW h t^{-1} of millable cane, assuming the best technology is adopted at the mill.



CF: Correction factor for CTL and trash to bagasse equivalence with 50% moisture content

Source: Adapted from Beeharry (1996)

Figure 2-3: Estimated yields of biomass components and energy obtainable for every tonne of clean cane sent to the mill

On a dry matter basis, bagasse, CTL, and trash have approximately similar gross calorific values of around 17 MJ kg^{-1} (Beeharry, 1996). Alonso-Pippo *et al.* (2009) stated that total sugarcane energy content on dry basis, excluding ash (around 2%–3% of weight), can be divided in three main parts: juice, bagasse and field residues and that the total energy for current commercial varieties was around 6625 MJ $tonne^{-1}$ of clean cane received from milling station (Table 2-4).

Table 2-4: Sugarcane energy content (average figures for currently commercial sugarcane varieties)

	1 tonne of sugarcane[a]	
Sugarcane parts (dry basis)	Mass (kg)	Energy (MJ)
Juice (sucrose + molasses + others)	142	2257
Fibre residues (bagasse)	140	2184
Sugarcane agriculture residues (SCAR)	140	2184
Total	**422**	**6625**

[a]: Sugarcane (clean) as received from milling station.

Source: Alonso-Pippo et al. (2009)

While bagasse is readily available at the mill for immediate use, CTL and trash (SCAR) involve additional efforts of baling in the field, transport and shredding before exploitation. Studies are currently being carried out in Mauritius and other countries on the efficient use of SCAR as an alternative source of bioenergy. However, maintenance of straw in the field brings clear benefits to the sugarcane production, such as protection against soil erosion, reduction in variation of soil temperature by protection from direct radiation, increasing the biological activity through the recycling of residues and addition of organic matter, better water infiltration; greater availability of water due to reduced evapotranspiration and better control of weeds. Some negative effects have also been associated with the maintenance of large amounts of trash over the soil such as the reduction of ratoon sprouting, increased risk of fire, greater incidence of sugarcane pest and disease, and difficulties in the mechanized cultivation (Franco *et al.*, 2013). Partial removal of the SCAR, up to 50%, is the focus of contemporary studies.

Seebaluck and Seeruttun (2009) reported that by increasing fibre by 1% in the cane stem, 13.34 kWh of surplus electricity can be generated for every tonne of cane sent to the mill. Using four million tonnes cane stalks as baseline, representing roughly the current cane tonnage produced in Mauritius, and increasing the fibre content by 1%, then 53.36 GWh (3% of national electricity demand) could become exportable, without any substantial cost incurred and assuming that the extra bagasse so generated were all used for co-generation. Hypothetically, *energy canes* with 25% fibre (compared to existing varieties with 12-13% fibre), then, could satisfy 33% additional electricity requirement of the island with all other factors kept constant. This simplistic linear extrapolation, however, is only indicative and does not account for various factors involved in energy cane management, harvest, transport, milling and processing. Also, fibres over 17% have a serious implication for the set up and rate of grinding of most existing sugar mills (Pers. Com. Kennedy, 2016). The rate of throughput is seriously slowed and this has repercussions throughout the whole of the processing complex of sugar production. Globally, energy output: input analyses with high biomass energy canes are lacking and, hence, one should be very cautious in using the figures as such.

2.2.4 Energy recovery from sugarcane by-products at the mill

Existing sugar industry evolved for maximizing the production of sugar and obtaining economic benefits from the by-products molasses and bagasse. Sugarcane mills employ some form of already profitable direct first generation (1G) technologies for utilizing crop biomass fibre. The current state-of-the-art system for bagasse cogeneration is the condensing extraction steam turbine (CEST), which can produce much more surplus electricity than the back pressure turbines commonly used at many existing factories (Table 2-5). CEST systems are used extensively in India, Mauritius and Réunion and to some extent in Brazil, where they allow export of surplus electricity to the grid during the harvest season (Johnson and Batidzirai, 2012; Seebaluck and Sobhanbanu, 2012). The surplus electricity obtainable is in some cases ten times what might be available from existing factory configurations that use back pressure turbines (Seebaluck *et al.*, 2008).

Table 2-5: Best practice electricity production surplus using bagasse with different systems

Country	**Power mode**	**Pressure**	**Temperature**	**Surplus exportable electricity**
Mauritius	Continuous	45 bars	475 ^{0}C	53 kWh t^{-1} cane
	CEST	82 bars	525 ^{0}C	130-140 kWh t^{-1} cane
India	CEST	67 bars	495 ^{0}C	90-120 kWh t^{-1} cane
	CEST	87 bars	515 ^{0}C	130-140 kWh t^{-1} cane
Brazil	Continuous	67 bars	480 ^{0}C	40-60 kWh t^{-1} cane

Source: Seebaluck et al. (2007)

There may be greater potential in 2G conversion technologies (which involve pre-treatment and fermentation of crop residues) to use sugarcane biomass for producing higher value liquid or gaseous biofuels (Botha and Moore, 2014). The state-of-the-art on sugarcane residues conversion into 2G biofuels, in general, is well-known. It has been intensively studied in several works, publications, and conference proceedings mainly in Brazil, USA, Columbia, and the EU (Alonso-Pippo *et al.*, 2009). The electricity generation potential of bagasse and other residues could be more than doubled by the adoption of a bagasse integrated gasification-combine cycle (BIG-CC), which is the process of converting biomass energy into an energy-rich gas (Seebaluck and Sobhanbanu, 2012). Research on bagasse gasification has been carried out on pilot scales and this technology is yet to emerge on a commercial scale.

2.3 Sugarcane breeding - a brief overview

2.3.1 Taxonomy and early breeding activities

Sugarcane (*Saccharum* spp., 2n = 100-130) belongs to the *Andropogonae* tribe, which encompasses only polyploid species, and to the subtribe *Saccharinae* (Daniels and Roach, 1987). Current commercial cultivars are highly polyploid and aneuploid, with about 120 chromosomes. Sugarcane scientists have adopted the term '*Saccharum* complex', originally coined by Mukherjee (1957), to describe a subset of genera within *Saccharinae* closely enough related to *Saccharum* to have contributed to its genetic background. Genera within the S*accharum* complex include *Erianthus, Miscanthus, Narenga, Saccharum* and *Sclerostachya (*Amalraj and Balasundaram, 2005). Six species have traditionally been included in the *Saccharum* genus by sugarcane geneticists:

- *S. officinarum* (x = 10, 2n = 80) (noble cane)
- *S. spontaneum* (x = 8, 2n = 40-128)
- *S. robustum* (x = 10, 2n = 60, 80)
- *S. edule* (2n = 60-122)
- *S. barberi* (2n = 116-120)
- *S. sinense* (2n = 81-124)

The history of sugarcane improvement in early years was mainly one of noble cane (*S. officinarum*) variety substitution, making use of naturally occurring types which gave improved yields due to better adaptation or greater resistance to diseases. The early recognition of New Guinea and the Indonesian archipelago as a major centre of diversity for *S. officinarum* made that area the target of major collection activity. Although the fertility of sugarcane had been reported in Barbados in 1858, it was not until 1888 that fertility of sugarcane and production of seedlings from true seeds were recognized. It was from inter-crossing of noble canes that early breeders sought more productive, better adaptation and disease resistant genotypes with good factory qualities (Roach and Daniels, 1987). The intra-specific crosses among nobles proved to be effective to some extent in improving sugar yield and resistance to certain diseases.

The stimulus for 'interspecific hybridization' (breeding noble canes with sugarcane wild relatives) was the serious effect of sereh disease on sugarcane crops in Java. In the early 20th century, breeders in India and Indonesia initiated programmes that utilized interspecific hybrids derived from crosses between *S. officinarum* and *S. spontaneum* (Daniels and Roach, 1987). The initial interspecific hybrids were crossed back to *S. officinarum* clones to retain sufficiently high sugar content, in a process termed as "nobilisation" (Bremer, 1961). The objective was mainly to dilute the side effects of the wild clones while trying to develop disease resistant varieties. Generally, two to three successive backcrosses (BC1, BC2 and BC3) are sufficient to attain acceptable levels of sucrose content (Figure 2-4). These hybridizations not only solved many of the disease problems but they also provided spectacular increases in yield, improved ratooning ability, and adaptability to various abiotic stresses (Roach, 1972). Today, commercial varieties, with relatively high sucrose content and thick stalk diameter, are also used instead of noble canes in many sugarcane breeding programmes.

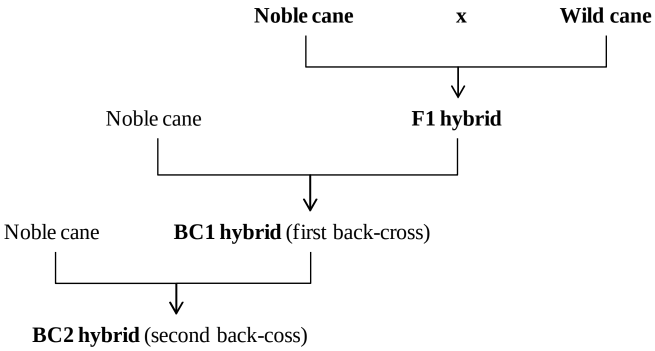


Figure 2-4: Genetic base-broadening through “nobilisation”. The noble canes include the *S. officinarum spp*. or, commercial hybrids with high sucrose content

Interspecific hybrid varieties, termed as “wonder canes” (POJ 2364, POJ 2878, Co 206, Co 213), that resulted from early breeding activities, formed the genetic foundation of modern sugarcane varieties. All present-day cultivars are genetically complex and are derived from the interbreeding of these first interspecific hybrids. Altogether, it is estimated that 19 *S. officinarum* clones (four with high frequency), a few *S. spontaneum* (two with high frequency) clones, and one *S. barberi* clone were involved in these interspecific crosses (Arceneaux, 1967).

It has also been noted worldwide that much effort in introgression breeding in recent decades has not led to commensurate commercial successes (Stalker, 1980; Berding and Roach, 1987; Wang *et al.*, 2008). The process has traditionally become a long-term and risky investment. The time and risk factors have clearly acted to reduce the level of resources devoted in most sugarcane breeding programmes to introgression breeding, regardless of general agreement among sugarcane breeders of its potential value. In spite of all the promises introgression breeding may hold, in general, it is difficult to estimate its impact or success in the last few decades as new publications are lacking on the current contribution of wild sugarcane relatives and recent attempts to increase the rate of sugarcane improvement for sugar yield by widening the genetic base have so far proved disappointing (Wang *et al.*, 2008). Nevertheless, today, a new sugarcane genotype paradigm is emerging, focusing on biomass production to enable better exploration of the crop for ethanol or energy production and further ensure sustainability of the sugarcane industry. This entails a reorientation of breeding of the sugarcane crop towards higher fibre content and yield. Populations derived from crosses between sugarcane and related wild species provide a good source of variation from which various types of canes with high biomass can be identified. Various sugarcane producing countries are showing renewed interest in introgression breeding for the generation of new varieties with higher fibre for multiple end-uses.

2.3.2 Current sugarcane breeding programmes

Current sugarcane breeding programmes mainly use advanced generation hybrids as parents with high breeding values and use of wild canes has been relegated to a side activity for genetic base broadening. Sugarcane breeding programmes typically commence by the crossing of heterozygous parents to produce true seeds. Seedlings derived are planted in nurseries and/or transplanted directly in the field for screening. Thereon the clones are propagated vegetatively through stem cuttings and evaluated over larger plots in successive selection stages, their numbers being reduced at each stage. The production and testing of new sugarcane varieties range between 8 and 20 years (Skinner *et al.*, 1987). Numerous combinations of selection rates, criteria, plot sizes and trial designs exist. As sugarcane is a perennial crop, ratooning ability needs to be tested. Typically, four to eight ratoons are grown commercially but this varies in different countries. Usually, testing for ratooning ability is done over two to three ratoons only, and the effects of ratoons and years are generally completely confounded. Figure 2-5 represents a simplified selection programme adopted in Mauritius. Following the hybridization activities (crossing), about 50 000 seedlings, each representing a potential variety, are produced annually. Selection takes place in six stages in the field. The first four stages represent the preliminary phase where genotypes are evaluated in unique locations. The best 30-40 selected candidates enter the final phase selection (variety trials 1 and 2) whereby genotypes are evaluated in several locations in larger plots and longer crop cycles. The whole selection process takes around 15 years when the best candidate is released for commercial exploitation.

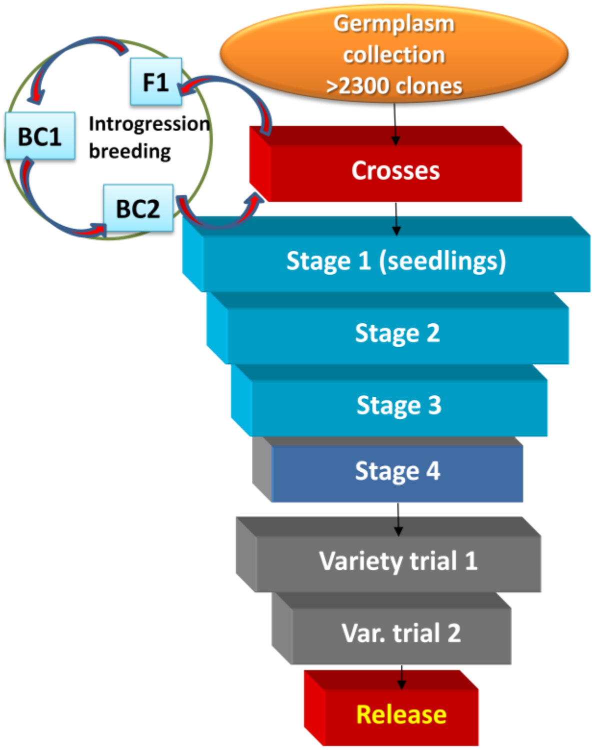


Figure 2-5: A simplified schema of the sugarcane breeding programme adopted in Mauritius

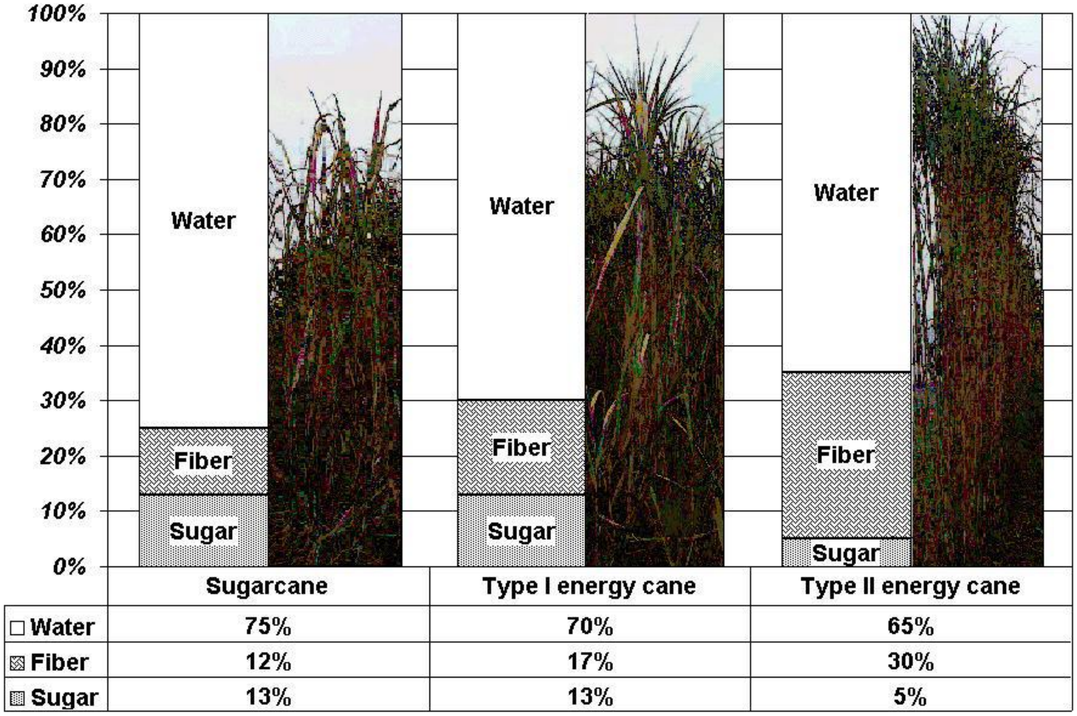
2.4 Energy cane: concept and achievements

2.4.1 Energy cane definition

The concept of energy cane was initially proposed by Alexander in 1985 to differentiate between two sugarcane management systems: one for the production of sugar and the other for the production of energy. He argued that biomass yield could be in the range of two to three fold that of current expectations if (1) biomass oriented genotypes are utilised, (2) the whole plant including tops and leaves are exploited and (3) the crop is cultivated as a growth commodity whereby total biomass yield is optimised, as opposed to maximising sucrose content and sugar yield. In the recent past, energy cane has been increasingly used to describe a number of systems that, in addition to a changed management system, could involve higher fibre and higher biomass varieties. Chong and O'Shea (2012) reported that the term generally refers to varieties containing higher fibre and lower sucrose levels than traditional sugarcane varieties. Sugarcane breeding programmes have historically focused on improving extractable sucrose yields while maintaining acceptable levels of fibre. In many cases, sucrose concentration below a level and fibre beyond a threshold were considered a liability because of added costs in harvest, transport and milling. As a result, the current commercial sugarcane varieties tend to show relatively high sucrose content and much lower fibre content than those present in wild grasses and sugarcane relatives.

In the past two decades, biomass has acquired valuable importance as a source of renewable energy and it was realized that breeding canes for fibre and not only for sugar, as Alexander (1985) had stated, could be exploited to support this growing interest. Then, the term “energy cane” was adopted as a designation for this new kind of plant. Sugarcane breeders are focusing their attention in search for candidate energy cane varieties with higher fibre from their existing germplasm collections, ongoing selection programmes and through a renewed interest in introgression breeding. To most sugarcane breeders, biomass breeding closely parallels the involvement of wild species (*S. spontaneum*, *S. robustum*) and species closely related to sugarcane (*Erianthus*, *Miscanthus*). Significant genetic diversity for sucrose and fibre percentages exists in the sugarcane wild relatives that served as the foundation of present day sugarcane cultivars (Matsuoka *et al.*, 2014). Ming *et al.* (2006) described three biomass breeding objectives involving sugarcane wild relatives: (1) maximizing soluble and insoluble solids, (2) maximizing soluble solids and (3) maximizing insoluble solids. For maximizing soluble and insoluble solids, the authors considered early generation *Saccharum* hybrids involving *S. spontaneum* as a wild relative to have the greatest potential as energy cane candidates. The second objective of maximizing soluble solids involves relaxation of the standard for the sucrose fraction (purity) so that a larger group of candidates could come under consideration. The third focus of maximizing insoluble solids encompasses a far wider range of potential candidates extending beyond the sugarcane crop and its allied genera. The authors considered genera closely related to *Saccharum*, namely *Erianthus* and *Miscanthus*, both within the *Saccharum* complex, to be of greatest interest to sugarcane breeders.

Tew and Cobill (2008) further described three different types of canes that can be achieved through sugarcane breeding (Figure 2-6): Traditional sugarcane is grown primarily for sugar. In the case of energy canes, the vegetative biomass is an important product, and this is either a by-product, in the case of the "Type I" energy canes, or the main product, in the case of the "Type II" energy canes.



	Sugarcane	Type I energy cane	Type II energy cane
□ Water	75%	70%	65%
▨ Fiber	12%	17%	30%
▨ Sugar	13%	13%	5%

Source: Tew and Cobill (2008)

Figure 2-6: Variation in use and composition among sugarcane and Type I and Type II energy canes

The differences among the cane types are in the relative composition of the cane stem, in terms of sugar, fibre and water content. Type I energy cane varieties would be selected and optimized for both sugar and fibre content so they would be processed in existing sugarcane mills. Type II energy cane would be bred, selected, and cultivated for fibre content too high to be processed in existing sugarcane mill operations. The Type II canes would be used as feedstock for electricity generation and production of cellulosic biofuels.

Based on evaluation of a population of early generation hybrids, Santchurn *et al.* (2014) defined clearly discernible four types of canes: *Type 1* to *Type 4* canes (Table 2-6). *Type 1* canes were the conventional commercial type varieties with high sucrose and low fibre in the cane stem. *Type 2* canes were those "enhanced fibre type" with high sucrose and higher fibre and were complementary to Tew and Cobill's Type I energy cane. *Type 3* canes, termed as multi-purpose type, comprised varieties with lower sucrose and higher fibre than those of the existing commercial varieties. This type of cane involves relaxation of standards for sucrose so that a larger group of candidates could come under consideration. *Type 4* canes were those pure fibre types with very high fibre and negligible to no sugar.

Table 2-6: Description of different types of cane with respect to their sucrose, fibre content and biomass yield

Sugarcane type	**Nomenclature**	**Sucrose**	**Fibre**	**Major output**
Type 1	Conventional	13 %	12 %	High sugar yield
Type 2	Enhanced fibre	13 %	>14 %	High sugar yield
Type 3	Multi-purpose	<12 %	>14 %	High dry matter yield
Type 4	Purely fibre cane	<5 %	>22%	High dry matter yield

Source: Santchurn et al. (2014)

This new categorization was supported by Matsuoka *et al.* (2014) who argued that rather than considering energy canes as two distinct types, it would be proper to treat it as a continuum with high sugar-low fibre at one extreme and high fibre-low sugar at the other one. When conventional sugarcane variety is crossed with *S. spontaneum* the progeny shows a wide range of sugar to fibre ratios (mainly *Type 3* and *Type 4* canes) which could be useful for exploitation for different end-uses and physiological studies concerning partitioning of all carbohydrates.

2.4.2 Studies on energy canes

In the 1970s, faced with socio-economic-political crisis in Puerto-Rico, sugar mills suffered severe financial difficulties that were aggravated by rapid rise of petroleum products (Alexander, 1985). Alexander, along with a group of sugarcane researchers, proposed that the crop was a producer of biomass unequalled by any other plant when managed as a growth commodity. However, much of their efforts for a decade to convince stakeholders of the potential of the crop did not succeed in affecting any change. Later, in 1990s, biomass acquired importance as a renewable source of energy and breeders realized that breeding cane for fibre and not for sugar could be exploited for this growing interest (Legendre and Burner, 1995; Mislevy *et al.*, 1995). Alexander was clearly ahead of his time, but now it is a relevant issue and it should not be overlooked anymore (Matsuoka *et al.*, 2014). The concept has now achieved global interest.

The PROALCOHOL programme of Brazil designed to meet the transportation fuel requirement of the country through ethanol substitution has amply demonstrated the success of the bioethanol-based economy. The sustained capacity to improve and diversify its production by investing in research and development is one of the most important factors underlying the success and growth of Brazil's sugar/ethanol complex. The BIOEN programme in Brazil is aiming to integrate comprehensive research on sugarcane and other plants that can be used as biofuels sources, thus assuring Brazil's position among the leaders in the area of bioenergy (Matsuoka *et al.*, 2012). The other traditional Brazilian sugarcane breeding programmes, CTC, IAC, and RIDESA, and private companies, like Vignis, are also pursuing energy cane cultivars to some extent (Matsuoka *et al.*, 2014).

In USA, Legendre and Burner (1995) found that first generation hybrids (F1) involving sugarcane wild relatives are best suited for energy cane, pointing out that backcrosses reduce biomass yield components and that the higher the number of backcrosses the higher that dilution. The joint Louisiana State University (LSU) and the Houma-USDA programme succeeded in producing some energy cane cultivars, and one, US79-1002, presented percentage of fibre as high as 28% and exceptionally high productivity: 211 t ha^{-1} against 58 t ha^{-1} for a conventional sugarcane cultivar (Giamalva *et al.*, 1985). With the persistence of the interest in biomass energy, the traditional sugarcane breeding programmes of US mainland proceeded with their energy cane breeding programmes. As a result, high biomass genotypes, namely L 79-1002, HoCP 91-552, and Ho 00-961 were released as high-fibre sugarcane cultivars.

Confronted with the EU (European Union) sugar reforms (2006-2009), ACP (African-Caribbean-Pacific) sugar industries started restructuring in an attempt to survive and prevent closure. The common theme among all the restructuring plans had been energy production. The West Indies Central Sugar Cane Breeding Station (WICSCBS) identified a few biomass varieties with high fibre from their interspecific derived germplasm collection. A few promising candidates were tested in selection stages and in semi-industrial trials (Rao and Kennedy, 2004; Kennedy, 2005; Rao *et al.*, 2007; Harm de Boer, 2008). Those clones are currently gaining popularity worldwide as dedicated energy canes with high fibre (Tew and Cobill, 2008; Chopart and Marie, 2012; Carvalho-Netto *et al.*, 2014). Since the early 1980s, the MSIRI in Mauritius has embarked on a genetic base-broadening programme that makes use of wild species to produce new parents and commercial varieties, including high fibre varieties. The genetic base-broadening programme has recently been strengthened with the introduction of new *S. spontaneum* and high fibre clones in the gene pool (MSIRI, 2008).

Other countries, like Australia, China, Hawaii, India, Japan and Taiwan, are also pursuing research on high fibre energy canes and on the efficient use of sugarcane by-products (Terajima *et al.* 2007; Wang *et al.*, 2008; Rao and Weerathaworn, 2009; Ming, 2012; Govindaraj and Nair, 2014). New candidates are being proposed for multiple end-uses, mainly sugar and bioenergy production.

Those studies clearly show the endeavour among contemporary sugarcane breeders to explore further introgression breeding towards a new crop ideotype with enhanced photosynthetic capacity, higher fibre and total aboveground biomass yield. High fibre, vigour and biomass are known major components of hybrids having *S. spontaneum* as genitor, thereby validating the interest among breeders in exploiting those wild species. Unlocking the barriers with latest and molecular techniques for successful hybridization with related genera, mainly *Erianthus* and *Miscanthus spp.*, is also a major research thrust among sugarcane scientists. Although various breeding stations claim to have produced viable seedlings involving *Erianthus arundinaceous* clones as parents (Govindaraj and Nair, 2014; Shen *et al.*, 2014; Gao *et al.*, 2015; Huang *et al.*, 2015; Piperidis *et al.*, 2015; Rajeshwari *et al.*, 2015), Kennedy argued that very few progenies were true hybrids (personal communication, 2015). Other studies in more temperate countries involve hybrids, termed as “miscanes”, between sugarcane and *Miscanthus* species, mainly *Miscanthus x giganteus* (Jakob *et al.*, 2009; Jessup, 2009; Głowacka *et al.*, 2016). These wild relatives are expected to covey resistance to frost in order to allow cultivation of energy canes in more temperate regions.

2.5 Prospects of high biomass canes in Mauritius

The risks of confining to a mono-product, raw sugar, were known for long. In his monograph, Paturau (1989) identified about 38 end-products which he considered as potentially important or of economic interest. The short and long term diversification scenarios within the sugarcane industry were known but ‘*timing and pricing’* were not. Well before the threat of the EU sugar reform, the island’s sugar industry had already intensified its effort in research and utilization of cane biomass for the generation of electricity and its export to the national grid (Baguant, 1984; Beeharry, 1996; Deepchand, 2000; Kong Win Chang *et al.*, 2001; Lau Ah Wing, 2008). Efforts were also made towards the production of ethanol from cane sugar as a source of bio-fuel primarily for the export market. This area still remains to be judiciously exploited.

Traditionally bagasse was burned in specially designed furnaces for raising process steam and for producing motive power for the manufacture of raw sugar. This activity was viewed as a way of disposing of the bagasse to avoid additional handling cost rather than as a fuel-saving alternative. One sugar factory, namely St. Antoine sugar estate, first exported electricity to the national grid in 1957 using surplus bagasse as fuel. It was a modest 280 MWh/year, believed to be the world’s first commercial, electrical export to the grid from the sugarcane industry. In the 1980s, besides sugar production, energy generation from bagasse complemented by coal became a major activity of the sugar industry during the harvest season. Over the last two decades, the high degree of volatility of oil markets has increased the awareness amongst policy makers of the need to decrease dependence on fossil fuels by increasing use of sustainable energies.

Since mid 1980s, both government and the privately owned sugar industry agreed that to sustain the viability of the sugar industry, value added from within the sector had to be generated from enhanced use of sugar by-products. Various policy initiatives and fiscal measures (Table 2.8) that followed to this end are considered a success story in Mauritius and in the African continent (Autrey, 2004; Deenapanray, 2009; Deepchand, 2005; Kong Win Chang *et al.*, 2001). Most recently, in 2015, the price of bagasse was raised from MUR 125 to MUR 1225 per tonne sugar for planters producing up to 60 tonnes of sugar. Still, the impacts of the new challenges facing the local sugar industry are far-reaching and various recent government-funded reports and blue-prints (MAAS, 2006; LTES, 2009; LMC International Ltd., 2015) put emphasis, among various other measures, on increased diversification through the use of new varieties with higher fibre and total biomass, commonly termed as "high biomass canes".

Table 2.8: Landmark on bagasse energy enhancement and other by-products

Year	Landmarks, policy initiatives and fiscal measures	Emphasis
1985	Sugar Sector Action Plan	Bagasse energy policy evoked
1988	Sugar Industry Efficiency Act	Fiscal incentives
1991	Bagasse energy development Programme	Renewable energy policy
1997	Blue Print for Centralization of milling activities	Investment in bagasse energy and ethanol production
2001	Sugar Sector Strategic Plan	Optimize use of sugarcane resources. Investments in co-generation units
2006	Multi-Annual Adaptation Strategy	Co-generation annexed to each plant (4 clusters)
2010	Mauritius Cane Industry Authority (MCIA)	Valorization of cane parts and increased profitability of planters through rationalization of expenses of sugarcane service providing organizations
2015	LMC International report	Increased diversification through the use of high biomass cane varieties
2015	High Level Implementation Committee of LMC report	Fiscal incentives (Increased price of bagasse from MUR 125.00 to MUR 1225.00 for every tonne of sugar and creation of Sugarcane Sustainability Fund

A prerequisite to the sustained renewable long-term energy strategy is the generation of a critical quantity of biomass for cogeneration. Mauritius is a small island where prospects of increasing the land area under sugarcane are non-existent. Figure 2-7 depicts the evolution of sugarcane crop harvested over the last seven decades. Following a sharp rise in the 1950s, at the expense of natural tropical forests, sugarcane cultivation reached its peak (around 87 000 ha) in the 1960s. As from early 1980s, there has been a progressive reduction in the area devoted to the crop. This decline has been alarmingly sharp in the last decade. By year 2016, about 21 290 ha of sugarcane lands, representing 28% of the area cultivated in year 2000 (SIFB, 2000-2016), have been either used for urbanization, or to strengthen other sectors of the island's economy, or simply abandoned.

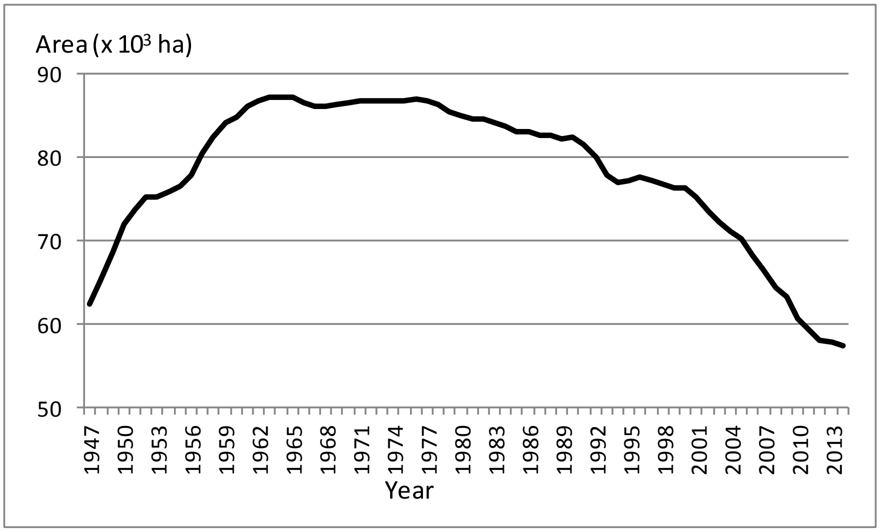
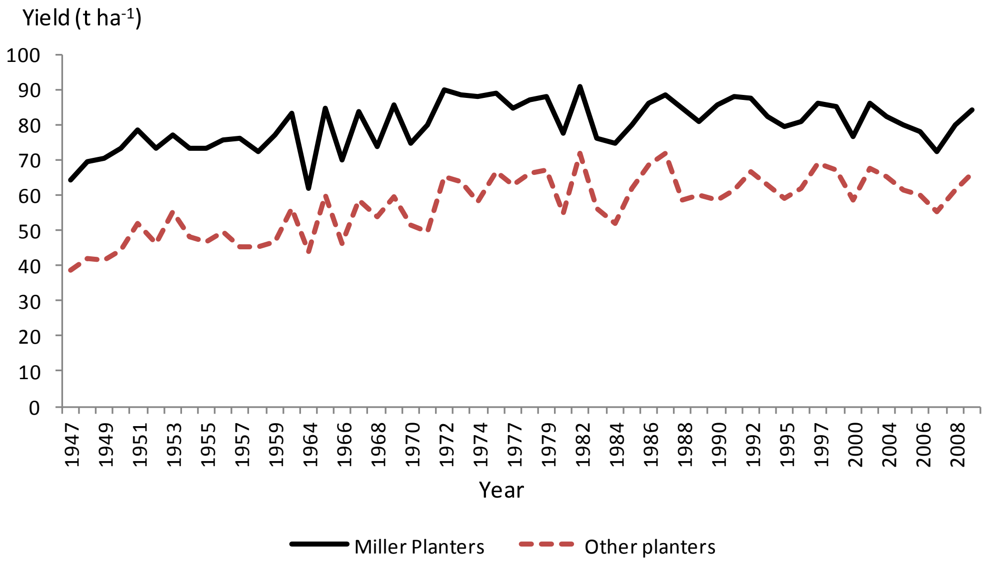


Figure 2-7: Evolution of sugarcane lands cultivated in Mauritius (3-year moving average)

Sources: MSIRI annual reports 1953-2011 and Statistics Mauritius, 2015

In addition, in Mauritius, sugarcane is cultivated by three different categories of farmers (Table 2.9), based on the land area they occupy. The non-miller planters are producing merely 77% (about -18 t ha^{-1}) of cane yield per hectare than the miller planters (Figure 2-8).



Source: MSIRI Annual reports 1953-2011

Figure 2-8: Yield trend among miller and non-miller planters in Mauritius

The small farmers consists of some 13 921 individuals who have been identified as the most vulnerable group. Government's major concern is to effectively group the small farmers into clusters, under the Sugarcane Planters Regrouping Project (SPRP, previously called "FORIP"), so that they benefit from economies of scale and remain in the sugar industry.

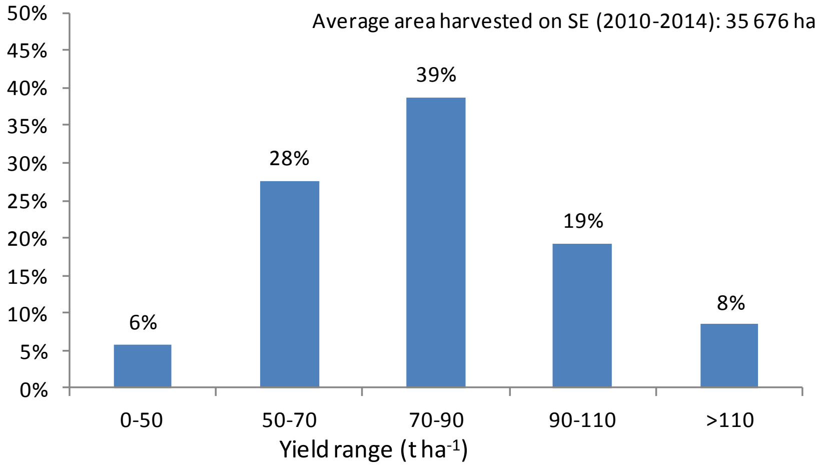
Table 2.9: Area (ha) and percentage area cultivated by different type of sugarcane farmers

Year	Sugar Estates (>250ha)	Large Planters (≥10 ha)	Small Planters* (<10 ha)	Total area (ha)
2006	39925 (56 %)	9311 (13 %)	22161 (31 %)	71397
2010	39365 (61 %)	6576 (10 %)	18191 (28 %)	64132
2013	39606 (68 %)	3979 (7 %)	14731 (25 %)	58316
2016	38358 (69 %)	3391 (6 %)	13921 (25 %)	55670

**: Excluding farmers grouped into cooperatives*

Source: Sugar Industry Fund Board (SIFB) – 2006-2016

Most of the small farmers occupy land that can be considered marginal. However, there is no reliable report on their individual field status and yield. Within the well established Sugar Estates, marginal areas can be defined as those where production in terms of cane yield is well below average. The current national average cane yield is around 74 t ha^{-1}. Five years (2010-2014) average cane yield per hectare among the Sugar Estates show that around 2000 ha (6%) are definitely very marginal with yields below 50 t ha^{-1} (Figure 2-9). Nearly 10 000 ha (28%) are producing 50-70 t ha^{-1} of millable cane. With the rising costs of production and absence of corrective measures, most of these sugarcane lands will soon be declared unsustainable for sugar production.



Source: MSIRI Land Index database

Figure 2-9: Percentage area of cane yield range among sugar estates; five years average (2010-14)

Given the current trend where about 1000 ha of land are lost annually, the Mauritian sugar industry is expected to operate with some 50 000 ha, or less, of sugarcane land in the very near future. As a result, it will be difficult to achieve the set national objectives as the total bagasse generated is expected to get reduced proportionately. Significantly more bioenergy can be produced from sugarcane if the production system is not focused on the production and recovery of sucrose alone but on the maximum use of the total aboveground biomass and on the exploitation of higher fibre energy canes. Utilizing the whole potential of the crop and involving different types of high biomass varieties requires integration of knowledge across many disciplines and is the collective responsibility of policy makers, planners, scientists, investors, sugarcane producers and several other stakeholders. The major focal areas are:

- The creation of new varieties that can produce high biomass without jeopardizing sugar yield to those *energy canes* that can produce very high fibre for cogeneration and 2G biofuels.
- Sugarcane being a seasonal crop, careful exploitation of different types of high biomass varieties can provide feedstock for mills to operate year-round.
- Optimal use of sugarcane straw left in the field can substantially increase surplus electricity for export.
- Studies are also vital in fields of crop husbandry, harvest and transports, and optimal operations at the mill with respect to energy cane management.
- An important aspect is on the economics of high biomass canes cultivation and distribution of benefits to stakeholders, principally the sugarcane growers.
- Detailed analyses with the new energy canes need to be conducted to determine that there is a large positive net energy balance in producing and processing biofuels and that the entire system reduces the GHG emissions well below those of fossil fuels.

In the short-term, the major research opportunities seem to be in identifying promising species (which is the focus of this study) and understanding how to produce them with low inputs, particularly in available sub-optimal and abandoned lands.

Chapter 3

Marginal environments and seasonal effects on yield, quality and morphological traits of high biomass sugarcane genotypes

3 Marginal environments and seasonal effects on yield, quality and morphological traits of high biomass sugarcane genotypes

Abstract

High biomass sugarcane varieties with high fibre content are generally expected to be cultivated in sub-optimal environments for bioenergy production year-round. In this study, a highly selected population of nine biomass varieties of variable sucrose to fibre ratios were evaluated in two contrasting marginal environments (super-humid and dry) of Mauritius and at the beginning and end (June and December) of the harvest season. Data were collected on cane quality, biomass and morphology traits in 12 months old plant cane crops. The ratoon results are described in Chapter 6. Linear mixed model analyses were developed for combined analyses. The main effect, variety, was highly significant for all the variables. Location and harvest period effects were generally significant except for a few morphological traits. The interactions for variety by location and variety by harvest date varied for the different parameters. The cane quality traits showed higher interactions across harvest dates than across locations. Conversely, the cane biomass traits showed higher differential performance across locations than across harvest dates. Cane diameter and stalk number per unit area showed little interactions across environments. In the super-humid environment, high fibre, low sucrose genotypes were best biomass yielders. M 1395/87, a high fibre cane, produced the highest cane dry matter (158% higher than commercial controls) at early harvest in June. It was out-yielded by another high fibre cane, WI 81456 (157% higher than commercial controls), at late harvest in December. In the dry low-lands, clones with relatively high sucrose were more productive across both harvest dates. Commercial variety R 579 was the highest biomass yielder in June. M 1334/84, a commercial type test genotype, ensured highest biomass (24% higher than commercial controls) and sugar yields (20% higher than commercial controls) in December. Generally, the high fibre clones had high density of thin, tall and light cane stalks compared to the high sucrose types that were relatively thicker, shorter and heavier with lower stalk number per unit area.

Keywords: sugarcane, biomass, seasonal effect, extreme environments, genotype-environment-interaction

3.1 Introduction

Since the last decade, there has been a paradigm shift in various sugarcane producing countries from maximizing sugar to the creation of sugarcane varieties for bioenergy production in order to enhance the sustainability of their sugarcane industry and the long-term energy security (Rao and Kennedy, 2004; Ramdoyal and Badaloo, 2007; Rao *et al*., 2007; Terajima *et al*., 2007; Tew and Cobill, 2008; Wang *et al*., 2008; Govindaraj and Nair, 2014). Mauritius is a small island where avenues of increasing land area for agriculture are limited and so far sugar remains more remunerative than fibre, all efforts to diversify within the sector should not be at the expense of sugar yield. It is envisaged that high sucrose with enhanced fibre varieties could be exploited in fertile lands and high fibre low sucrose energy canes can be cultivated in marginal and abandoned lands for the generation of a critical mass of feedstock for bioenergy production.

In Mauritius, marginal lands for sugarcane cultivation can be considered as low cane yielding areas that mainly comprise very undulating lands where mechanization of cultural operations is difficult, dry coastal areas where irrigation facilities are non-existent and super-humid uplands where high rainfall coupled with acidic soils and limited sunshine-hours impact upon yield. Abandoned sugarcane lands are a major cause of concern of the Mauritian government.

Sugarcane is also a seasonal crop and the ripening phase in Mauritius starts with the onset of winter, about the month of April to May (Julien, 1974; Julien and Soopramanien, 1976; Mamet *et al.*, 1996; Soopramanien and Julien, 1980). In summer (October to April) the crop benefits from the warm climatic conditions and rainfall for active growth. The sugarcane harvest season extends from mid-June to mid-December, with peak sucrose contents in most varieties being reached around the months of September and October. There is a growing interest among sugarcane stakeholders to extend the harvest season and new precocious types of varieties (high sucrose at pre-harvest season) are deemed important (Nayamuth *et al*., 2005). High fibre varieties offer the possibility of extending the milling activities year-round for the continuous generation of electricity as, contrary to conventional sugarcane where maximum sugar is the main interest, the drive for energy cane is fibre content, or ultimately biomass, and fibre does not vary during the course of the year as is the case with sugar (Matsuoka *et al*., 2014). However, whether high fibre energy canes maintain their high yields across the year, giving due consideration to the climatic conditions prevailing in Mauritius, has not been studied.

The objectives of this study were to test a population of highly selected biomass genotypes in two contrasting extreme environments (super-humid and dry zones) of the island and to investigate on the dynamics of biomass accumulation at two distinct periods of the year (June and December) at the same crop age. The study also aimed at quantifying the different biomass yield components obtainable from the different types of clones and assessing the morphological characteristics of the best performing ones that could influence their successful industrial exploitation.

3.2 Materials and methods

3.2.1 Test genotypes

Overall, nine potentially high biomass genotypes, comprising five locally bred (M 1156/00, M 1334/84, M 1395/87, M 196/07 and M 202/07), three imported from West Indies CBS (WI 79460, WI 79461 and WI 81456) and one recently imported from Reunion Island (R 585), were retained for the study. Seven of the test clones were early generation hybrids involving wild sugarcane relatives as immediate parents or grandparents. One test candidate, M 1334/84, is a commercial type hybrid with high cane yield that reached the release stage of the routine MSIRI breeding programme in the early 2000s. In spite of its high biomass, it was not released for commercial exploitation because its sucrose content during the harvest season was then considered low for commercial exploitation. M 196/07 and M 202/07 were new entries from the MSIRI interspecific breeding programme. Three widely cultivated commercial varieties, M 1400/86, R 570 and R 579, were included in the trials for comparison purposes.

3.2.2 Locations, trials and layout

Lands were secured in two contrasting environments of the island (Table 3-1). One was in the northern plains situated in the dry environment at an altitude of 90 m, with an annual rainfall of 1300 mm. The soil type is a Latosolic reddish Prairie (L2 soil) as per Parish and Feillafé's (1965) soil classification. In the area, sugarcane fields are irrigated. For the purpose of this study, the trials implemented were not irrigated to simulate the dry marginal conditions of the island. The second was in the super-humid zone in the upland at an altitude of 455 m, with an annual rainfall of 3200 mm. The soil type is Humic Ferruginous Latosol (F1 soil). At each site, two trials were implemented: one for very early harvest (June) and the other for very late harvest (December). Overall, thus, four trials were established with the same varieties. A randomized complete block design (Sokal and Rohlf, 2000) was adopted with three replicates for each trial. The experimental plots consisted of four 10 m long rows interspaced at 1.5 m in the dry zone and three 9 m rows in the super-humid environment spaced at 1.5 m. The middle rows were used for agronomic measurements to minimise inter-plot competition. Planting was done in June 2014. The trials earmarked for late harvest were stubble shaved in December 2014 to ensure uniformity in crop age during data collection and harvest.

Table 3-1: Details on the locations of the four trials

Zone	**Region**	**Soil type**	**Location**	**Altitude (m)**	**Av. annual rainfall (mm)**	**Irrigation**	**Harvest date**
Dry	North	L2	Ferret	90	1300	Nil	June
Dry	North	L2	Ferret	90	1300	Nil	December
Super-humid	Centre	F1	Valetta	455	3200	Nil	June
Super-humid	Centre	F1	Valetta	455	3200	Nil	December

Source: Parish and Feillafé (1965); Annual rainfall: Long term mean (1971-2000)

3.2.3 Data collection

Data collection consisted of measuring:

- cane quality parameters: Brix %, Pol %, fibre % and dry matter % from cane samples analyzed in the laboratory,
- cane biomass parameters: cane yield, sugar yield, fibre yield, sugarcane field residue yield and total biomass yield in terms of tonnes per hectare (t ha^{-1}) fresh and dry weights, and
- cane morphological traits on standing canes in the field: stalk diameter (cm), stalk height (cm), number of canes per unit area, unit stem cane fresh and dry weights (kg), unit stem cane tops and leaves (CTL) fresh and dry weights (kg) and ratings of growth habit, flowering and Breeder's Preference.

Overall, 20 variables were obtained as summarized in Table 3-2. Variables measured could be classified into three categories:

(i) Cane quality traits,
(ii) Cane biomass traits, and
(iii) Cane morphology traits

Cane samples, comprised of ten clean millable cane stalks, were taken at random from each plot at the respective harvest dates for the determination of cane quality parameters from laboratory analyses. Biomass yield in tonne per hectare (t ha^{-1}) included mature trash free cane stems devoid of non-millable parts and the field residues, namely immature cane tops, green and clinging dry leaves (CTL).

(i) Cane quality traits

Brix %, the proportion of total soluble solids in the cane juice, was derived from the diluted Brix measured in the laboratory. Pol %, the apparent sucrose content in the juice, was determined using a laboratory polarimeter based on the method of de St. Antoine (MSIRI, 1968). Fibre % was obtained by direct determination of the fibre content of the cane according to the method of de Saint Antoine and Froberville (MSIRI, 1964). Dry matter % (DM %) of the cane was the sum total of soluble and insoluble solids (Brix % + fibre %). It was used as common denominator to estimate the dry weight percentages of Brix, Pol and fibre in the cane stem. Impurity was equivalent to soluble solids in the cane juice that were not sucrose and was calculated from the difference between Brix % and Pol %. Purity was the proportion of Pol % to Brix %. High purity, that is, a high proportion of sucrose over reducing sugars (glucose and fructose) favours an efficient recovery of crystallized sugar, and below certain purity level there is no crystallization at all (Matsuoka *et al.*, 2014). Generally, a crop is considered fit for harvest when its purity coefficient is 85%. Pol to Fibre index (PF index) was a derived variable obtained by the proportion of Pol % to Fibre % and demarcated the partitioning of dry matter into sugar and fibre.

Table 3-2: A summary of traits measured and derived

Traits	**Remarks**
Cane quality characteristics	
Brix % (FW)*	Cane quality characteristics obtained from cane samples
Pol. % (FW)	Ten canes sampled at random per experimental plot
Fibre % (FW)	Samples milled: juice extract and fibre content analyzed
Dry matter % cane	Variables worked out in terms of fresh and dry weights
Yield parameters (t ha^{-1})	
Cane yield (FW)	Extrapolated from plot weight
Cane yield (DW)	Cane yield x dry matter % cane
CTL yield (FW)**	CTL fresh and dry weights measured from 10 canes per plot taken at random during sampling
CTL yield (DW)	
Sugar yield	Cane yield x Pol % cane
Fibre yield	Cane yield x fibre % cane
Impurity yield	Cane yield fresh weight x (Brix % - Pol %)
Total aboveground biomass (FW)	Cane yield + CTL yield fresh weight
Total aboveground biomass (DW)	Cane yield + CTL yield dry weight
Cane morphology	
Cane diameter (cm)	Five millable stalks measured at random per plot
Cane Height (cm)	Five millable stalks measured at random per plot
Stalk number /m	Total number of mature stalks per metre row
Ground cover	Rated 1 to 5, four months after planting
Lodging	Rated 1 to 5 in 12 months old crops
Flowering	Rated 1 to 5 in 12 months old crops
Breeder's Preference (Visual grade)	Rated 1 to 5 in 12 months old crops

**: In brackets: - FW: measurements in fresh weights; DW: measurements in dry weights*

***: CTL was composed of non-millable cane tops, green and clinging dry leaves from untrashed canes*

Rated characters: - 1 equals very poor and 5 equals best performance except flowering, where 1 equals non-flowering and 5 equals profuse flowering

(ii) Cane biomass traits

Biomass characters involved all aboveground traits that were weighed and extrapolated to tonnes per hectare (t ha^{-1}). These involved mature trash free cane stems and the non-millable parts, namely immature cane tops and, green and clinging dry leaves, termed as CTL. Biomass yield in tonnes per hectare (t ha^{-1}) included cane yield fresh weight (CY), Brix yield (BXY), sugar yield (SY), fibre yield (FY), impurity yield (IMY) and cane dry matter yield (DMY). Cane yield was estimated from plot weights. Brix yield was estimated from the product of cane yield and Brix % in the cane stem. Generally sugar yield is based on the amount of sugar that can be industrially extracted and is a fraction of total sugar stored in the cane stem. For the purpose of this study, interest was on the total sugar accumulated by the clones and sugar yield was calculated as the simple product of cane yield fresh weight and Pol %. Similarly, fibre yield (FY) was derived from the product of fibre % and cane yield. Dry matter yield was obtained by the product of cane yield fresh weight and dry matter % of canes obtained from laboratory analyses. Impurity yield

(IMY) was obtained from the difference between Brix yield and sugar yield. CTL of the ten canes that were sampled for laboratory analyses were collected in raffia bags and weighed. The values were standardised to t ha^{-1} as per the formula:

$$CTL\ fresh\ weight\ (t\ ha^{-1}) = \frac{CTL\ fresh\ weight\ (kg)}{10\ canes \times 1000\ kg} \times \frac{stalk\ number\ per\ plot \times 10000\ m^2}{plot\ area\ (m^2)} \qquad [Eq.\ 1]$$

The dry weight estimates were obtained by oven drying of the field residues at 105^0C over 48 hours. CTL dry weights in t ha^{-1} were calculated similarly using the dry weight estimators.

(i) Cane morphology traits

Cane height and cane diameter were measured on five millable canes taken randomly from the middle part of the experimental plots. The average values were retained for statistical analyses. Number of stalks per plot was counted over 3 m length and standardized to stalk number per metre row. Unit cane and CTL weights were obtained by weighing cane and CTL samples cut for laboratory analyses as described above. Unit stem weight consisted of the unit cane and unit CTL weights combined. Observations on growth habit, flowering and "Breeder's Preference" were made using a 5-point-scale, where 1 = very poor, 2 = poor, 3 = average, 4 = good and 5 = best in performance. Lodging was rated visually based on the extent of inclination of the cane stems towards the ground. A totally lodged genotype was rated 1 and one with fully erect canes as 5. Non-flowering clones were rated as 1 and those with profuse flowering as 5. Breeder's Preference, also termed as visual grade (VG), was a single value given based on the overall appearance and potential of the clone and integrated the crop vigour, cane morphology and other visible parameters broadly acceptable to farmers. Least desirable genotypes were rated as 1 and the most desirable ones as 5.

3.2.4 Statistical model and analyses

ASReml-W software (Gilmour *et al.*, 2009) was used for the combined analyses. Except for a few missing plots, the data was balanced across locations and harvest dates. The standard full basic model for a single-trait data in the four trials could be described as follows:

$$Y_{ijkl} = \mu + L_i + R\ (L)_{ik} + G_l + GL_{il} + RG\ (L)_{ikl} + H_j + HL_{ij} + GH_{jl} + GHL_{ijl} + \varepsilon_{ijkl} \qquad [Eq.\ 2]$$

where, Y_{ijkl} is the observation for genotype l, in harvest period j, in location i, in rep k, μ equals the overall mean (fixed), L_i, the effect of ith location (fixed), $R\ (L)_{ik}$, the effect of k^{th} replication within the i^{th} location (random), G_l, the effect of the l^{th} genotype (fixed), GL_{il} is the interaction of the l^{th} clone with the i^{th} location (fixed), $RG\ (L)_{ikl}$ represents the interaction genotype l and replication k within location i (random), H_j is the effect of the j^{th} harvest (fixed), HL_{ij} is the interaction term between the j^{th} harvest, and the i^{th} location (fixed), GH_{jl} represents the interaction of the l^{th} clone with the j^{th} harvest (fixed), GHL_{ijl} is the interaction between the l^{th}

clone, the jth harvest, and the ith location (fixed), and ε_{ijkl} represents the random residual term associated with Y_{ijkl}.

The main effects, genotype, location, harvest date and their interactions were considered fixed. The random part of the model consisted of replications within locations and their interactions with genotypes. Terms in the fixed part were tested for significance using the Wald's F statistics. The assumptions of linearity, homoscedasticity and presence of influential data points were verified from the residual plots against the fitted values. Appropriate transformations were made to resolve the mean variance relationships for specific traits.

Broad sense heritabilities (*H*) were calculated for individual variables and were based on the standard formula $H = \frac{\sigma_g^2}{\sigma_p^2}$ where σ_g^2= genetic variance and σ_p^2= phenotypic variance. The two genetic parameters could be calculated from METs data using the standard methodology (Wricke and Weber, 1986) as follows:

$$\sigma_g^2 = \frac{MS_g + MS_{glh} - MS_{gl} - MS_{gh}}{rlh} \quad \text{[Eq. 3]}$$

$$\sigma_p^2 = \sigma_g^2 + \frac{\sigma_{gl}^2}{l} + \frac{\sigma_{gh}^2}{h} + \frac{\sigma_{glh}^2}{lh} + \frac{\sigma_e^2}{rlh} \quad \text{[Eq. 4]}$$

where MS represents the Mean Square, MS_g equals to MS pertaining to variety, MS_{glh}, MS of interaction variety by location by harvest, MS_{gl}, MS of interaction variety by location, MS_{gh}, MS of interaction variety by harvest and r stands for replicates, l for location and h for harvest date.

The selection index defined by Santchurn *et al.* (2014) was used to categorize the selectable clones into four different types of high biomass sugarcane varieties (see Table 2-6, page 20).

3.3 Results

Generally, the clones in the various trials germinated well, except one, M 1156/00. It showed signs of poor establishment in all replicates in the dry zone and no germination in the super-humid zone. M 1156/00 is a rare progeny of inter-generic crosses between the genus *Erianthus arundinaceous* (comprising many wild grasses) and sugarcane. The clone, however, proved to be a self of the wild cane after investigation using microsatellite markers (Joomun *et al.*, 2005). This could explain the cause of the erratic germination. For this experiment, the clone was ignored in the analyses. Another test variety, M 1334/84 germinated well in all trials. However, in the super-humid environment, it remained stunted in all replicates. Particularly for early harvest in June, sampling for laboratory analyses was avoided as the cane stalks were too short for reliable inferences.

3.3.1 Statistical analyses

The statistical analyses consisted of testing the quality of the data and significance of the terms included in the model. Generally, the residual plots were well scattered. For certain parameters, the residual plots indicated the presence of mean variance relationships. Square root or log transformations (see Appendixes 3-1 and 3-2) of the source dataset corrected the dependence.

Table 3-3: Significance tests of major traits and terms in the fixed part of the model

Variables	**Variety**	**Location**	**Harvest period**	**Interactions**		
	(var)	**(loc)**	**(harv)**	**loc x var**	**harv x var**	**loc x harv x var**
Cane quality components						
Brix %	***	***	***	ns	***	ns
Pol %	***	***	***	*	***	**
Fibre %	***	**	***	***	***	**
Dry matter %	***	***	***	***	***	ns
Aboveground biomass yields (t ha^{-1})						
Cane yield FW	***	***	***	***	*	**
Cane yield DW	***	***	***	***	**	**
CTL yield FW	***	***	***	***	*	***
CTL yield DW	***	***	***	***	*	***
Sugar yield	***	***	***	***	***	*
Fibre yield	***	***	***	***	**	**
Impurity yield	***	**	**	***	***	**
Total biomass yield FW	***	***	***	***	ns	**
Total biomass yield DW	***	***	***	***	*	***
Aboveground morphological components						
Cane diameter (cm)	***	ns	***	*	ns	ns
Cane height (cm)	***	**	**	*	*	**
Stalk number (m^{-1})	***	***	***	ns	ns	*

*: Significant at P=0.05; **: Significant at P=0.01; ***: Significant at P=0.001; ns = non-significant;
CTL: cane tops and green and clinging dry leaves;FW: fresh weight; DW: dry weight; Impurity: soluble solids other than sugar in the cane

The main effect variety showed very highly significant differences (P <0.001) for all the traits evaluated (Table 3-3). Main effects location and harvest period were highly significant (P <0.01) to very highly significant (P <0.001). Location effect was non-significant for cane diameter. The first order interactions of variety with location (var x loc) were significant for most traits except Brix % and stalk number per unit area. The interactions of variety with harvest date (var x harv) were significant for most variables, except total biomass yield fresh weight, cane diameter and stalk number per unit area. The second order interactions of variety by location by harvest date (var x loc x harv) were non-significant at P = 0.05 for Brix %, cane dry matter % and cane diameter. At P = 0.001, the second order interactions were non-significant for all the cane quality components and most of the biomass parameters. Overall, the significant interactions for the majority of the traits confirmed the differential performance of genotypes in the two different locations and harvest dates.

The strengths of the interactions for specific traits could be verified from the variance components (Table 3-4). For the cane quality traits, the var x loc interactions were relatively marginal with respect to their corresponding genetic and total phenotypic variances. However, var x harv interactions, particularly for sucrose content estimates (Brix and Pol %) were substantial (values in bold in Table 3-4) and almost equal to the genetic variances. For fibre content, the interaction remained below 10% of the respective genetic variance.

Table 3-4: Genetic parameters and heritability estimates of the measured traits

Variables	σ_g^2	σ_{gl}^2	σ_{gh}^2	σ_{glh}^2	σ_e^2	σ_p^2	H		**SE**
Cane quality traits (%)									
Brix %	1.087	0.006	**0.803**	0.019	0.671	1.552	0.701	±	0.201
Pol %	1.605	0.000	**1.056**	0.457	0.750	2.310	0.695	±	0.203
Fibre %	3.622	0.319	0.276	0.818	0.828	4.266	0.849	±	0.104
Dry matter %	0.997	0.161	0.374	0.364	2.480	1.573	0.634	±	0.275
Cane biomass traits (t ha^{-1})									
Cane yield (FW)	3.472	**104.904**	0.000	**98.411**	123.171	90.787	0.038	±	0.641
Cane yield (DW)	5.996	**4.412**	0.945	**9.775**	11.430	12.070	0.497	±	0.380
CTL yield (FW)	18.192	**5.999**	0.000	**25.618**	38.500	30.890	0.211	±	0.527
CTL yield (DW)	1.530	**0.505**	0.000	**2.155**	3.238	2.598	0.589	±	0.274
Sugar yield	0.000	**1.844**	0.000	**1.359**	1.979	1.426	0.000	±	0.000
Fibre yield	6.809	0.181	3.637	2.434	3.723	9.637	0.707	±	0.204
Impurity yield	0.195	0.000	0.055	**0.340**	0.406	0.341	0.571	±	0.286
Total biomass yield (FW)	35.633	**150.051**	0.000	**151.393**	244.314	168.860	0.211	±	0.527
Total biomass yield (DW)	10.635	**7.095**	0.000	**14.758**	22.201	19.722	0.539	±	0.308
Cane morphology traits									
Cane diameter (cm)	6.880	0.081	0.000	0.000	3.728	7.231	0.952	±	0.033
Cane height (cm)	474.38	0.000	0.001	424.79	708.90	639.630	0.742	±	0.149
Stalk number (m^{-1})	7.823	0.292	0.000	2.129	7.017	9.950	0.786	±	0.132

@: FW: fresh weight; DW: dry weight; H: broad sense heritability; SE: standard error

These results confirmed that, except for fibre content whose means could be generalised, averaging cane quality traits across locations would be meaningful while averaging across harvest dates would result in confounding estimates. The cane biomass variables showed very high var x loc and var x loc x harv interactions (values in bold in Table 3-4), which confirmed that averages for the traits across locations would be misleading. Best interpretations of varietal performances for biomass traits would therefore be within individual trials, although var x harv interactions remained relatively insignificant. The cane morphology traits showed relatively high genetic variances and the first order interactions with location and harvest dates were relatively negligible. While cane diameter and stalk number per unit area also showed minimal var x loc x harv interactions, cane height, on the other hand, had nearly equal second order interaction to genetic variance.

Generally, the heritability estimates were highest for cane diameter, fibre %, stalk number and cane height. They were lowest for sugar yield and the fresh weights of cane, CTL and total biomass yields. These could most probably be due to the very contrasting marginal environments, extreme harvest dates and unripe canes in June.

3.3.2 Individual trial analyses (narrow inferences)

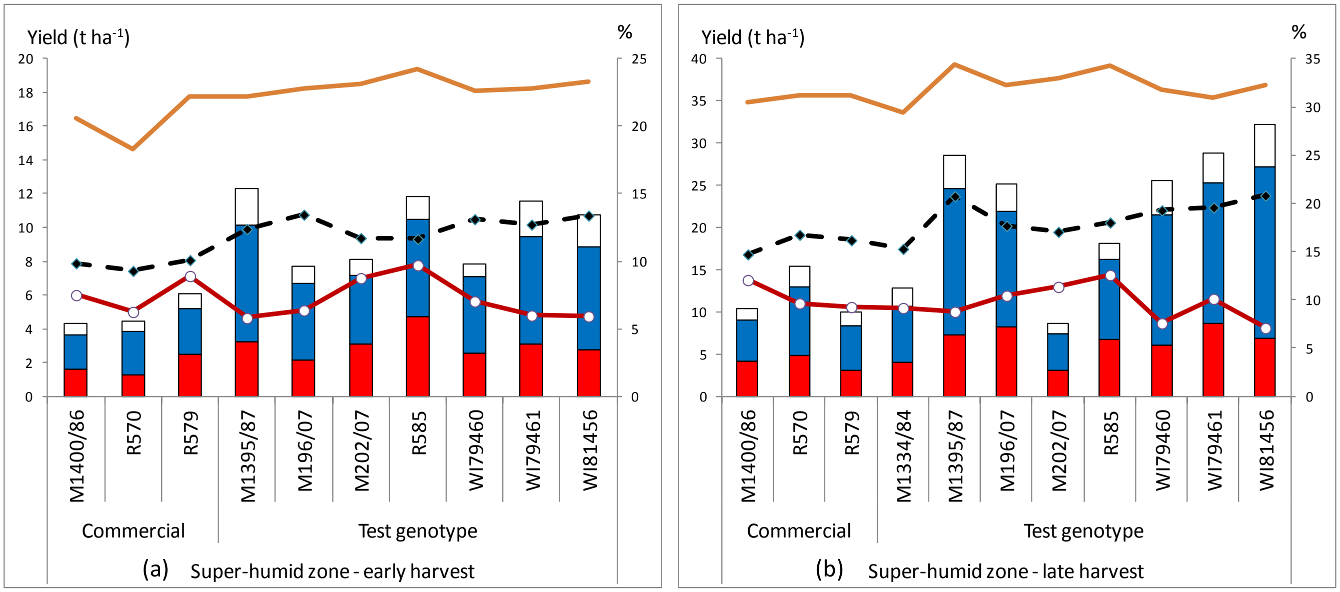
The performances of the individual clones for major cane quality and biomass traits are presented in Appendixes 3-1 and 3-2 and demonstrated in Figure 3-1. Generally, biomass yields were lowest in the super-humid environment, particularly at early harvest [Figure 3-1(a) and Appendix 3-2]. The dry zone was more productive, mainly at late harvest [Figure 3-1(d) and Appendix 3-2]. Furthermore, the dry matter content in the stem was lower at early harvest than at late harvest (Figure 3-1 and Appendix 3-1). Lowest dry matter trial mean was obtained in the super-humid zone at early harvest (average = 23%). Highest mean was observed in the dry zone at late harvest (average = 37%). These results confirmed that the dry matter content for same variety at same crop age was not constant, but varied with the environment. Results on the best performing clones per environment are detailed below.

3.3.2.1 Super-humid zone, early harvest (June)

The whole trial was highly influenced by the very wet conditions prevailing in the super-humid zone in 2015. The commercial varieties were the most severely affected with cane dry matter yield averaging 4.77 t ha^{-1}. Few clones resisted the stress conditions and yielded about twice the biomass produced (Total dry matter yield) by the commercial varieties [Figure 3-1(a) and Appendix 3-2]. In spite of relatively low sucrose content of certain clones, almost all the test genotypes produced significantly higher sugar yield than those of the controls. In terms of fibre yield, the test genotypes were significantly superior to the commercial check varieties. The best performing dry biomass yielders were M 1395/87, R 585, WI 79461 and WI 81456. Genotype M 1395/87 ranked top for fibre yield and total cane dry matter yield as well. Highest sugar yield was obtained from R 585, which had sucrose content significantly higher than those of the commercial varieties. WI 81456 and WI 79461 were among the best fibre yielders with relatively high fibre content.

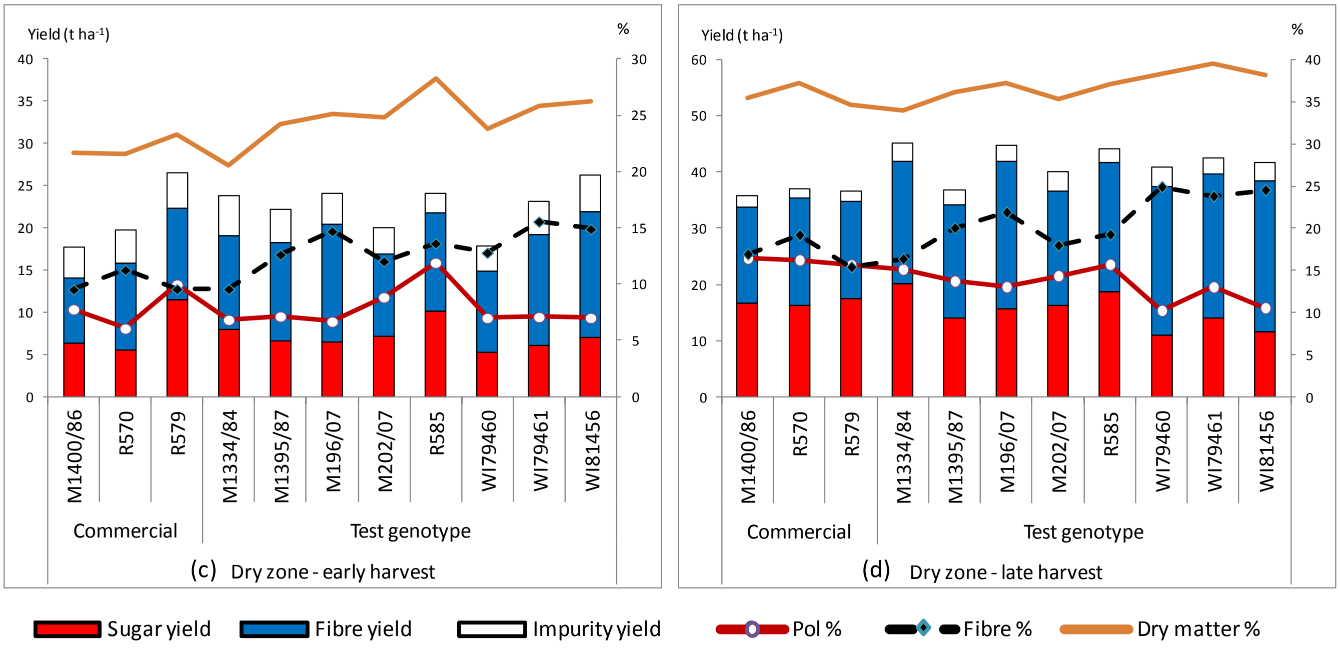
3.3.2.2 Super-humid zone, late harvest (December)

With the exception of two clones (M 202/07 and M 1334/84), the test genotypes produced significantly higher biomass than those of the commercial varieties [Figure 3-1(b) and Appendix 3-2]. The best cane dry biomass yielders were M 1395/87, M 196/07 and the three West Indies clones. WI 81456 was top ranking and was followed by M 1395/87 (Appendix 3-2). R 585 had the highest sucrose content (Appendix 3-1). However, due to its high biomass yield, WI 79461 produced the highest amount of sugar. M 1395/87 and WI 81456 had the highest level of fibre in the cane stem and were the highest fibre yielders in the trial.



(a) Super-humid zone - early harvest

(b) Super-humid zone - late harvest



(c) Dry zone - early harvest

(d) Dry zone - late harvest

Figure 3-1: Performance of individual clones for major cane quality traits (in %) and cane dry matter yield components (sugar yield, fibre yield and impurity yield in t ha^{-1}) in the four contrasting environments

3.3.2.3 Dry zone, early harvest (June)

Cane biomass yield on a dry weight basis in the dry zone at early harvest averaged 22 t ha^{-1} and the commercial controls 21.3 t ha^{-1} [Figure 3-1(c) and Appendix 3-2]. High sucrose content was observed in R 585 and commercial variety R 579 (Appendix 3-1). R 585 also had relatively high fibre and ranked first in terms of total dry matter content. The West Indies clones, WI 79461 and WI 81456, accumulated the highest fibre content. Commercial variety R 579 accumulated the highest amount of cane and total aboveground dry biomass (Appendix 3-2). It was closely followed by WI 81456, M 196/07, R 585 and M 1334/84. R 579 and R 585 were the highest sugar yielders while WI 81456 and M 196/07 were the best fibre yielders. In terms of biomass yield, the differences between the commercial controls and the test genotypes were not as discriminative as in the super-humid zone.

3.3.2.4 Dry zone, late harvest (December)

An appreciably good performance was observed at late harvest in the dry environment [Figure 3-1(d) and Appendix 3-2]. Cane dry biomass averaged 41 t ha^{-1} with the commercial controls attaining 37 t ha^{-1}. The dry matter contents in the clones were relatively higher than in the other environments (Appendix 3-1). The commercial varieties, known to have about 28% dry matter in the cane stalk, attained 35%. Similar trends were observed for sucrose and fibre contents. The commercial varieties and two test clones, R 585 and M 1334/84, were ranked relatively high in sucrose content. The West Indies clones had relatively high fibre and total dry matter contents. Highest cane dry matter yield was observed with M 1334/84. It was closely followed by M 196/07 and R 585. M 1334/84 also ranked first for sugar yield. The contrasts between M 1334/84 and the individual commercial controls for total cane dry matter yields were significant. The West Indies clones and M 196/07 were the best fibre yielders.

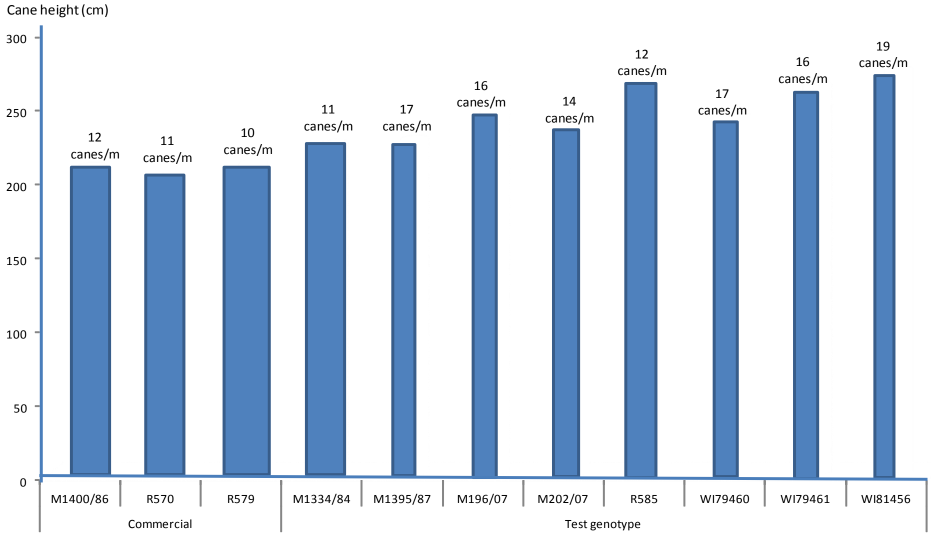
3.3.3 Overall performances (broad inferences)

Based on the observations made on variance components (see Table 3-4), the only overall and reliable broad inferences that could be made were on fibre content and cane morphology traits, with a point of caution for cane height (because of significant contribution of var x loc x harv interaction to the total phenotypic variance). Fibre content of the commercial varieties was at 13.24% while the test genotypes averaged 16.80%. The highest average fibre % obtained was 18.42% by test clone WI 81456. Generally, the commercial varieties had relatively thick and short stems and had about 11 mature canes per metre row (Table 3-5 and Figure 3-2). The early generation hybrids (M 1395/87, M 196/07, M 202/07 and the three West Indies clones) had thinner and taller cane stems with high stalk density per unit area. WI 81456 and M 1395/87 had the thinnest cane diameter (2.1 cm vs. 2.8 cm for commercial varieties). WI 81456 was also the tallest in the population (272 cm vs. 206 cm for commercial varieties) and had the highest number of stalks per metre row (19 canes vs. 11 canes for commercial varieties). Unit canes of the early generation hybrids were about 26% lighter than those of the average of the commercial varieties (0.83 kg vs. 1.12 kg). Each metre length of individual canes of these high fibre clones weighed about 40% lighter than those of the commercial varieties. Commercial variety R 570 had the highest unit cane CTL weight (0.43 kg cane^{-1}) while WI 81456 produced the lowest amount (0.23 kg/cane). The remaining clones yielded around 0.33 kg of CTL per cane fresh weight.

Table 3-5: Broad inferences on cane morphological attributes of individual genotypes

Variety	**SNO (m^{-1} row)**	**Diameter (cm)**	**Height (cm)**	**Unit cane wgt (kg)**	**Unit cane wgt (kg m^{-1} length)**	**% cane wgt (kg) to commercial average**	**% cane wgt (kg m^{-1} length) to commercial average**
M1400/86	11.6	2.7	207.9	1.05	0.50	93%	93%
R570	11.1	2.7	201.1	1.07	0.53	96%	98%
R579	9.7	2.9	209.7	1.24	0.59	110%	109%
Control average	*10.8*	*2.8*	*206.2*	*1.12*	*0.54*	*100%*	*100%*
M1334/84	11.4	2.7	223.2	1.12	0.50	100%	93%
M1395/87	16.8	2.1	225.8	0.77	0.34	69%	63%
M196/07	16.5	2.2	245.2	0.85	0.35	76%	64%
M202/07	13.6	2.3	234.2	0.80	0.34	72%	63%
R585	11.9	2.6	268.3	1.17	0.43	104%	80%
WI79460	17.0	2.3	240.4	0.78	0.33	70%	60%
WI79461	15.8	2.3	262.3	0.88	0.34	79%	62%
WI81456	19.1	2.1	272.2	0.87	0.32	78%	59%
Test genotype average	*15.3*	*2.3*	*246.4*	*0.91*	*0.37*	*81%*	*68%*

SNO: stalk number per metre row; wgt: weight (kg)



Bar width: cane diameter; bar length: cane height; bar labels: stalk number per metre row

Figure 3-2: Morphological characteristics of individual genotypes

Sucrose accumulation could be reliably averaged across locations (Table 3-6). In June, the Pol % of the 12-month-aged commercial varieties averaged 7.75% (range: 6.16-9.45%), which was well below the norm of 12-13% usually observed in ripe canes. Most of the test genotypes had Pol % nearly equal (average = 7.44%; range: 6.47-10.82%) to those of the commercial varieties.

One genotype, R 585, demarcated itself with the highest score of 10.82%. In December, sucrose content of the commercial varieties attained 13.22% (range: 12.46-14.25%), which indicated that the canes were at or near maturity. The test candidates averaged 11.43% (range: 8.83-14.15%). Lowest values were observed with WI 79460 and WI 81456, and the highest level was attained by R 585.

Table 3-6: Sucrose level (Pol %) in 12 months old crops in June and December

Variety	**June**	**December**
M1400/86	7.64	14.25
R570	6.16	12.94
R579	9.45	12.46
Control average	*7.75*	*13.22*
M1334/84	-	12.15
M1395/87	6.47	11.25
M196/07	6.53	11.75
M202/07	8.80	12.86
R585	10.82	14.15
WI79460	7.02	8.92
WI79461	6.54	11.58
WI81456	6.47	8.83
Test genotype average	*7.52*	*11.43*

3.3.4 Categorization of selectable genotypes

The selection index (Santchurn *et al.*, 2014), developed in order to categorize the selectable clones into four different types of high biomass sugarcane varieties (see Table 2-6, page 20), was applied to the dataset. The commercial control varieties performed rather poorly in terms of biomass yield in the super-humid region (Figure 3-1a-b). In consequence, all the test genotypes were selectable and categorized into three cane types (Table 3-7).

In the dry zone at early harvest, all the test genotypes showed sucrose content equal to significantly higher than that of the average of the commercial varieties and none of the test candidates showed significantly low biomass yield. As a result, all the clones were rated as either *Type 1* or *Type 2* canes. At late harvest in the dry zone, however, the differences were more pronounced. The commercial varieties accumulated ample amounts of sucrose to rank among the top sugar yielders. The selection model in the dry zone at late harvest categorized only three biomass genotypes, M 1334/84 (*Type 1* cane), M 196/07 (*Type 3* cane) and R 585 (*Type 2* cane). In contrast to the average of the commercial varieties, the remaining test genotypes showed significantly low sucrose levels and non-significant to significantly low dry biomass yields. Overall, six test genotypes with variable sucrose to fibre ratios were among the top three biomass yielders per environment (Table 3-8).

Table 3-7: Ranking of total biomass and cane types of selectable genotypes in individual environments

Region	Super-humid zone				Dry zone			
Harvest period	Early		Late		Early		Late	
Varieties	Rank	Cane type	Rank	Cane type	Rank	Cane type	Rank	Cane type
M1400/86	**9**	**Type 1**	**10**	**Type 1**	**11**	**Type 1**	**11**	**Type 1**
R570	**10**	**Type 1**	**7**	**Type 1**	**9**	**ns**	**9**	**Type 2**
R579	**8**	**Type 1**	**9**	**Type 1**	**1**	**Type 1**	**8**	**Type 1**
M1334/84	-	-	8	Type 1	5	Type 1	1	Type 1
M1395/87	1	Type 3	2	Type 3	6	Type 2	10	ns
M196/07	7	Type 2	5	Type 1	4	Type 2	2	Type 3
M202/07	5	Type 1	11	Type 1	8	Type 1	7	ns
R585	2	Type 1	6	Type 2	3	Type 2	3	Type 2
WI79460	6	Type 2	4	Type 3	10	Type 2	6	ns
WI79461	3	Type 3	3	Type 2	7	Type 2	4	ns
WI81456	4	Type 3	1	Type 3	2	Type 2	5	ns

In bold: Commercial controls; Type 1: Existing commercial type - high sucrose low fibre; Type 2: High sucrose high fibre type; Type 3: Low sucrose high fibre type; ns: not selectable

Table 3-8: Three best ranking test genotypes from each trial

Region	Super-humid zone				Dry zone			
Harvest period	Early		Late		Early		Late	
Rank	Genotype	Cane type	Genotype	Cane type	Genotype	Cane type	Genotype	Cane type
1	M1395/87	Type 3	WI81456	Type 3	R579	Type 1	M1334/84	Type 1
2	R585	Type 1	M1395/87	Type 3	WI81456	Type 2	M196/07	Type 3
3	WI79461	Type 3	WI79461	Type 2	R585	Type 2	R585	Type 2

M 1334/84 was best performing as commercial *Type 1* cane in the dry zone at late harvest. R 585, as an enhanced fibre *Type 2* cane, appeared among the best three in three of the four trials. The remaining four clones were *Type 3* canes with low sucrose and high fibre content. M 1395/87, WI 79461 and WI 81456 showed good performance in the super-humid zone. M 196/07 was more specifically adapted for late harvest in the dry zone.

3.3.5 Characterization of the best clones for other morphological parameters

Average morphology ratings of six selected biomass clones are given in Table 3-9. In the super-humid environment, almost all the six elite genotypes showed poor to average ground cover four months after planting. Best performance was observed in clone M 1395/87. In the dry zone, all the genotypes showed better crop establishment. M 1395/87 ensured its superiority in ground cover, while WI 79461 maintained its average performance. The good ground cover by M 1334/84 (poor in the super-humid region) was remarkable. The cane stems of the selected clones were fairly erect across all environments. One exception was R 585 that had lodged to highly lodged stalks at harvest. M 1334/84 and R 585 did not flower at all in any of the four trials. Others showed moderate to profuse flowering behaviour mainly at early harvest. WI 79461, WI 81456 and M 1395/87 were top ranking in terms of flowered stalks per unit area. Broadly, in relation to biomass potential, the West Indies clones were visually rated as excellent in almost all trials. M 1395/87 and M 196/07 were generally rated as good. M 1334/84 was graded poor at early harvest in the super-humid zone, mainly because of its stunted growth, and good to excellent in the dry zone. R 585 was generally least appreciated and was rated as poor in the dry zone at late harvest, essentially due to its highly lodged cane stems at harvest.

Table 3-9: Average morphology ratings of selected high biomass clones in different environments

Genotype	**M1334/84**	**M1395/87**	**M196/07**	**R585**	**WI79461**	**WI81456**
Ground cover						
Super-humid zone, early harvest	Poor	Average	Fairly Poor	Average	Average	Fairly Poor
Super-humid zone, late harvest	Fairly Poor	Good	Fairly Poor	Fairly Poor	Average	Average
Dry zone, early harvest	Excellent	Excellent	Excellent	Excellent	Average	Good
Dry zone, late harvest	Good	Excellent	Good	Good	Average	Average
Average ground cover	*Average*	*Good*	*Average*	*Good*	*Average*	*Average*
Growth habit						
Super-humid zone, early harvest	Fairly Erect	Fairly Erect	Fairly Erect	Lodged	Erect	Fairly Erect
Super-humid zone, late harvest	Fairly Erect	Fairly Erect	Fairly Erect	Lodged	Erect	Fairly Erect
Dry zone, early harvest	Fairly Erect	Fairly Erect	Semi-Erect	Lodged	Fairly Erect	Fairly Erect
Dry zone, late harvest	Fairly Erect	Fairly Erect	Fairly Erect	Very lodged	Erect	Fairly Erect
Average growth habit	*Fairly Erect*	*Fairly Erect*	*Fairly Erect*	*Lodged*	*Erect*	*Fairly Erect*
Flowering behaviour						
Super-humid zone, early harvest	Nil	Profuse	High	Nil	Profuse	High
Super-humid zone, late harvest	Nil	Average	Average	Nil	Nil	Nil
Dry zone, early harvest	Nil	Profuse	Average	Nil	Profuse	High
Dry zone, late harvest	Nil	Average	Average	Nil	Nil	Nil
Average flowering	*Nil*	*High*	*Average*	*Nil*	*High*	*Average*
Breeder's Preference						
Super-humid zone, early harvest	Poor	Good	Average	Average	Excellent	Excellent
Super-humid zone, late harvest	Good	Good	Good	Good	Good	Excellent
Dry zone, early harvest	Good	Good	Good	Average	Good	Excellent
Dry zone, late harvest	Excellent	Good	Good	Poor	Excellent	Excellent
Average Breeder's Preference	*Good*	*Good*	*Good*	*Average*	*Excellent*	*Excellent*

3.4 Discussion

Generally under the stress environments, relatively high unexplained variations were expected. In the super-humid zone, due to excessive rainfall, a generally low growth rate was observed. The very moist environment and the delay in canopy cover favoured proliferation of weeds. Several manual weeding interventions were necessary to ensure good expression of the genotypes. Still, the performance of the commercial controls in terms of biomass accumulation was below expectations. On the whole, the early harvest season results in the humid zone were least appreciable. Nevertheless, interest from this study was on those clones that could resist the harsh conditions prevailing in those environments and still produce high biomass.

Explained variations with the combined analyses of the multiple environment trials were not only on the main effect variety, but also on its interactions with location and harvest date that pertained to measuring the differential performances of genotypes across environments. The plant cane results showed considerable and significant interactions in the four trials. For cane quality traits, higher differential performance was observed between var x harv interaction than between var x loc interaction. This could be explained mainly by the sucrose accumulation pattern across the two harvest dates. There was good evidence that in 12 months old plant cane crops, certain varieties that had high sucrose in June were superseded by others in December. Commercial variety R 570 had the lowest sucrose content at early harvest and ranked second best at late harvest. It was also clear that at very early harvest most clones were not mature enough in terms of sucrose accumulation. For fibre accumulation, however, the interactions between early and late harvests were of lower magnitude. Generally, fibre content tended to be more stable, with minimum changes in rank across the two extreme harvest periods. The commercial varieties remained among the low fibre canes and the highest fibre clones were top ranking at both harvest periods and locations. These differential performances confirmed that maturity behaviour in terms of sucrose accumulation varied with season while fibre content remained more stable. For cane biomass parameters, the var x loc interactions were more pronounced than var x harv interactions. M 1395/87, WI 81456 and WI 79461 ranked among the best biomass yielders in the super-humid zone at both early and late harvests. M 1334/84, R 579 and WI 81456 maintained relatively good ranks in the dry zone irrespective of harvest dates. These results pertained to the adaptation of genotypes across environments.

From this study, six best biomass genotypes identified were of different cane types (Table 3-8). Generally, the high fibre varieties adapted well in the super-humid zone. In the dry zone, mainly commercial type or enhanced fibre type varieties were best biomass yielders. CTL broadly represented 26% of aboveground biomass fresh weight. Among the six best genotypes identified, M 1395/87 produced relatively high amount of CTL (30%) fresh weight per cane stem while genotype WI 81456 produced the least (22%). The difference between the two means was significant. Field residues generation, collection and use in sugarcane remain areas of intensive research to maximize biomass exploitation for bioenergy production (Panray Beeharry, 2001; Hassuani *et al.*, 2005; Franco *et al.*, 2013; Antonio Bizzo *et al.*, 2014; Smithers, 2014). From the breeding perspective, CTL yield per genotype can become an important objective and criterion for selection of biomass varieties.

The crop morphology has important bearings on profitability, crop husbandry, yield and, most importantly, adoption of new promising genotypes by farmers. A fast growing variety ensures rapid ground cover that would lead to more efficient weed control. Labourers would be reluctant to reap very thin, dense and hard rind high fibre canes. Very tall and thin canes would be prone to lodging with moderate winds. Highly lodged canes, in turn, would not only be a nuisance for crop husbandry and manual harvest, but also inappropriate for mechanized harvest. The breeder's overall rating (Breeder's Preference) tends to combine into one grade the general balance of all the desirable morphological traits and simulate, as far as possible, farmers' appreciation of new candidates. Although, from the agronomic performance point of view, most genotypes can be attractive, the morphological attributes of individual candidates in sugarcane remain important determining factors for successful adoption by farmers and industrial exploitation. The least appreciated clone from the six best biomass yielders was R 585 because of its highly lodged canes at harvest.

3.5 Conclusions

In this study, the interactions between variety and location and between variety and harvest date were significant for the majority of the traits. The interactions for cane quality traits were more important with harvest periods than with locations. For aboveground biomass yields, the varieties showed higher interactions with locations than with harvest dates.

The selection index used was less representative at very early harvest because of immature control varieties. At late harvest, the differences were more discriminative. Overall, six test genotypes were identified among the best biomass yielders and included M 1395/87, M 196/07, WI 81456, WI 79461, M 1334/84 and R 585. The first four were classified as *Type 3* canes with significantly low sucrose and high fibre in the cane stems. M 1334/84 was of commercial type, *Type 1* cane, with appreciable sucrose level and low fibre. R 585 was categorized as *Type 2* cane, with relatively high sucrose and moderately high fibre.

In the super-humid environment, M 1395/87 was the overall best biomass yielder (early and late harvests confounded) with 158% higher total dry matter yield than the average of the commercial varieties. WI 81456 and WI 79461 followed with around 125% higher dry matter yield. These high fibre canes had high density of thin and tall stalks that were about 26% lighter than those of the commercial varieties. All the high fibre clones flowered at early harvest, which designated the end of the vegetative growth phase.

In the dry zone, the commercial type varieties were superior to the high fibre canes. One exception was M 196/07 that had 19% of dry matter yield significantly higher than the mean of controls at late harvest. M 1334/84, a commercial type clone, was the overall best aboveground dry matter yielder. At late harvest, it produced 24% and 20% of total dry matter and sucrose yields significantly higher than those of the commercial varieties. Clone R 585, an enhanced fibre type cane, was the third best genotype at both early and late harvests in the dry environment. Total dry matter yield was 12% higher than those of the check varieties. The lodging behaviour of R 585 could be a major disadvantage for industrial exploitation. Among the six best genotypes identified, M 1395/87 produced a relatively high amount of CTL (30%) fresh weight per cane stem while genotype WI 81456 produced the least (22%).

The morphological attributes of each selected candidate would certainly impact upon cost of production and adoption rate by growers. Higher precision in the characterization and quantum gains are expected with additional evaluations in ratoon crops and are elaborated in Chapter 6.

Appendix 3-1: Means of cane quality traits fresh weight in individual environments

Environment	Variety$^{@}$	Brix %^{sq}	Pol %	Fibre %	Dry matter %^{lg}
Dry zone, early harvest	**M1400/86**	**12.1**	**7.8**	**9.5**	**21.6**
	R570	**10.3**	**6.1**	**11.3**	**21.5**
	R579	**13.8**	**10.0**	**9.6**	**23.3**
	M1334/84	10.9	6.8	9.6	20.5
	M1395/87	11.5	7.1	12.6	24.2
	M196/07	10.4	6.7	14.7	25.1
	M202/07	12.8	8.8	12.0	24.8
	R585	14.7	11.9	13.6	28.2
	WI79460	10.9	7.0	12.8	23.8
	WI79461	11.6	7.1	15.6	25.8
	WI81456	11.4	7.0	14.9	26.3
Dry zone, late harvest	**M1400/86**	**18.6**	**16.4**	**16.9**	**35.5**
	R570	**18.0**	**16.2**	**19.2**	**37.1**
	R579	**17.3**	**15.6**	**15.4**	**34.6**
	M1334/84	17.6	15.1	16.4	33.9
	M1395/87	16.1	13.7	20.0	36.1
	M196/07	15.3	13.0	21.9	37.2
	M202/07	17.4	14.3	18.0	35.3
	R585	17.8	15.7	19.3	37.0
	WI79460	13.4	10.2	24.9	38.3
	WI79461	15.7	13.0	23.8	39.4
	WI81456	13.6	10.6	24.5	38.2
Super-humid zone, early harvest	**M1400/86**	**10.8**	**7.5**	**9.9**	**20.6**
	R570	**9.1**	**6.3**	**9.3**	**18.3**
	R579	**12.1**	**8.9**	**10.1**	**22.2**
	M1334/84	-	-	-	-
	M1395/87	9.8	5.8	12.4	22.2
	M196/07	9.3	6.4	13.5	22.8
	M202/07	11.4	8.8	11.7	23.1
	R585	12.5	9.7	11.7	24.2
	WI79460	9.5	7.0	13.1	22.6
	WI79461	10.1	6.0	12.7	22.8
	WI81456	10.0	5.9	13.4	23.3
Super-humid zone, late harvest	**M1400/86**	**15.7**	**12.1**	**14.7**	**30.5**
	R570	**14.4**	**9.7**	**16.8**	**31.2**
	R579	**14.4**	**9.3**	**16.2**	**31.2**
	M1334/84	14.1	9.2	15.3	29.4
	M1395/87	13.6	8.8	20.8	34.4
	M196/07	14.5	10.5	17.7	32.2
	M202/07	16.0	11.4	17.1	33.0
	R585	16.2	12.6	18.0	34.3
	WI79460	12.5	7.6	19.3	31.8
	WI79461	14.3	10.1	19.6	30.9
	WI81456	12.2	7.1	20.8	32.3
Overall SED		0.10*	0.73	0.86	0.05*

$^{@}$*: In bold: Commercial control varieties;* ^{lg}*: data analysed using log transformation;* ^{sq}*: data analysed using square root transformation; *: SED values apply to transformed data*

Appendix 3-2: Means, in t ha^{-1}, of biomass traits in individual environments

Environment	**Variety$^{@}$**	**Cane yield FW**	**Cane yield DW^{sq}**	**CTL yield FW^{lg}**	**CTL yield DW^{sq}**	**Sugar yield^{sq}**	**Fibre yield^{lg}**	**Impurity yield^{sq}**	**Total biomass yield FW**	**Total biomass yield DW^{sq}**
Dry zone, early harvest	**M1400/86**	**82.3**	**17.7**	**24.5**	**7.1**	**6.3**	**7.8**	**3.6**	**107.4**	**24.9**
	R570	**92.1**	**19.8**	**36.5**	**10.6**	**5.6**	**10.2**	**3.9**	**128.7**	**30.5**
	R579	**114.7**	**26.7**	**27.0**	**7.8**	**11.4**	**10.8**	**4.3**	**142.6**	**34.7**
	M1334/84	116.7	23.9	26.2	7.6	7.9	11.1	4.8	143.3	31.6
	M1395/87	92.3	22.3	38.5	11.2	6.6	11.6	4.0	131.2	33.5
	M196/07	96.2	24.1	30.9	9.0	6.4	14.1	3.6	127.5	33.2
	M202/07	81.7	20.2	23.6	6.8	7.2	9.8	3.0	106.0	27.2
	R585	85.7	24.1	25.2	7.3	10.2	11.6	2.4	111.0	31.5
	WI79460	75.7	17.9	37.1	10.7	5.3	9.6	3.0	113.0	28.7
	WI79461	85.5	22.1	45.7	13.2	6.0	13.2	3.9	131.9	35.5
	WI81456	100.8	26.4	24.3	7.0	7.0	14.9	4.4	125.9	33.6
Dry zone, late harvest	**M1400/86**	**101.4**	**36.0**	**38.5**	**11.2**	**16.6**	**17.1**	**2.0**	**140.4**	**47.2**
	R570	**100.4**	**37.2**	**53.1**	**15.4**	**16.2**	**19.1**	**1.7**	**154.3**	**52.7**
	R579	**112.7**	**39.1**	**22.5**	**6.5**	**17.5**	**17.2**	**1.9**	**136.1**	**45.7**
	M1334/84	133.7	45.2	51.3	14.9	20.1	21.7	3.3	186.7	60.4
	M1395/87	103.1	37.0	41.9	12.2	14.0	20.3	2.5	145.1	49.2
	M196/07	120.2	44.7	36.9	10.7	15.7	26.3	2.7	158.1	55.6
	M202/07	114.0	40.2	53.4	15.5	16.3	20.2	3.4	167.5	55.7
	R585	119.8	44.3	41.5	12.0	18.8	23.0	2.5	161.5	56.3
	WI79460	109.3	41.0	45.2	13.1	10.9	26.5	3.4	140.3	50.9
	WI79461	108.1	42.6	35.4	10.3	14.0	25.6	2.9	145.2	53.2
	WI81456	111.1	41.9	36.9	10.7	11.6	26.8	3.3	149.4	53.0
Super-humid, early harvest	**M1400/86**	**21.7**	**4.4**	**6.4**	**1.8**	**1.6**	**2.0**	**0.7**	**28.1**	**6.2**
	R570	**21.5**	**3.8**	**6.9**	**2.0**	**1.3**	**2.6**	**0.6**	**29.2**	**5.9**
	R579	**29.4**	**6.2**	**8.8**	**2.5**	**2.5**	**2.7**	**0.9**	**38.6**	**8.8**
	M1334/84	26.7	-	11.8	-	-	-	-	38.1	-
	M1395/87	55.8	12.3	26.6	7.7	3.2	6.9	2.2	82.5	20.1
	M196/07	33.8	7.7	15.7	4.5	2.1	4.5	1.0	50.7	12.5
	M202/07	36.1	8.2	12.2	3.5	3.1	4.1	0.9	48.5	11.8
	R585	49.0	11.8	13.6	3.9	4.7	5.7	1.4	62.7	15.8
	WI79460	36.0	8.0	16.3	4.7	2.5	4.6	0.7	52.9	12.8
	WI79461	52.0	11.7	18.1	5.2	3.1	6.4	2.1	70.3	17.0
	WI81456	46.6	10.8	16.0	4.6	2.7	6.1	1.9	63.0	15.5
Super-humid, late harvest	**M1400/86**	**34.0**	**10.4**	**8.4**	**2.4**	**4.1**	**5.0**	**1.3**	**42.4**	**12.8**
	R570	**49.4**	**15.4**	**17.3**	**5.0**	**4.8**	**8.3**	**2.3**	**67.3**	**20.5**
	R579	**33.5**	**11.2**	**7.5**	**2.2**	**3.1**	**5.3**	**1.7**	**41.2**	**13.4**
	M1334/84	43.7	12.8	12.8	3.7	4.0	6.6	2.1	56.7	16.6
	M1395/87	83.4	28.6	32.9	9.5	7.3	17.3	4.0	116.4	38.2
	M196/07	78.1	25.2	27.8	8.1	8.2	13.8	3.2	106.1	33.3
	M202/07	26.8	8.8	6.2	1.8	3.0	4.4	1.2	33.1	10.6
	R585	53.1	16.9	15.2	4.4	6.7	9.5	1.9	68.4	21.3
	WI79460	81.7	25.7	21.8	6.3	6.1	15.4	4.0	104.6	32.2
	WI79461	86.2	26.4	22.5	6.5	8.6	16.6	3.6	109.6	33.1
	WI81456	97.8	31.6	17.3	5.0	6.9	20.3	5.0	115.2	36.7
Overall SED		10.56	0.33*	0.22*	0.21*	0.21*	0.15*	0.17*	14.50	0.34*

*$^{@}$: In bold: Commercial control varieties; FW: Fresh weight; DW: Dry weight; ^{lg}: data analysed using log transformation; ^{sq}: data analysed using square root transformation; *: SED values apply to transformed data*

Chapter 4

Genotype x environment interaction, adaptability and stability of biomass sugarcane varieties in Mauritius

Comment from author:

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4 Genotype x environment interaction, adaptability and stability of biomass sugarcane varieties in Mauritius

Abstract

Genotype by environment interaction (GEI) is a major issue in plant breeding, which complicates selection and requires breeders to assess the adaptability and stability of promising genotypes before release. Various techniques have been developed in the past to model and analyse GEI. Current trends involve the use of **A**dditive **M**ain effects and **M**ultiplicative **I**nteraction (AMMI) and **G**enotype x **E**nvironment **E**ffects (GGE) multivariate techniques that include good visualization tools that show major response patterns. In this study, 22 genotypes with high biomass potential were assessed for cane yield at five locations corresponding to five major soil types in Mauritius and over three harvest cycles, and analysed for adaptation and stability. The study provides preliminary indications of the presence of two mega-environments in the island of Mauritius: the low-altitude dry lands in the northern plains and the more humid central environments. Environments that were highly discriminating and those that were most representative for wide adaptation were defined. The variety by crop cycle interaction was significant only within locations. In consequence analyses involving crop cycle were done separately within two contrasting locations. Plant cane results were found least representative of the performance of varieties across ratoons. The best varieties overall were three West Indies clones, WI 79460, WI 79461 and WI 81456, and two commercial varieties, R 570 and M 1400/86. The West Indies genotypes were found adapted to the humid and super-humid environments while the commercial varieties had highest cane yield in the dry lands. These elite varieties were also stable across crop cycles, except R 570 that showed better performance at plant cane in one environment. AMMI and GGE analyses of GEI were found useful to define mega-environments in Mauritius and improve precision in selection while reducing the cost by eliminating unnecessary test locations and crop cycles.

Key words: sugarcane, GEI, AMMI model, GGE biplot, stability, adaptation

4.1 Introduction

Successful adoption of new varieties not only depends on the high yielding ability, but also on adaptability and stability across environments. While adaptability refers to good performance over a geographic region under conditions of variable climate and environment, stability of yield is generally defined as the ability of a genotype to avoid substantial fluctuations in yield over a range of environmental conditions. Environment refers to both spatial (different sites) and temporal (different harvests or years) dimensions. The analysis of differential genotypic expression across environments, commonly termed as genotype by environment interaction (GEI), attempts to address these problems. The complexity of GEI is a major concern to breeders since it reduces the progress from selection and makes cultivar recommendation difficult. In the past, agricultural research has been geared towards high yielding cultivars. Lately, however, genotypes that provide high average yields with minimum GEI (i.e., high stability) have been gaining importance over increased yields (Rosielle and Hamblin, 1981; Ceccarelli, 1989; Gauch and Zobel, 1997). GEI is also a major element in determining many important aspects of a breeding programme including (i) whether to aim for wide or specific adaptation; (ii) choice of locations for selection; (iii) whether selection in early generations is conducted in stress or stress-free environments; and (iv) the trade-off between multi-environment testing of large numbers of genotypes and subjecting fewer lines to intensive trait-based selection (Fox *et al.*, 1997). The knowledge of GEI can also help to reduce the cost of extensive genotype evaluation by eliminating unnecessary testing sites and by fine-tuning the breeding programmes (Kang and Magari, 1996).

Understanding the relationship between crop performance and environment has been a research focus among breeders, biometricians and quantitative geneticists since the early 1900s. Whenever an interaction is significant, the use of main effects, e.g. overall cane yield across environments, is questionable. Various methods have been developed to reveal patterns in multi-environment trials (METs) data and many stability measures have been proposed (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Shukla, 1972; Wricke and Weber, 1986; Kang, 1988; Zobel *et al.*, 1988; Gauch, 1992). The large number of methods proposed mitigates their widespread use (Romagosa and Fox, 1993). Each analytical alternative seems to have some merit and thus looking into their inter-relationships appears important. Each approach attempts to fill gaps left by others. Fox *et al.* (1997) concluded that in the field of GEI, it is essential that statistical expertise should be matched with parallel biological understanding of the crop involved.

Current trends involve the use of biplot analysis techniques, all of which conform to the general linear-bilinear models. They incorporate multivariate methods using principal component analysis (PCA) that offers the possibility of presenting the total variations into fewer dimensions. While both PCA and biplot analysis use singular value decomposition (SVD) (Pearson, 1901) as a key mathematical technique, biplot analysis is a fuller use of SVD to allow two interacting factors to be visualized simultaneously (Yan and Tinker, 2006). The **A**dditive **M**ain effects and **M**ultiplicative **I**nteraction (AMMI) model (Zobel *et al.*, 1988) and the **G**enotype main effects and **G**enotype x **E**nvironment effects (GGE) model (Gauch, 1992) have been the two most commonly used models for the biplot analysis (Yang *et al.*, 2009). Several reviews have comprehensively compared AMMI and GGE with respect to their suitability for GEI analysis (Yan *et al.*, 2007; Gauch, 2006; Gauch *et al.*, 2008; Yang *et al.*, 2009; McDermott and Coe, 2012). They are both useful for quick visualization and exploration of patterns inherent in the complex GE two-way data table and have broader relevance for agricultural researchers. AMMI generates a family of models and the most common are AMMI1 and AMMI2 models. AMMI1 model considers the main effects as well as the first principal component axis (PCA1) to interpret the residual matrix. AMMI2 considers the main effects and two axes, PCA1 and PCA2, for non-additive variation (Fox *et al.*, 1997). More recently, the term “GGE biplot” was proposed and various biplot visualization methods developed to address specific questions relative to genotype by environment data (Yan *et al.*, 2000; Yan and Tinker, 2006). The term “GGE” emphasizes the understanding that G and GE are the two sources of variation that are relevant to genotype evaluation and must be considered simultaneously for appropriate genotype and test environment evaluation. GGE biplot analysis has evolved into a comprehensive analysis system whereby most questions that may be asked of a genotype by environment table can be presented graphically (Yan and Kang, 2002; Yan and Tinker, 2006).

Mauritius is a tropical island of volcanic origin and consists of a coastal plain rising gradually towards a central plateau bordered by mountain ranges. In summer (November to April) the climate is tropical whereas during the winter months it is sub-tropical. Temperatures range from 15^0C to 29^0C and rainfall is in the range of 900-5000 mm. There exists a mosaic of microclimates and soil types (Parish and Feillafé, 1965) within three main agro-climatic zones: the super-humid central plateau (rainfall >2500mm), the humid or intermediate zone (rainfall 1500-2500 mm) and the sub-humid regions (rainfall <1500 mm). Varietal recommendation has traditionally focused on five major soil types. The purpose of this study was to use AMMI and GGE algorithms to examine the GEI in sugarcane yield data in Mauritius. The aim was to obtain reliable information on the adaptability and stability of high biomass sugarcane genotypes across locations and crop cycle. The analyses were also expected to provide information on the possible definition of mega-environments in Mauritius that could help reduce the extensive evaluation of genotypes at advanced stages of selection.

4.2 Materials and methods

Five trials were established in five major soil types (Parish and Feillafé, 1965) in 2009 and 2010 (Table 4-1). Two trials were in the super-humid zone (annual rainfall >2500 mm) at Flacq Union of Estates Ltd. (FUEL) and Mon Desert Alma (MDA) in B- and F-soils in the central and eastern part of the island, respectively. One trial was established at Britannia (BRIT) in the humid H-soil (annual rainfall: 1500-2500 mm) in the south. Two trials were in the sub-humid environment (annual rainfall <1500 mm) in the north at Mon Loisir (MLOI) and Belle Vue (BVUE) in L- and P-soils, respectively. The trial at MLOI was irrigated while the one at BVUE was rain fed and harvested mechanically. MDA and BVUE could be considered as two contrasting sub-optimal environments.

Table 4-1: Agro-climatic details of five locations where high biomass trials were established

Region	**Soil type**	**Location code**	**Irrigation**	**Altitude (m)**	**Latitude**	**Longitude**	**Av. annual rainfall (mm)**	**Zone**
East	B1	FUEL	Nil	354	20^{0}18’S	57^{0}39’E	3500	Super-humid
Centre	F1	MDA	Nil	470	20^{0}15’S	57^{0}31’E	3250	Super-humid
South	H2	BRIT	Nil	180	20^{0}27’S	57^{0}33’E	2300	Humid
North	L1	MLOI	Yes	10	20^{0}02’S	57^{0}37’E	1200	Sub-humid
North	P2	BVUE	Nil	80	20^{0}07’S	57^{0}40’E	1300	Sub-humid

Source: Parish and Feillafé (1965); Annual rainfall: Long term mean (1971-2000)

Not all test genotypes were planted in all trials (Table 4-2). This resulted in partially balanced METs which reflect the real scenario in breeding programmes worldwide (Balzarini *et al.*, 2002; Piepho and Eeuwijk, 2002). The best estimates of the missing values were obtained using the mixed model equation for multi-environment trials (METs) as described by Balzarini *et al.* (2002). The test genotypes included nine locally bred early generation hybrids selected from the MSIRI breeding programme, four high biomass clones (with prefix WI) imported in 2007 from West Indies Central Sugar Cane Breeding Station (WISCBS) and one (with prefix SM) imported from Taiwan. Four to six commercial varieties adapted to the different regions were used as commercial controls. The long varietal names were abbreviated to simpler codes as per Table 4-2 to make the visual displays more legible.

Randomized complete block design with three replicates was adopted at each location. The trials were evaluated over three annual harvests: plant cane (first harvest), first ratoon (second harvest) and second ratoon (third harvest) at mid-period of the milling season. The plot size consisted of four rows of 10 m length and the inter-row spacing was at 1.5 m. The two middle rows of each plot were harvested and the clean canes, devoid of cane tops and leaves, were weighed to estimate cane yield.

Cane yield per hectare (TCH) was used for genotype-location analyses. Environment consisted of location x crop cycle and the blocks were within locations and crop cycle. A similar approach was adopted by Rea *et al.* (2011) and Silveira *et al.* (2013). Genotype-crop cycle analyses were done in two individual contrasting locations, Mon Desert Alma (MDA) and Mon Loisir (MLOI), and were considered adequate in understanding the performance of high biomass varieties across ratoons.

Table 4-2: High biomass varieties evaluated at five locations

	BRIT	**BVUE**	**FUEL**	**MDA**	**MLOI**
Commercial varieties					
M1176/77	√	√	-	-	√
M1394/86	-	-	√	√	-
M1400/86	√	√	√	√	√
M1672/90	√	√	√	√	-
M2593/92	√	√	-	-	√
R570	√	√	-	-	√
R573	√	√	-	-	√
R579	-	-	√	√	-
Test varieties					
M1303/87	√	√	√	√	√
M1384/87	√	√	√	√	√
M1395/87	√	√	√	√	√
M1748/88	√	√	√	√	√
M3305/87	√	√	√	-	-
M377/91	√	√	√	-	-
M733/90	√	√	√	-	√
M816/86	√	√	√	√	-
M816/90	√	√	√	-	√
SM81022	√	√	√	√	√
WI79460	√	√	√	√	√
WI79461	√	√	√	√	√
WI80542	√	√	√	√	√
WI81456	√	√	√	√	√

√: Planted; -: not included in trial

Genstat -17th edition (Payne *et al.*, 2014) software was used. The data were checked for the homogeneity of variances using *Bartlett's test* before embarking on the AMMI and GGE biplot analyses. For AMMI, the model used was:

$$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + e_{ij} \quad \text{[Eq. 1]}$$

where Y_{ij} is the observed mean yield of the i^{th} genotype in the j^{th} environment, μ is the general mean, G_i and E_j represent the effects of the genotype and environment, respectively, λ_k is the singular value of the k^{th} axis in the principal component analysis, α_{ik} is the eigenvector of the i^{th} genotype for the k^{th} axis, γ_{jk} is the eigenvector of the j^{th} environment for the k^{th} axis, n is the number of principal components in the model, and e_{ij} is the average of the corresponding random errors.

The GGE model fitted was:

$$Y_{ij} - \bar{Y}_j = \lambda_1 \xi_{i1} \eta_{1j} + \lambda_2 \xi_{i2} \eta_{2j} + \epsilon_{ij} \qquad \text{[Eq. 2]}$$

where Y_{ij} is the observed mean yield of the i^{th} genotype in the j^{th} environment; $\bar{Y}_j$ is the mean of genotypes in the j^{th} environment; $\lambda 1$ and $\lambda 2$ are the singular values of the 1st and 2nd largest principal components, PC1 and PC2, respectively; ξ_{i1} and ξ_{j2} are the eigenvectors of the i^{th} genotype for PC1 and PC2, respectively; η_{1j} *and* η_{2j} are the eigenvectors of environment j for PC1 and PC2 respectively; and ε_{ij} is the residual term associated with the average of the i^{th} genotype in the j^{th} environment centred by the effect of the j^{th} environment.

In this study, the strengths of the inferences made through the biplots were verified using basic statistics, ANOVAs and correlation coefficients. Most of the trends involved changes in ranks in different environments. In consequence, Pearson's correlation and Spearman's rank correlation techniques (Sokal and Rohlf, 2000) were used to cross verify the observed patterns.

4.3 Results

4.3.1 Variety by location interaction

4.3.1.1 AMMI Analyses

Bartlett's test for homogeneity of variances for cane yield was non-significant ($P > 0.05$). Treatment combination that comprised genotype (G), location (L) and GEI, accounted for 89% of total variation, the block effect 6% and the remaining 4% by the residual (Table 4-3). Genotype explained 45% of total variation, location 20% and GEI 24%. Four PCAs explained the total GEI variations, of which the first two interaction principal component analyses (IPCAs) captured 82%. The mean cane yields per location and the first two IPCAs scores are given in Table 4-4.

Table 4-3: AMMI analysis of variance of cane yield (t ha^{-1})

Source	df	Sum of square	Mean square	Variance ratio	F prob.	Explained	Accumulated
Block	10	5291	529.1	31.00	<0.001	6%	
Treatments	109	74566	684.1	40.09	<0.001	89%	
Genotype (G)	21	37641	1792.4	105.04	<0.001	45%	
Location (E)	4	16640	4160	7.86	<0.001	20%	
GEI	84	20286	241.5	14.15	<0.001	24%	
IPCA1	24	12380	515.8	30.23	<0.001	*61.03%*	*61.03%*
IPCA2	22	4159	189.1	11.08	<0.001	*20.50%*	*81.53%*
IPCA3	20	2527	126.4	7.40	<0.001	*12.46%*	*93.99%*
IPCA4	18	1220	67.8	3.97	<0.001	*6.01%*	*100.00%*
Error	210	3584	17.1			4%	
Total	329	83441	253.6				

The block source of variation refers to replicate within location and crop cycle

IPCA: Interaction Principal Component Analysis; F pr: F-probability; v.r.: variance ratio

Table 4-4: Cane yield (t ha^{-1}) of genotypes across locations and their corresponding IPCA values

		LOCATION					Mean		
Variety	Code	BRIT	BVUE	FUEL	MDA	MLOI	yield	IPCA1	IPCA2
M1176/77	1176	81.57	76.08	78.30	86.14	92.05	82.83	-0.095	0.431
M1394/86	1394	77.53	70.33	80.85	75.60	89.84	78.83	0.569	1.078
M1400/86	1400	80.08	81.21	77.66	76.92	116.67	86.51	2.814	-1.261
M1672/90	1672	80.11	72.10	75.59	57.39	85.06	74.05	1.942	2.639
M2593/92	2593	90.05	67.85	73.69	81.54	77.99	78.22	-1.085	1.601
R570	570	86.18	79.28	89.18	97.03	116.88	93.71	0.787	-1.735
R573	573	80.84	58.41	78.59	86.44	111.32	83.12	0.771	-2.771
R579	579	81.76	74.56	72.25	92.65	94.07	83.06	-0.576	-0.783
M1303/87	M1	57.92	40.29	61.69	67.36	68.45	59.14	-0.963	-0.179
M1384/87	M2	65.74	60.59	67.46	67.83	76.15	67.55	0.123	1.011
M1395/87	M3	74.50	70.00	68.71	74.49	83.25	74.19	0.241	0.805
M1748/88	M4	54.45	59.07	66.88	53.08	75.07	61.71	1.498	1.640
M3305/87	M5	61.67	54.32	59.89	66.72	74.41	63.40	-0.033	0.152
M377/91	M6	58.24	56.27	44.37	61.05	68.74	57.74	0.223	-0.019
M733/90	M7	69.41	65.03	78.28	78.09	83.06	74.78	-0.242	0.808
M816/86	M8	61.07	67.57	63.94	61.77	77.35	66.34	1.073	1.350
M816/90	M9	70.59	58.81	56.14	72.33	87.18	69.01	0.467	-1.273
SM81022	SM8	64.74	68.22	50.33	65.60	95.94	68.97	2.152	-1.730
WI79460	WI60	88.37	68.75	80.18	115.77	86.03	87.82	-3.627	-1.114
WI79461	WI61	89.43	70.00	86.32	115.69	77.29	87.75	-4.275	0.387
WI80542	WI42	71.78	65.44	65.63	72.65	92.51	73.60	1.009	-0.658
WI81456	WI56	91.84	86.74	87.01	118.91	94.27	95.75	-2.774	-0.378

IPCA: Interaction Principal Component Analysis; Commercial varieties in bold

AMMI1 biplot (Figure 4-1) fitted the mean yields of the genotypes and locations along with the first dimension measure (IPCA1) of the GEI. It provided a direct measure of the yield potential and the stability of the genotypes being examined. Along the X-axis, MLOI had the highest mean yield and BVUE the lowest. The best performing varieties were further to the right. Thus, the overall ranking of genotypes in terms of yield were WI56>570>WI60>WI461>1400>…>M1>M6. The Y-axis showed the best one dimension (IPCA1) measure of genotype by environment (GE) effect of each genotype. Clones close to the X-axis had small GE effects while those further away had large effects. Clones M6, M5, M2, M3, M7 and 1176 were, in consequence, most stable. WI60, WI61, WI56 and 1400 were least stable. Combining stability with yield among the best clones, WI56 was top ranking but 570, the second best, was more stable across locations.

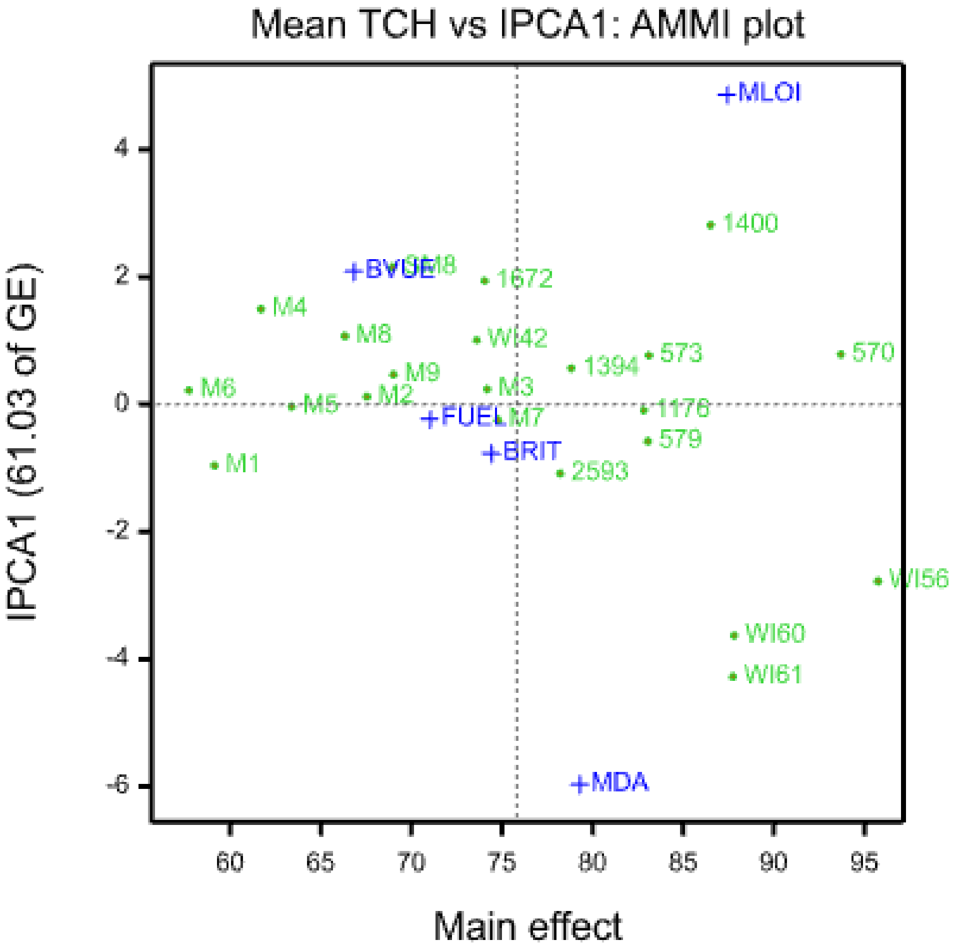


Figure 4-1: AMMI1 biplot for cane yield across locations

Among the best performing genotypes, commercial varieties 1400 and 570 clustered closer to MLOI, while WI60 and WI61 and WI56 regrouped more towards MDA. This interaction trend is more discernible with the AMMI biplot with the first two principal components (IPCA1 and IPCA2) (Figure 4-2). Genotypes in a quadrant were expected to be adapted to locations in that quadrant. The most stable clones clustered towards the origin. Genotypes that showed best positive interaction at MDA were WI60, WI61 and WI56, as explained by the perpendicular projections on the environment vector. On the other hand, 1672, found on the negative direction of the vector showed negative interaction with the super-humid environment of MDA. Similar observations could be made for the other environments. For instance, SM8 and 1400 showed good positive GEI with MLOI.

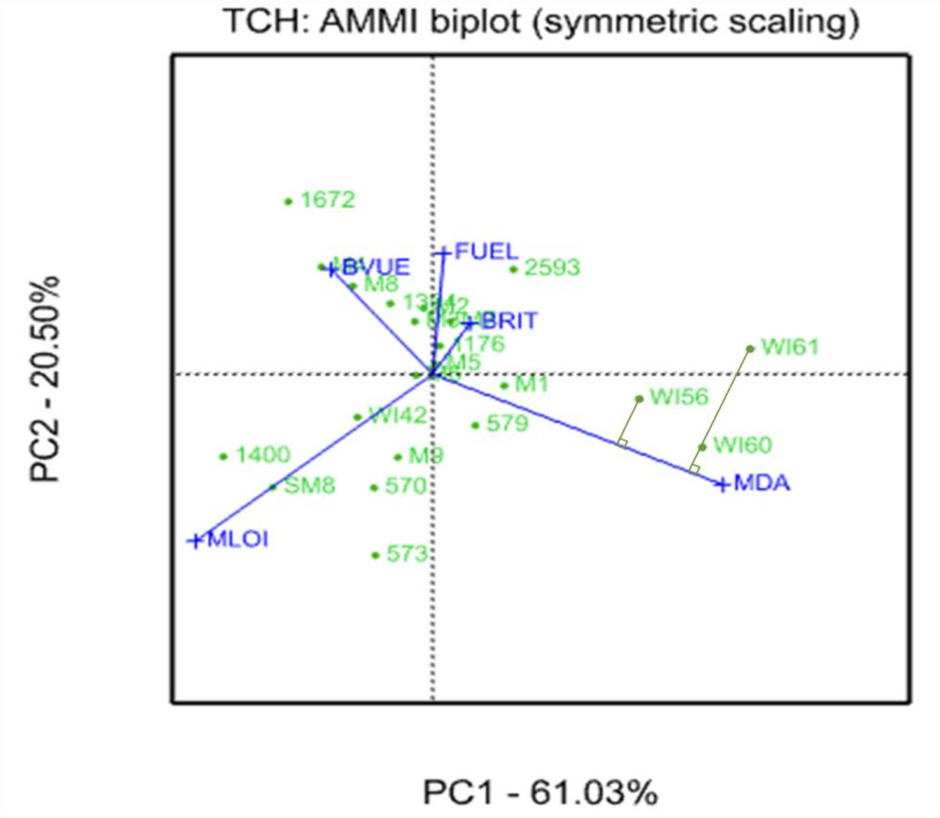
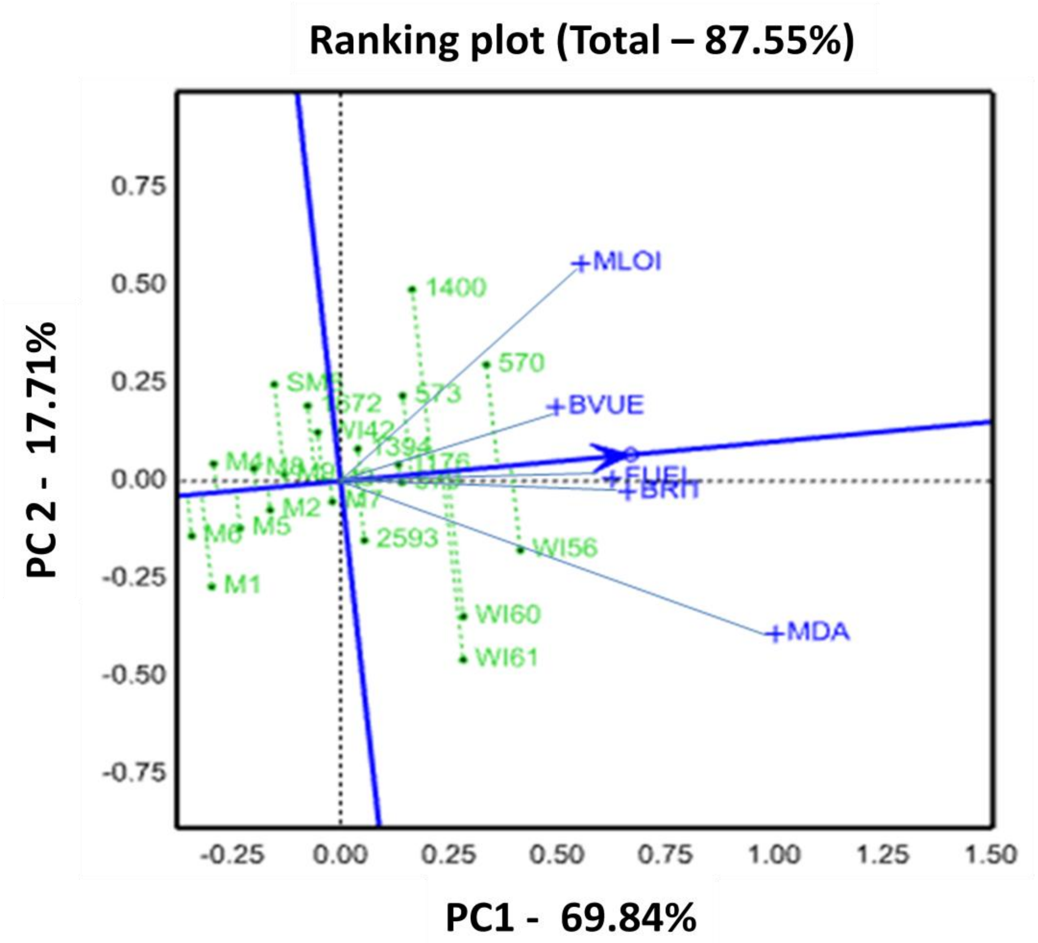


Figure 4-2: AMMI2 model biplot for cane yield across locations

4.3.1.2 GGE evaluation of test environments

Figure 4-3 is the environment vector view of the GGE biplot for the variety-location data. It is based on an environment-centred GE table without any scaling. The biplot explained 88% (70% by PC1 and 18% by PC2) of total variation of both genotype and GEI combined. The angle between any two environment vectors approximated the correlation between them. The distance between two environments measured the dissimilarity in discriminating the genotypes. Thus, FUEL and BRIT would give almost similar GEI results, but generally different from MLOI and

MDA. The length of the environment vectors measured the discriminating ability of the environments. MLOI and MDA were thus the most informative locations. In Figure 4-3, an Average Environment Coordination (AEC), represented by a small circle, is included in the graph that corresponds to an "ideal environment" in Mauritius.



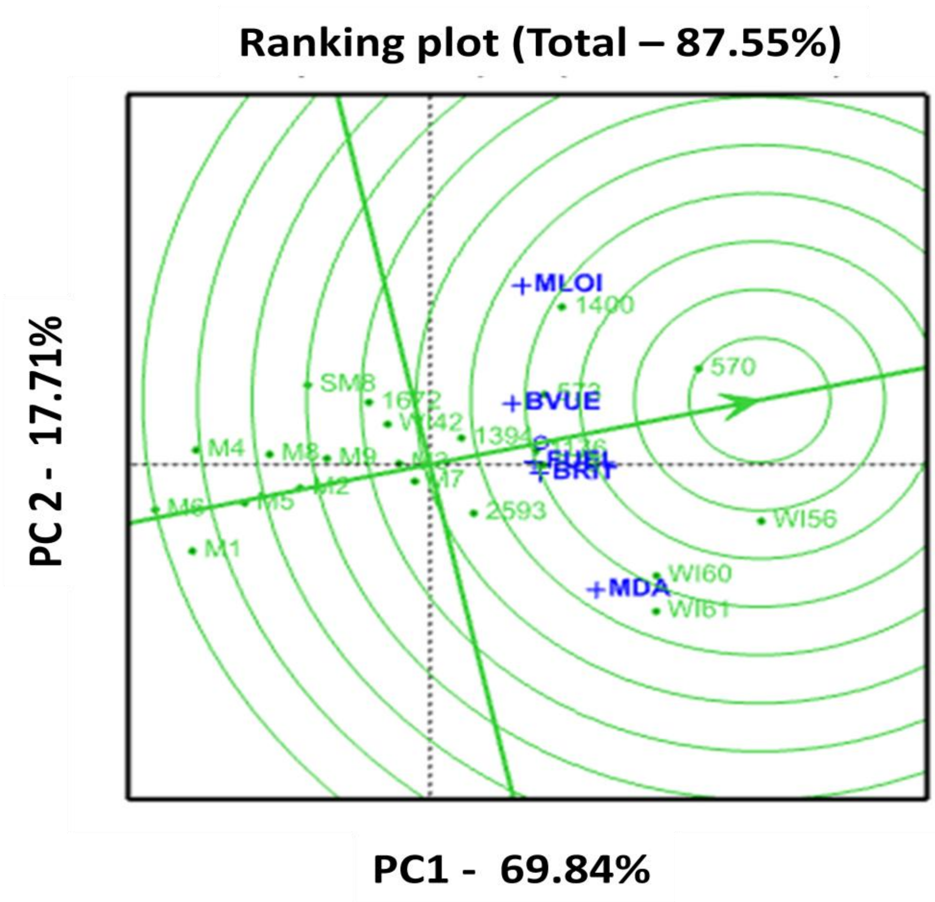
○ : *Average Environment Coordination (AEC)*

Figure 4-3: GGE biplot – relationship among environments

The average environment axis (AEA) is represented by a single arrowed line that passes through the origin. Test environments having smaller angle with the AEA (e.g. FUEL, BRIT) were more representative of the other test environments. Environments that were both discriminating and representative were good test environments for generally adapted varieties. Discriminating but non-representative test environments (e.g., MLOI and MDA) were useful for specifically adapted varieties. Genotypes to the left of the thick perpendicular line to the AEA passing through the origin demarcated below average performance. The perpendicular lines of genotype to the AEA pointed to the ranking of the genotypes in relation to the ideal environment. The pattern of the environments in the above biplot suggested that, for general adaptation, the environments of FUEL and BRIT were most representative but lacked the discriminating ability. MDA and MLOI represented two contrasting discriminating environments for specific adaptation. In general, thus, the pattern pointed to the presence of three mega-environments, the dry irrigated land of MLOI, the super-humid environment of MDA and the remaining three locations grouped together.

4.3.1.3 GGE evaluation of test genotypes

For evaluations on genotypes with GGE biplot, genotype focused scaling was used. Figure 4-4 defines an ideal genotype (the centre of the concentric circles) to be a point on the AEA ("absolutely stable") in the positive direction and has a vector length equal to the longest vectors of the genotypes on the positive side of the AEA (Yan and Tinker, 2006). The concentric circles help visualize the distance of the different test clones from the ideal genotype.



○: *Average Environment Coordination (AEC)*

Figure 4-4: GGE biplot - mean yield and stability of genotypes

Genotypes located on the ideal genotype axis were most stable and those further away (perpendicular to the AEA) were more unstable. Thus, M2, M3, M5, M6, M7 and 1176 were the most stable clones. In Figure 4-4, genotypes located closer to the ideal genotype were more desirable than others. From the biplot, WI56 was the highest cane yielder. However, 570, the second best ranking genotype, ensured high yield and higher stability than WI56 across locations. These results were similar to those obtained from AMMI1 biplot (Figure 4-1).

4.3.1.4 GGE - Which-won-where indications

GGE biplot has an attractive feature to show a “which-won-where” pattern in a genotype by environment dataset (Figure 4-5). The polygon connects the furthest genotypes from the biplot origin. Genotypes located on the vertices of the polygon performed either the best or the poorest in one or more environments. Perpendicular lines to each side of the polygon represent equality lines that divide the biplot into sectors. The difference between two genotypes varies by environment, being proportional to the distance of the environment to the equality line (Yan and Tinker, 2006).

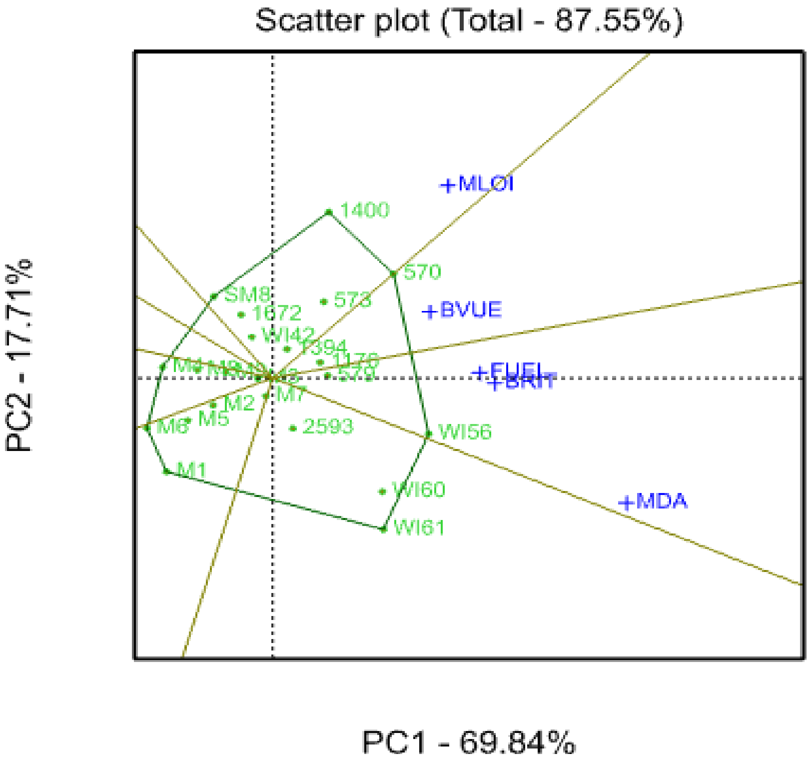


Figure 4-5: Environment-centred which-won-where view of the GGE biplot to show which genotype performed best in which environment

In Figure 4-5, the equality line between 1400 and 570 indicated that (a) the difference between 1400 and 570 was negligible at MLOI, (b) 570 was more stable than 1400 in the two environments and (c) 1400 performed best at MLOI and 570 at BVUE. Similarly, the equality line between 570 and WI56 indicated that 570 did better at MLOI and BVUE whereas WI56 was better in the remaining environments. The winning genotype for each sector was the one located on the respective vertex. In consequence, 1400 was the winner at MLOI, 570 at BVUE and WI56 at FUEL, BRIT and MDA.

The angles between the vectors of WI61 and WI60 with those of the environments MDA, BRIT and FUEL were acute, indicating positive interactions of the clones in those locations. Other vertices represented by M1, M6, M4 and SM8 were poor yielding genotypes generally showing negative interactions (obtuse angles) with the five locations. Furthermore, the delineation into sectors tended to categorize Mauritius into two mega-environments: BRIT, FUEL and MDA formed one group and, BVUE and MLOI formed another.

4.3.1.5 Cross-validation of trends across locations

The strengths of the relationships among locations were verified using basic statistics and correlations (Table 4-5). The Pearson's correlations of genotype means among locations were generally significant ($P < 0.05$) and the highest positive associations were obtained between BRIT and FUEL ($r = 0.79^{***}$), and between BRIT and MDA ($r = 0.82^{***}$). Least correlation coefficient was obtained between MDA and MLOI ($r = 0.34^{ns}$). Spearman's rank correlations gave similar trends indicating that the ranks of genotypes experienced minimum changes at BRIT, FUEL and MDA ($\rho \approx 0.8^{***}$). Ranking of genotypes was mostly affected between MLOI and FUEL ($\rho = 0.47^{*}$) and between MLOI and MDA ($\rho = 0.52^{*}$). These findings support the biplots trends by confirming that experiments at MDA, BRIT and FUEL would give almost the same results while the ranking would change considerably at MLOI. The environment of BVUE appeared to be closer to FUEL and Mon Loisir.

Table 4-5: Basic statistics and correlations of means of individual genotypes across locations

	BRIT	**BVUE**	**FUEL**	**MDA**	**MLOI**
Pearson's correlations					
BVUE	0.71***				
FUEL	0.79***	0.62**			
MDA	0.82***	0.52*	0.70***		
MLOI	0.51*	0.61**	0.48*	0.34^{ns}	
Spearman's rank correlations					
BVUE	0.70***				
FUEL	0.79***	0.66***			
MDA	0.86***	0.53*	0.79***		
MLOI	0.55**	0.65***	0.47*	0.52*	
Mean yield (t ha^{-1})	74.45	66.86	71.04	79.32	87.43
Min (t ha^{-1})	49.18	35.57	38.89	48.47	58.89
Max (t ha^{-1})	103.91	91.89	93.99	130.73	125.26
SD genotype	12.85	11.07	12.25	19.30	14.75

*ns: non-significant; *: significant at P = 0.05; **: significant at P = 0.01; ***: significant at P = 0.001*

A measure of the discriminating ability of the different environments could be verified by the variance among genotypes within locations. The higher the variance among genotypes in a location, the higher would be the discriminating ability. The standard deviations (SDs), as a measure of variance, were highest at MDA (SD = 19.30 t ha^{-1}) and lowest at Belle Vue (SD = 11.07 t ha^{-1}) (Table 4-5). These results corresponded to the lengths of the environment vectors in the preceding biplots.

4.3.2 Variety by crop cycle interaction

4.3.2.1 AMMI and GGE analyses

The AMMI ANOVAs for GEI within two individual locations are given in (Table 4-6). The main effects and the interactions var x cc were significant ($P < 0.05$) in both trials and the treatment combinations accounted for >80% of total variation. About 8% were attributable to variety by crop cycle interaction (var x cc).

Table 4-6: AMMI analysis of variance within each location

Source	df	SS	MS	F	F pr	Explained %	Accumulated %
Site: MDA							
Rep	6	4182	697	5.21	<0.001	3%	
Treatments	41	129212	3152	23.57	<0.001	90%	
Genotypes (var)	13	63032	4849	36.26	<0.001	44%	
Crop cycle (cc)	2	56509	28254	40.54	<0.001	39%	
var x cc	26	9671	372	2.78	<0.001	7%	
IPCA 1	14	7438	531	3.97	<0.001	77%	77%
IPCA 2	12	2233	186	1.39	0.1879	23%	100%
Residuals	0	0				0%	
Error	78	10431	134			7%	
Total	125	143825	1151				
Site: MLOI							
Rep	6	6432	1072	8.18	<0.001	6%	
Treatments	47	86114	1832	13.97	<0.001	83%	
Genotypes (var)	15	31810	2121	16.17	<0.001	30%	
Crop cycle (cc)	2	45246	22623	21.1	<0.001	43%	
var x cc	30	9059	302	2.3	0.0013	9%	
IPCA 1	16	6720	420	3.2	<0.001	74%	74%
IPCA 2	14	2338	167	1.27	0.2394	26%	100%
Residuals	0	0				0%	
Error	90	11801	131			11%	
Total	143	104347	730				

F pr: F-probability; IPCA: Interaction Principal Component Analysis; var x cc: variety by crop cycle interaction

Two interaction principal components (IPCA1 and IPCA2) explained the total variations in the GEI. In each environment, IPCA1 captured about 75% of the interaction information and was highly significant ($P < 0.01$). IPCA2 explained the remaining GEI variations and was non-significant.

Figure 4-6 displays the corresponding AMMI1 biplots for MDA and MLOI while Figure 4-7 shows the environment focused GGE biplot.

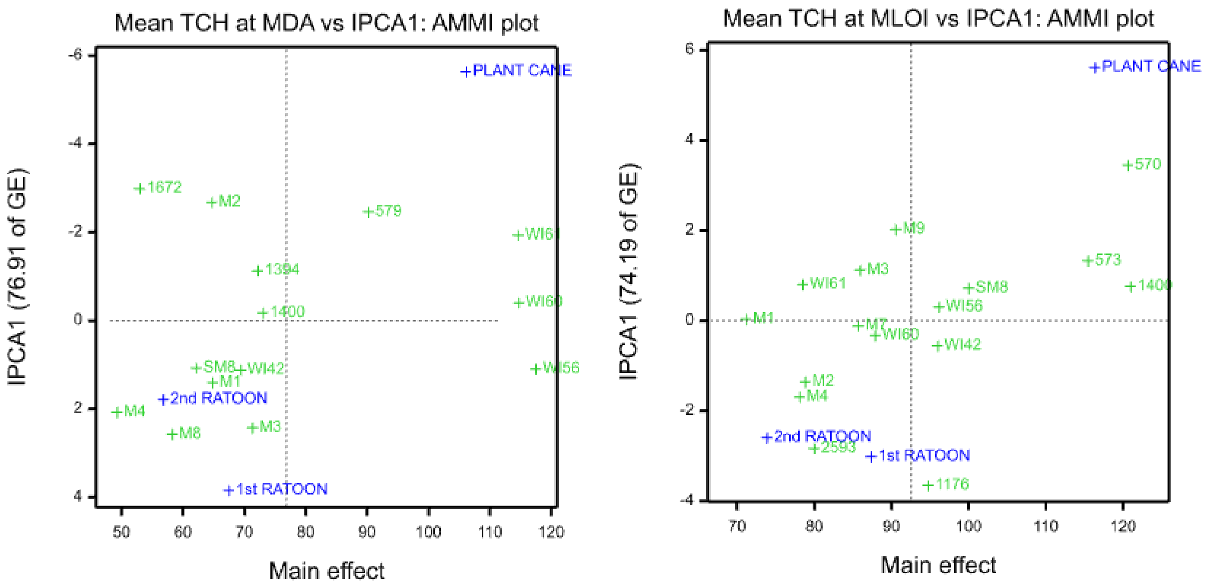
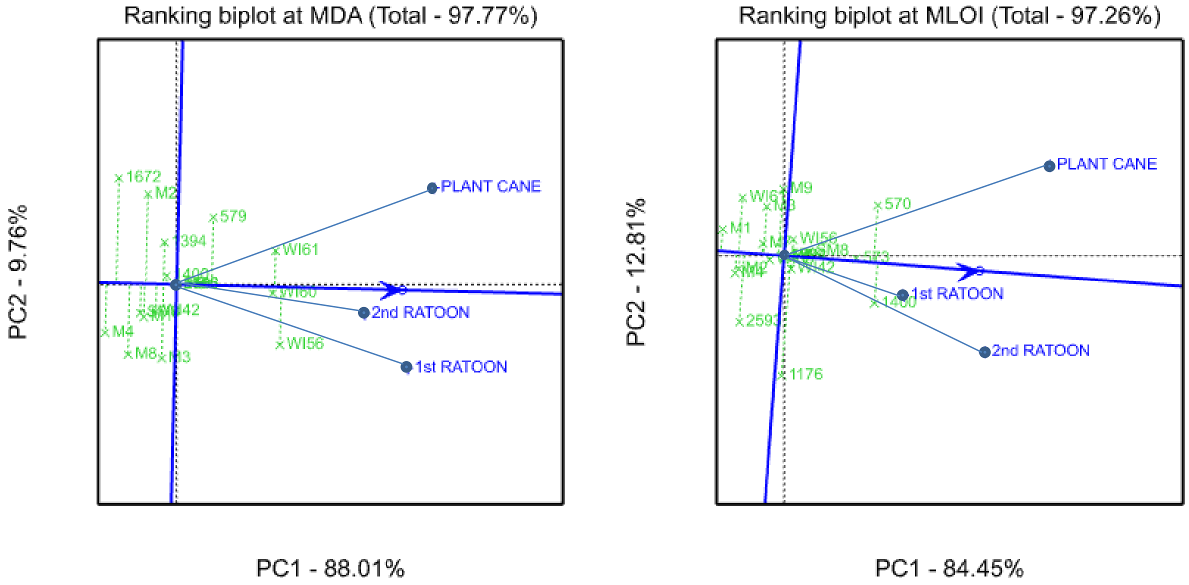


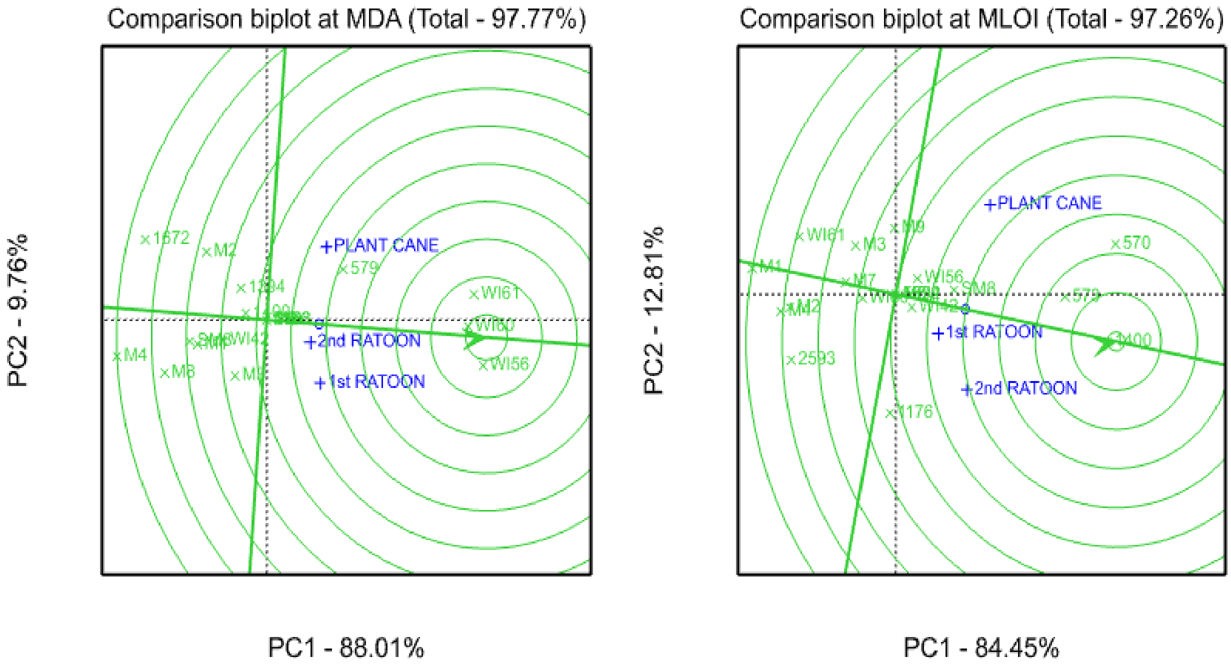
Figure 4-6: AMMI1 biplot of variety-crop cycle interaction in two locations



○: *Average Environment Coordination (AEC)*

Figure 4-7: Environment focused GGE biplots of genotypes and crop cycles in two locations

The plant cane crop ensured the highest cane yield and was most discriminative. However, it was least representative of performance in ratoons (Figure 4-7). The acute angle between first and second ratoon crops showed the close similarity between the two crop stages in providing the same GEI information. Both ratoon crops were generally more representative to the ideal crop cycle, characterized by the acute angle with the AEC. The West Indies clones were generally most stable and high yielding across crop cycles at MDA (Figure 4-8).



○ *: Average Environment Coordination (AEC)*

Figure 4-8: Genotype focused GGE biplots of genotypes and crop cycles in four locations

Commercial variety 1400 was the most stable at both sites and represented the ideal variety at MLOI. Clones showing high positive interactions with plant cane were least desirable. From Figure 4-8, clone 579 at MDA and 570 at MLOI showed such tendency. Conversely, clones showing positive interactions with ratoon crops, such as 1176 at MLOI, were more advantageous as the gain would be higher across years.

4.3.2.2 Cross-validation of trends across crop cycles

In an attempt to cross validate the above results across crop cycles, conventional split-plot ANOVA was used within each location where genotypes were assigned as main plot and crop cycle as sub-plot (Table 4-7). Appropriate least significant differences (LSDs) were used to verify any significant difference among the crop cycle means. In spite of the close similarity of ratoon crops, the crop cycle means were systematically and significantly different from one another at each location. The means on their own were therefore not that much informative. The performance and ranking of genotypes within the different crop cycles were felt more instructive in the cross-validation process.

The correlation coefficients of genotype means across crop cycles were significant ($P < 0.05$). Pearson's correlation coefficients generally confirmed the relatively lower associations between plant cane means and those of other crop cycles than between first and second ratoon crops. Spearman's rank correlation showed similar trends, though at a lower magnitude, especially at

MDA. These results confirmed the observations made with the biplot displays with respect to the dissimilarity of plant cane with ratoon crops.

Table 4-7: Basic statistics and correlations across crop cycles within each location

	MDA	**MLOI**
PC - mean yield	106.15	116.40
1R - mean yield	67.51	87.40
2R - mean yield	56.86	73.91
LSD (crop cycle)	4.32	4.96
Pearson's correlations		
PC vs. 1R	0.76**	0.72**
PC vs. 2R	0.83***	0.71**
1R vs. 2R	0.90***	0.85***
Spearman's rank correlation		
PC vs. 1R	0.50*	0.71**
PC vs. 2R	0.78**	0.68**
1R vs. 2R	0.70***	0.91***

: significant at P = 0.05; **: significant at P = 0.01; *: significant at P = 0.001*

4.4 Discussion

In this study, both AMMI and GGE methods defined the most stable genotypes across locations. However, high stability could be worthless if not also associated with high mean performance. Broadly, the best yielding genotypes were three West Indies clones, WI 79460 (WI60), WI 79461 (WI61) and WI 81456 (WI56), and two commercial varieties, M 1400/86 (1400) and R 570 (570) (Table 4-8). WI 81456 was the overall best yielder. However, R 570, the second best, was more stable across locations. The West Indies genotypes were exploitable mainly for their fibre for bioenergy production (Rao and Kennedy, 2004; Rao *et al.*, 2007). This study established their adaptation and stability in Mauritius. Those high fibre canes were exploitable in the humid environments of the island. The drier regions were more suitable for sugar production using existing commercial varieties. Except 570, all clones showed high stability across ratoons.

Table 4-8: Summary of GEI of the most promising varieties

			Stability		**Adaptation**
Genotype	**Code**	**Cane yield**	**Locations**	**Ratoons**	**Best environment(s)**
M 1400/86	**1400**	High	Average	High	MLOI (dry irrigated)
R 570	**570**	High	High	Average	BVUE (dry rain fed)
WI 81456	WI56	High	Average	High	MDA, BRIT, FUEL (humid, super-humid)
WI 79460	WI60	High	Low	High	MDA, BRIT, FUEL (humid, super-humid)
WI 79461	WI61	High	Low	High	MDA, BRIT, FUEL (humid, super-humid)

In Mauritius, recommendation domains for sugarcane cultivation have traditionally been based on soil types, irrespective of other environmental conditions prevailing in the region. However, conflicting economic factors are now exerting pressure on breeding programmes to become more efficient and produce more productive varieties while reducing costs. Studies to redefine agronomic zones based on tangible evidence on adaptation have never been attempted. The results from this study gave preliminary indications of the presence of mega-environments different from the classical description. The lengths and angles of environment vectors categorized the five locations into three mega-environments that pertained to the dry, humid and super-humid regions of the island. However, the "which-won-where" approach identified two major environments: the dry areas in the northern low-lands and the humid central regions. Cross-validation of the trends across locations favoured the GGE "which-won-where" classification. More precise demarcation of environments requires a full-fledged study with additional years of information from several locations. The biplot approach seems appropriate and can also help reduce the cost of extensive genotype evaluation by eliminating unnecessary testing sites. For instance, two sites, BRIT and FUEL, gave very similar results. One of them could be safely removed without losing information on the genotypes.

In countries where sugarcane is planted once and harvested over several years, stable performance of varieties across successive harvests is crucial. From this study, it was clear that plant cane alone was a poor predictor of performance across ratoons. The precision in selection could be increased by minimizing the importance of plant cane results and focusing on varieties that are stable and showing positive interactions with ratoons. The biplots provided information on varieties that tended to respond positively to plant cane and negatively to ratoon crops. Those varieties, although impressive in the first year, may lead to incorrect choice if results are based on first year data only. Conversely, greater attention needs to be given to high yielding genotypes with positive interactions across ratoons. Those clones would ensure higher yields with time. In parts of Brazil where selection is based on first two harvests, a selection model is adopted (TCH_5) whereby the weight given to plant cane is minimized by nearly one fifth and the remaining weights are assigned to the first ratoon crop (Silva *et al.*, 2014). At eRcane research station in Reunion Island, data is traditionnally avoided at plant cane at early stages of selection. On the other hand, Mamet and Domaingue (1999) found that, at early selection stages, selection could be as effective in plant cane as in ratoons. These observations point to more intensive investigations on ratooning ability of new genotypes at different stages of selection programmes and the relative weight that need to be given to plant cane data. The findings of this study, however, were conclusive on the disparity between plant cane and ratoon crops.

4.5 Conclusions

This study indicated the presence of two major environments in Mauritius: the dry zone in the northern plains and the humid central regions. Clones WI 79460, WI 79461 and WI 81456 and two commercial varieties, M 1400/86 and R 570, were among the best cane yielders. The West Indies clones were adapted to the humid environments while the commercial varieties were superior in the dry zone. Clone WI 81456 was the overall best biomass yielder, but R 570, the second best, was more stable across environments. The results also confirmed that plant cane results were least representative of the performance of varieties across ratoons and ranking of genotypes changed more drastically between plant cane and ratoon crops than between the ratoon crops. The best biomass varieties were generally stable across ratoons.

Additional years of information from several locations and crop cycles hold the potential of drawing a better demarcation of the sugarcane recommendation domains in Mauritius and improve selection precision by applying the appropriate weights to crop cycles at different selection stages. The biplot techniques are suitable tools for such analyses. Both AMMI and GGE analyses produced very interesting biplot displays that are useful for quick visualization and exploration of patterns inherent in the complex GE two-way tables. A point of caution is that biplots have no uncertainty measures and cannot be used directly for statistical tests. They are simply easier and faster to convey and grasp than tabular numerical information. Researchers should consider additional methods beyond this simple function if inferential statistics are felt important.

Chapter 5

Physiological studies on biomass accumulation in different types of sugarcane varieties

Comment from author:

- This Chapter is being submitted for publication.

5 Physiological studies on biomass accumulation in different types of sugarcane varieties

Abstract

Various studies were carried out on the sucrose accumulation pattern in contrast to fibre content that is gaining in importance for bioenergy production. This study was conducted to assess the accumulation pattern of both sucrose and fibre among different types of high biomass cane varieties. Twelve genotypes, consisting of five commercial control varieties, two high-sucrose-high-fibre clones and five low-sucrose-high-fibre clones, were earmarked for the analysis. These genotypes were commonly found in two variety trials implemented in randomized complete block designs with three replicates. Five monthly samples, starting from pre-harvest season in early May to mid-season harvest in September, were taken from the first ratoon crop in 2011. Genetic variance at each sampling date was measured in terms of broad sense heritability estimate (*H*) and genetic coefficient of variance (GCV). Broadly, all the genotypes followed the same trend in terms of total biomass accumulation, with a sharp rise from May to June (pre-harvest season) and a tendency to flatten thereafter. The trends in total biomass were highly influenced by sucrose accumulation pattern that showed a drastic rise at the pre-harvest season. Fibre content was generally found to be stable across the whole sampling period. Although it increased linearly and marginally up to September, variety by month interaction was found non-significant. Few genotypes showed high sucrose at early harvest and declined very rapidly. The genetic variances, *H* and GCVs were lowest for sucrose content in May and highest during the first half of the harvest season (June to September). Spearman's rank correlations also showed that highest changes in rank for sucrose content occurred between May and June. These findings confirmed that sampling for Pol % would be least effective when taken further away from the harvest season. Fibre content, on the other hand, showed high stability and relatively constant genetic variance and GCV and least rank changes in time. The study also elucidated the efficiency of using fresh and dry weight estimates of the cane quality traits.

Keywords: sugarcane, biomass, selection efficiency, sucrose and fibre accumulation

5.1 Introduction

Biomass accumulation in conventional sugarcane varieties essentially pertains to partitioning of photosynthates into soluble solids (mostly sugar) and fibre in the cane stem. The sugarcane crop cycle has been reported to comprise distinct vegetative (tillering and elongation), ripening (sucrose accumulation) and senescence phases (Soopramanien, 1979). During the vegetative phase, dry matter is partitioned in favour of fibre and reducing sugars (glucose and fructose) as opposed to sucrose (Alexander, 1973). Under unfavourable conditions for growth, around 80% of the biomass fixed is deposited as sucrose in mature internodes (Glasziou and Bull, 1967; Soopramanien, 1979; Soopramanien and Julien, 1980). A marked reduction in reducing sugars (glucose and fructose) accompanies this ripening process (Julien and Delaveau, 1977; Mamet, 1992). After peak maturation, in general, very few new leaves are formed whilst older leaves senesce and sucrose storage slows down. The plant uses stored sucrose for maintenance and hence the sucrose concentration declines (Mamet, 1992). The effect is known to vary with normal non-flowering stalks, flowering stalks, flowering stalks that form side shoots and those that do not form side shoots (Van Dillewijn, 1952).

In most major sugarcane producing areas of the world, gains in sugar yield have closely paralleled gains in cane yield (Simmonds, 1976; Tew, 1987; Hogarth *et al.*, 1997; Moore *et al.*, 1997; Ming *et al.*, 2006; Silveira *et al.*, 2015). In an experiment that compared all major commercial varieties grown in Barbados during the period of 1930 to 1985, Kennedy (2000) showed that gains from breeding and selection for cane yield were in the order of 1 tonne yr^{-1}, whereas there was no increase in sugar quality over the same period. In spite of its relatively high heritability, progress for sucrose content as a character has been rather limited. The lack of improvement of sugar content in more tropical varieties can be attributed, at least in part, to relatively low genetic variability for this character in mature cane as compared to cane yield (Hogarth *et al.*, 1981). In most genetic studies that have partitioned sucrose yield into its component parts (Miller, 1977; Kang *et al.*, 1983; Milligan *et al.*, 1990), authors have similarly concluded that cane yield is generally more important than sucrose content in determining sucrose yield, and stalk population is more important than stalk weight in determining cane yield. Thus, genetic improvement of sucrose yield will likely continue to be most effectively accomplished by selecting for cane yield through increasing stalk population, provided that sucrose content is not compromised (Tew and Cobill, 2008).

Various studies done in Mauritius on sucrose accumulation pattern have shown that optimum ripening is influenced by climate, planting date, time of harvest and variety (Julien, 1974; Julien and Soopramanien, 1976; Julien and Delaveau, 1977; Soopramanien and Julien, 1980; Mamet, 1992). The ripening phase starts with the onset of winter, about the month of April-May. The sugarcane harvest season extends from mid-June to mid-December, with peak sucrose contents in most varieties being reached around the months of September and October. Different varieties mature at different periods within the harvesting season. Commercial varieties have thus been categorized in three major groups, the early-maturing, late-maturing and high-sucrose types (MSIRI, 2001). Recent studies have identified a fourth category, the very early type of varieties that start accumulating sucrose as from March (Badaloo *et al.*, 2005; Nayamuth *et al.*, 2005).

While sucrose accumulation pattern has been adequately documented, studies are lacking on the evolution of fibre content across time. Fibre is believed not to vary during the course of the year as happens with sugar; fibre accumulates with time and so, in effect, it is stored in the field (Matsuoka *et al.*, 2014). This hypothesis needs to be verified under local sub-tropical conditions within the broader perspective of generation of sugarcane biomass as a feedstock for bioenergy production year-round. Furthermore, from the selection efficiency standpoint, data collection should be carried out when the genetic variance is highest. Various studies done under the local conditions have found higher genetic variations for sucrose content in March/April than in July (Mamet *et al.*, 1996; Badaloo *et al.*, 2005; Nayamuth *et al.*, 2005). The objective of this study was to assess the accumulation pattern of biomass, in the form of sugar and fibre, among different types of sugarcane varieties at different points in time and crop age. The study also aimed at establishing the peak genetic variance and impact on selection when data were collected at different crop age and periods of the year.

5.2 Materials and methods

5.2.1 Trials and type of varieties

Two of the five variety trials described in the previous chapter were used for the study: One trial was established in the dry irrigated region at Mon Loisir (MLOI) in the northern plains of the island (Table 5-1). The second was established at Britannia (BRIT) in the humid rain-fed environment in the southern part of the island. Data were collected in the first ratoon crop. At both locations, 12 common genotypes were sampled for cane quality assessment on a monthly interval from May until September, which corresponded to five sampling rounds as from eight month old crops. All data were collected in the first week of each month. The genotypes included five commercial controls with relatively high sucrose and low fibre (*Type 1 canes*), two enhanced fibre type (*Type 2* canes) with relatively high sucrose and high fibre and five relatively higher fibre and lower sucrose clones (*Type 3* canes).

Cane samples, comprising ten clean millable cane stalks, were taken from each plot for the determination of cane quality parameters from laboratory analyses as described in page 31.

Table 5-1: Details of two trials and genotypes sampled at five monthly pre-harvest periods

Harvest season	Mid-season (September)	
Location	Mon Loisir (MLOI)	Britannia (BRIT)
Environment	Dry irrigated	Humid rain-fed
Rainfall (mm)	1200	2300
Altitude (m)	10	180
Year planted	2009	2009
Crop cycle	1st ratoon	1st ratoon
Sampling frequency	Monthly (early May to early September)	
Cane types (common in both trials)		
Type 1 canes (commercial type): High sucrose, low fibre	M 1176/77, M 1400/86, M 2593/92, R 570 and R 573	
Type 2 canes (enhanced fibre type): High sucrose, high fibre	M 733/90 and M 816/90	
Type 3 canes (multi-purpose type): Low sucrose, higher fibre	M 1303/87, M 1395/87, WI 79460, WI 79461 and WI 81456	

5.2.2 Statistical protocol and genetic parameters

The trials were implemented in Randomized Complete Block designs with three replicates. A split-split-plot model was adopted for the analysis where location was assigned as whole plot, variety as sub-plot and sampling date as sub-sub-plot. The model formula could be described as follows:

$$Y_{ijkl} = \mu + L_i + R\,(L)_{ij} + G_k + GL_{ik} + RG\,(L)_{ijk} + M_l + ML_{il} + MG_{kl} + GML_{ikl} + \varepsilon_{ijkl} \qquad \text{[Eq. 1]}$$

where Y_{ijkl} is the observation for Genotype k, in Month l, in Location i, in Rep j nested within Location i, μ is the overall mean (fixed), $L_i$represents the effect of ith location, $R\,(L)_{ij}$, the effect of jth replication nested within the ith location, G_k represents the effect of the kth genotype, GL_{ik} equals to the interaction of the kth clone with the ith location, $RG\,(L)_{ijk}$ represents the interaction genotype k and replication j nested within location i, M_l is the effect of the lth month, ML_{il}, the interaction of the lth month with the ith location, MG_{kl}, the interaction of the kth clone with the lth month, GML_{ikl} is the interaction term between the kth clone, the lth month and the ith location and ε_{ijkl} equals to the random residual term associated with Y_{ijkl}.

Locations, varieties, months and their interactions were considered fixed and the interactions with replicates as random. Genetic parameters, namely, genetic variance (σ_g^2), phenotypic variance (σ_p^2), genetic coefficient of variance (GCV) and broad sense heritability estimates (H) were determined from the combined trials across locations at each sampling date. The genetic parameters were calculated using the standard methodology (Wricke and Weber, 1986) as follows:

Genetic and phenotypic parameters from the whole analysis were:

$$\sigma_g^2 = \frac{MS_{var} + MS_{var.loc.month} - MS_{var.month} - MS_{var.loc}}{rlm} \quad \text{[Eq. 2]}$$

$$\sigma_p^2 = \sigma_g^2 + \frac{\sigma_{gl}^2}{l} + \frac{\sigma_{gm}^2}{m} + \frac{\sigma_{glm}^2}{lm} + \frac{\sigma_e^2}{rlm} \quad \text{[Eq. 3]}$$

Genetic and phenotypic parameters at individual months were calculated as follows:

$$\sigma_g^2 = \frac{MS_{var} - MS_{var.loc}}{rl} \quad \text{[Eq. 4]}$$

$$\sigma_p^2 = \sigma_g^2 + \frac{\sigma_{gl}^2}{l} + \frac{\sigma_e^2}{rl} \quad \text{[Eq. 5]}$$

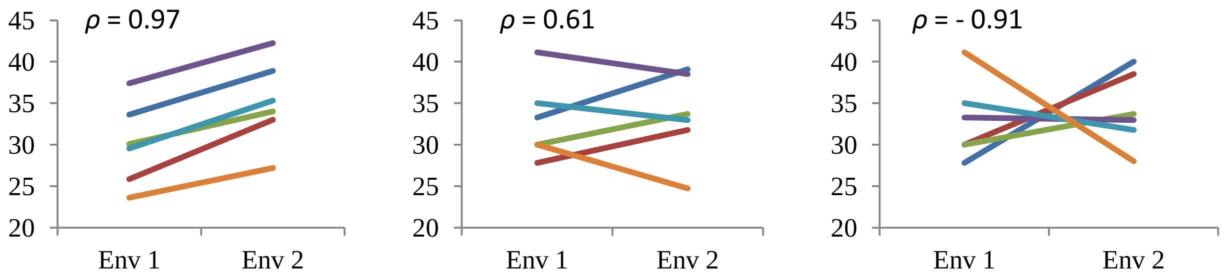
The derived genetic parameters from the above equations were:

Broad sense heritability = $H = \sigma_g^2 / \sigma_p^2$ [Eq. 6]

Genetic coefficient of variation % = GCV = $\frac{\sqrt{\sigma_g^2}}{\bar{x}} \; x \; 100$ [Eq. 7]

where MS represents Mean Square, g and var equal variety, l and loc represent location, m equals month, r is replicate, e is the experimental error and $\bar{x}$, overall average.

The differential performance across time was crucial in this study. The magnitudes of the interactions were measured using Spearman’s rank correlation coefficients as follows: assuming a set of varieties are tested in two environments (Figure 5-1), the magnitude of *var x loc* interaction could be measured by rank correlation coefficients obtained from the rank of the means of individual varieties across the two environments. When ρ = 1.0 then all lines would be parallel to one another (no interaction). Values close to 1.0 would suggest low interaction with minimal changes in rank. The interaction may be non-significant. Lower ρ -values would indicate higher interaction and changes in rank while values close to -1 would point to very high proportion of cross-over type of interaction. Genstat -17th edition (Payne *et al.*, 2014) software was used for the various analyses.



High ρ-values: low interactions and changes in rank

Lower ρ-values: higher interactions and changes in rank

Negative ρ-values: very high proportion of cross-over type of interactions

Figure 5-1: Simulation studies on magnitude of interaction and interaction correlation coefficient values

5.3 Results

5.3.1 Overall analysis of variance and genetic parameters

The overall univariate analysis of variances confirmed that the location main effect was non-significant at 99% probability for all the variables (Table 5-2). Genotypes and their first order interactions with locations (var x loc) and months (var x month) were very highly significant. One exception of high importance was the variety by month (var x month) interaction for fibre content that was non-significant. The second order interactions involving the three main effects were non-significant at P = 0.001 but significant at P = 0.05 for all the traits.

Table 5-2: Significance tests of main effects and their interactions

Main factors	Brix	Pol %	Fibre %	DM %
loc	0.958	0.417	0.033	0.149
var	<.001	<.001	<.001	<.001
loc x var	<.001	<.001	<.001	<.001
month	<.001	<.001	<.001	<.001
loc x month	<.001	<.001	<.001	<.001
var x month	<.001	<.001	0.143	<.001
loc x var x month	0.004	0.012	0.006	0.001

Highlighted cells: Not significant at P = 0.001;
loc: location; var: variety; DM: dry matter

The mean values of the individual genotypes averaged over location at each sampling month are presented in Table 5-3. With the multiple level of blocking, the standard error of differences (SEDs) and the least significant differences (LSDs) varied with the strata of analyses. Those differences for the individual cane quality traits are given in Table 5-4 and the appropriate values were used for specific contrasts.

Table 5-3: Mean values of genotypes at different months averaged over locations

Genotypes	**M1176/77**	**M1400/86**	**M2593/92**	**R570**	**R573**	M1303/87	M1395/87	M733/90	M816/90	WI79460	WI79461	WI81456
Brix %												
May	9.12	8.83	9.33	9.05	10.62	7.73	7.95	9.68	9.23	7.22	8.62	8.92
Jun	13.55	14.08	13.40	13.83	14.38	10.40	12.13	14.22	14.25	10.98	12.10	10.68
Jul	14.58	14.73	14.75	14.37	15.85	9.53	12.95	14.53	15.00	11.25	12.68	10.80
Aug	15.12	15.03	14.83	13.99	15.61	8.84	12.43	14.23	14.22	10.14	11.65	10.87
Sep	15.10	15.30	15.22	14.97	15.87	9.15	11.87	13.30	13.30	10.83	12.20	11.25
Pol %												
May	4.90	4.64	5.28	5.26	7.18	4.50	4.33	6.13	6.23	4.13	5.03	5.80
Jun	9.95	11.08	10.02	11.06	11.82	7.93	9.01	11.55	11.76	8.52	9.21	7.93
Jul	11.26	12.18	12.09	12.04	13.75	7.32	10.51	12.24	12.61	8.90	10.08	8.26
Aug	12.56	12.90	12.58	12.14	13.74	7.03	10.17	12.18	12.11	8.21	9.51	8.42
Sep	12.63	13.14	12.96	13.27	14.09	6.96	9.63	11.18	11.18	8.83	10.03	9.09
Fibre %												
May	8.78	9.12	9.12	10.95	11.43	19.37	15.53	12.70	12.20	17.40	17.00	18.48
Jun	9.33	9.52	10.08	11.50	11.80	20.82	16.35	13.88	12.45	19.47	17.45	18.03
Jul	10.92	10.65	10.97	12.15	12.45	21.08	17.47	14.50	12.62	19.95	18.73	18.72
Aug	10.35	11.08	11.01	12.48	12.51	22.41	17.48	14.09	14.46	20.59	18.97	18.96
Sep	11.43	10.20	11.52	12.68	12.70	21.30	18.70	13.57	12.75	20.93	19.65	20.63
Dry matter %												
May	17.88	17.97	18.42	20.00	22.03	27.07	23.50	22.37	21.40	24.60	26.00	27.38
Jun	22.90	23.60	23.50	25.33	26.17	31.22	28.48	28.08	26.68	30.45	29.53	28.75
Jul	25.52	25.38	25.70	26.50	28.33	30.62	30.47	29.00	27.62	32.07	31.43	29.52
Aug	25.49	26.08	25.82	26.45	28.12	30.35	29.91	28.34	28.66	30.73	30.64	29.83
Sep	26.55	25.50	26.73	27.63	28.58	30.43	30.55	26.87	26.05	31.77	31.82	31.88

Genotypes in bold: commercial varieties

Table 5-4: Critical differences for the different cane quality variables

Critical differences	Brix %		Pol %		Fibre %		Dry matter %	
	SED	$LSD_{0.05}$	SED	$LSD_{0.05}$	SED	$LSD_{0.05}$	SED	$LSD_{0.05}$
Loc	0.35	1.50	0.34	1.47	0.19	0.80	0.44	1.90
Var	0.28	0.57	0.31	0.62	0.35	0.71	0.49	0.99
Month	0.12	0.24	0.14	0.28	0.19	0.38	0.24	0.47
Loc x var	0.52	1.17	0.54	1.18	0.51	1.04	0.80	1.69
Variety at the same level of location	0.40	0.80	0.44	0.88	0.50	1.00	0.70	1.41
Loc x month	0.38	1.24	0.39	1.18	0.31	0.66	0.54	1.44
Month at the same level of location	0.17	0.34	0.20	0.39	0.27	0.54	0.34	0.67
Var x month	0.47	0.94	0.54	1.04	0.69	1.36	0.89	1.76
Month at the same level of variety	0.43	0.84	0.49	0.96	0.67	1.31	0.83	1.64
Loc x var x month	0.75	1.51	0.82	1.65	0.99	1.94	1.32	2.63
Var x month at the same level of location	0.67	1.32	0.76	1.49	0.98	1.93	1.26	2.49
Month at the same level of loc x var table	0.61	1.19	0.69	1.36	0.94	1.86	1.18	2.32
Variety at the same level of loc x month table	0.67	1.32	0.76	1.49	0.98	1.93	1.26	2.49

SED: Standard error of difference; $LSD_{0.05}$*: Least significance difference at* $P = 0.05$

Loc: location; Var: variety

The genetic variances for all the cane quality traits, in both fresh and dry weights, largely contributed to the total phenotypic variances, leading to relatively high heritability estimates (H >0.8) (Table 5-5). Nevertheless, for sucrose content (Pol %) and cane dry matter content (DM %), the magnitudes of genotype x month and genotype x location interactions were relatively high respectively (Table 5-5). For fibre content (both fresh and dry weights), the temporal and spatial interactions with genotype were almost negligible. Generally, the heritability values for sucrose and fibre measured in dry weights were slightly higher than their corresponding fresh weight estimates.

Table 5-5: Genetic parameters (variances and heritability) from the overall analysis

Variable	σ_g^2	σ_{gl}^2	σ_{gm}^2	σ_{glm}^2	σ_e^2	σ_p^2	H	±	SE
Brix %	2.535	0.391	0.422	0.144	0.550	2.847	0.890	±	0.057
Pol %	2.161	0.573	0.618	0.154	0.718	2.625	0.823	±	0.095
Fibre %	15.823	0.734	0.000	0.329	1.328	16.267	0.973	±	0.016
DM %	5.234	1.733	0.244	0.666	2.084	6.285	0.833	±	0.098
Brix% DM	95.704	1.942	0.695	0.372	5.996	97.109	0.986	±	0.009
Pol% DM	68.429	2.807	5.520	0.585	6.414	71.209	0.961	±	0.019
Fib% DM	95.665	2.144	0.702	0.377	5.999	97.115	0.985	±	0.009

DM: Dry matter; SE: Standard error

5.3.2 Biomass accumulation across time

In this series of trials, the performances at specific locations were of little importance compared to the overall performances across time. In consequence, and also because location main effect was non-significant (Table 5-2) and genotype x location variances were largely inferior to genotypic variances for the cane quality traits (Table 5-5), the following results focus on broad trends across sampling dates.

Generally, sucrose accumulation (Pol %) showed a sharp rise from May to June (+3.64%) and a tendency to increase marginally thereafter (+0.59% per month) (Figure 5-2a). Brix % showed a similar curve to Pol % except that the gap between the two traits, representing mainly reducing sugars in the cane stem (impurity), was widest in May (Impurity = 3.57%) and narrowed towards September (Impurity = 2.11%). Fibre accumulation increased relatively marginally but significantly from May (12.47%) to September (15.33%). The total cane dry matter, in consequence, increased progressively from May to September with the sharpest rise in May to June, essentially due to sucrose accumulation.

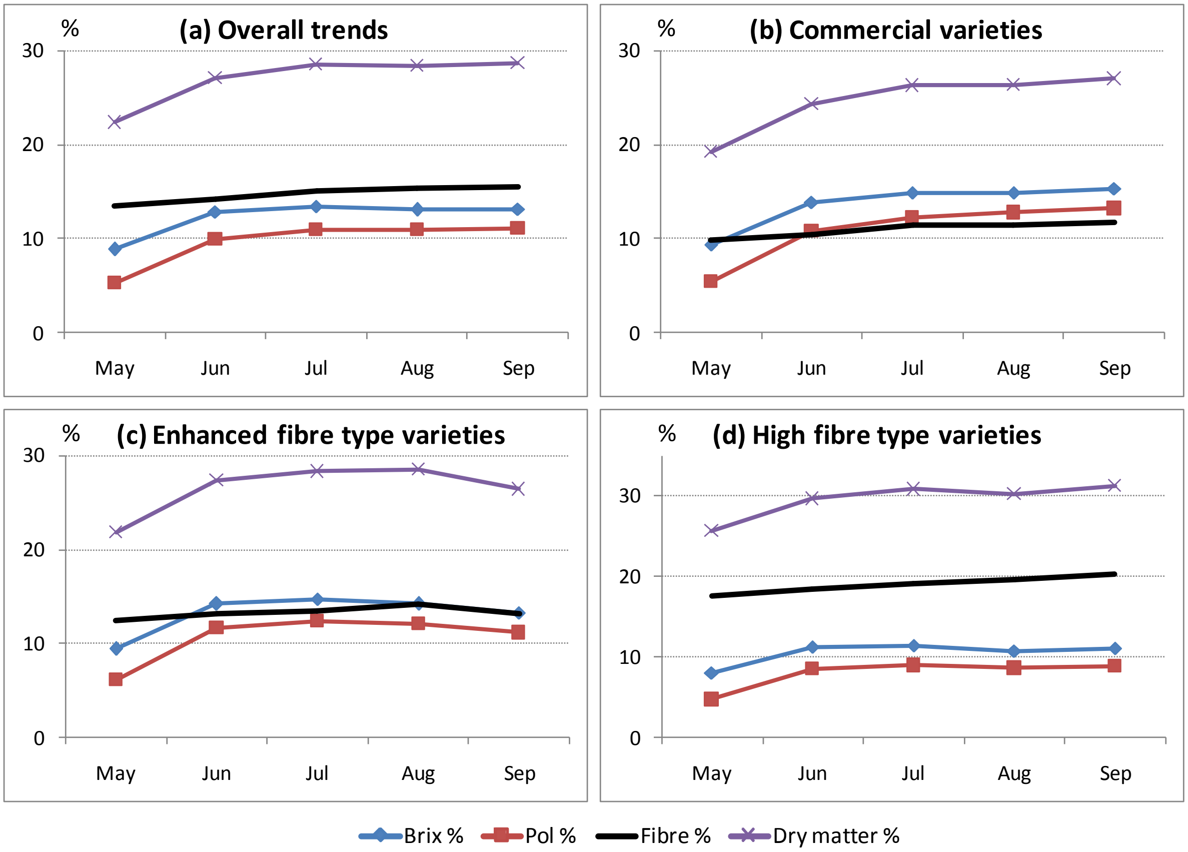


Figure 5-2: Biomass accumulation among different types of canes

The five commercial varieties, as *Type 1* canes, showed trends similar to the overall performances (Figure 5-2b), except that sucrose content was low in May (average = 4.9%) and surpassed fibre content as from July to reach their peak in September (average = 13.8%). Fibre level remained relatively low; 8.9% in May and increased linearly to 11.0% in September. The two *Type 2* canes (enhanced fibre type) differed from the rest by showing their peak dry matter accumulation in August rather than in September (Figure 5-2c). Their sucrose content generally reached a maximum in July, a period when they were equivalent to the commercial varieties, and declined thereafter. Their fibre content was around 14%. The remaining five *Type 3* canes had the highest dry matter content, which rose from 24% in May to around 32% in September, the highest significant change occurring between May and June (Figure 5-2d). This was mainly due to sucrose accumulation pattern, which started from around 5% (as the commercial varieties) in May and stayed relatively low at around 9% from June to September. Fibre content increased progressively from 16% in May to reach its highest, 21%, in September.

The Pearson's correlation coefficients (Table 5-6) were significant and high between Brix % and Pol % ($r > 0.95$*** as from June), which indicated that any one of the two traits could be used as an estimate for sucrose content. Pol % and fibre content showed no association in May and progressively became significantly negative in June ($r = -0.35$**) to highly significantly negative as from July (r = -0.60***), to reach the peak in September (r = -0.73***). Fibre content was generally found highly correlated with dry matter content (r > 0.83***) while the association between Pol % and dry matter tended to be low and non-significant.

Table 5-6: Pearson's correlation coefficients between variables across location, variety and replicate at different sampling dates

Comparisons	May		Jun		Jul		Aug		Sep	
Brix – Pol %	0.89	***	0.96	***	0.97	***	0.99	***	0.99	***
Brix - Fibre	-0.35	**	-0.55	***	-0.70	***	-0.74	***	-0.76	***
Brix - Dry matter	-0.09	ns	-0.13	ns	-0.26	*	-0.27	*	-0.31	**
Pol % - Fibre	0.00	ns	-0.35	**	-0.60	***	-0.69	***	-0.73	***
Pol % -Dry matter	0.24	*	0.09	ns	-0.13	ns	-0.20	ns	-0.26	*
Fibre - Dry matter	0.96	***	0.90	***	0.85	***	0.83	***	0.85	***

: Significant at P=0.05; **: Significant at P=0.01; *: Significant at P=0.001; ns = non-significant*

5.3.3 Sucrose accumulation pattern among the individual genotypes

Sucrose accumulation (Pol %) during the period May to September was studied among the individual genotypes by averaging across locations for reasons given in section 8.3.2. Figure 5-3 illustrates the trends observed for the different types of canes, where the commercial varieties (*Type 1* canes) are represented by thick bold lines, the enhanced fibre type canes (*Type 2* canes) by broken lines and the high fibre clones (*Type 3* canes) by dotted lines.

The graph depicts clearly that all the commercial varieties accumulated the largest amount of sucrose (Pol %) between May and June, during the ripening phase which coincided with the onset of the winter season. Certain cultivars continued their progression up to September while others attained their peak at the early period of the harvest season (early-maturing varieties). One variety, R 573, maintained high sucrose content all across the period (see Table 5-3) and could be considered as high sucrose type for early and middle season harvest. The two enhanced fibre type clones (broken lines) confirmed that their peak sucrose accumulation was of short duration, particularly in July, a period when their sucrose content was equivalent to those of the commercial varieties. A progressive and significant decline was observed thereafter. Such a trend was also observable among the high fibre clones (dotted lines). The amount of sucrose accumulated by the *Type 3* canes was significantly lower than those of the commercial varieties. Generally, all the test genotypes (exclusive of commercial checks) flowered profusely as from mid-May, which may partially explain the drop in sucrose content in later months. Flowered stalks most probably used the stored sucrose for subsistence.

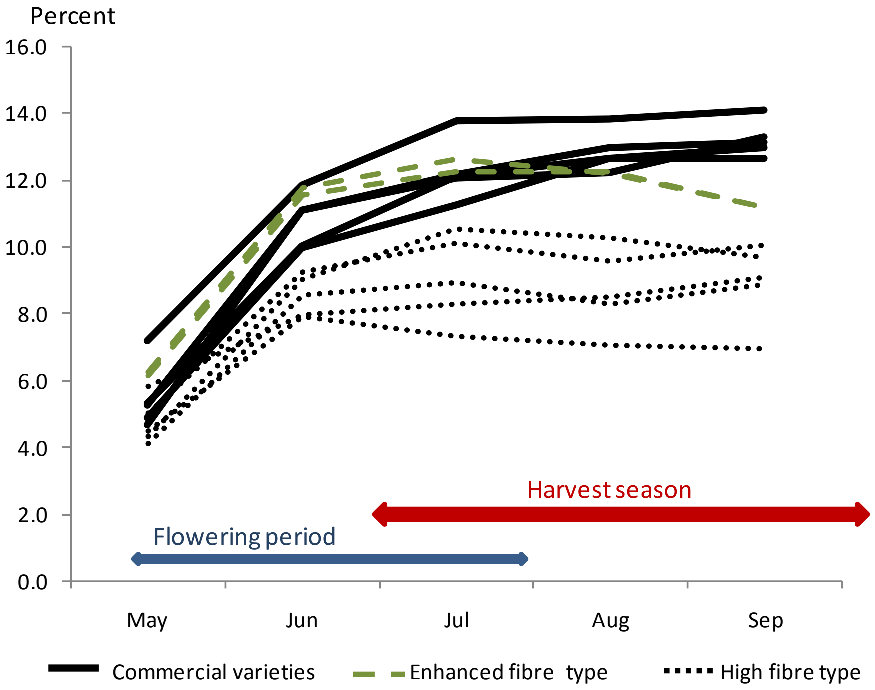


Figure 5-3: Sucrose accumulation (Pol %) pattern among different types of varieties (combined analysis across locations)

5.3.4 Fibre accumulation pattern among the individual genotypes

Similar to the general trends observed in Figure 5-2, fibre accumulation among the different genotypes showed a more or less steady, linear and marginal rise from May to September (Figure 5-4). The slight divergences were most probably due to environment as the var x month interaction was non-significant (Table 5-2). The different types of canes in relation to fibre content were clearly distinctive in the graph with the commercial varieties (*Type 1* canes) systematically occupying the lowest position (at around 11%) during the whole sampling period, the enhanced fibre type (*Type 2* canes) slightly above (at around 14%) and the high fibre canes (*Type 3* canes) taking the topmost position (at around 19%). Two commercial control varieties (R 570 and R 573) maintained relatively higher fibre content (around 12%) while the remaining three checks (M 1176/77, M 2593/92 and M 1400/86) had the lowest fibre (around 10%). The topmost clone in terms of fibre content was M 1303/87 with an average fibre of 21% (see Table 5-3).

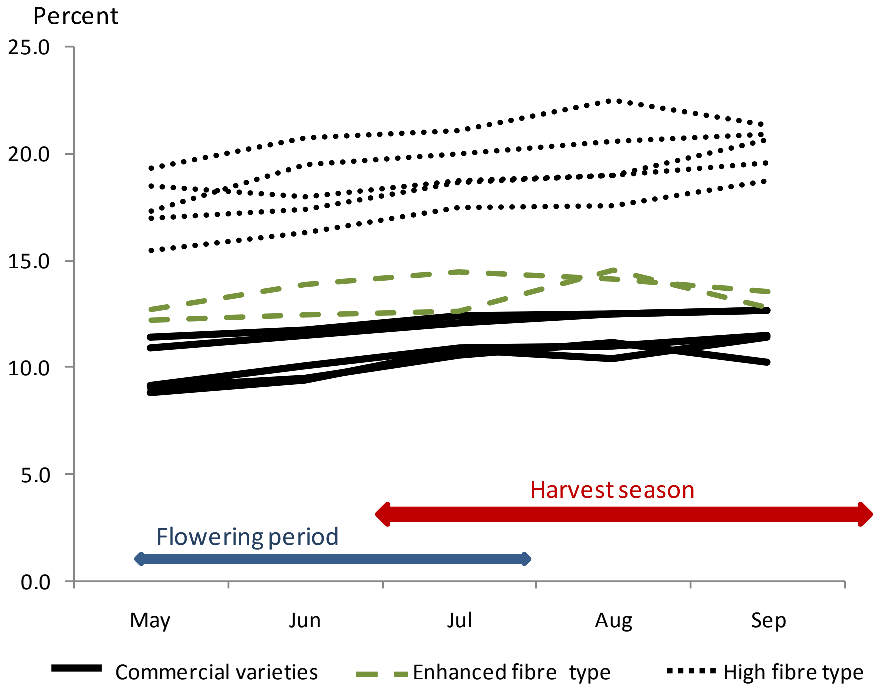


Figure 5-4: Fibre accumulation pattern among different types of varieties (combined analysis across locations)

5.3.5 Dry matter accumulation pattern among the individual genotypes

The combined effect of soluble solids and fibre accumulation among the individual clones across the sampling periods are shown in Figure 5-5. Wider variance among genotypes could be observed in May to June and narrowest around August. All the genotypes showed a sharp rise at the pre-harvest season, between May and June, and a tendency to flatten thereafter. The commercial varieties (*Type 1* canes) averaged around 26% from June to September. The two enhanced fibre type clones (*Type 2* canes) maintained their peak dry matter content of 28% from June to August and dropped significantly to 26% in September. The high fibre clones (*Type 3* canes) generally maintained their dry matter content at 31% from June to September.

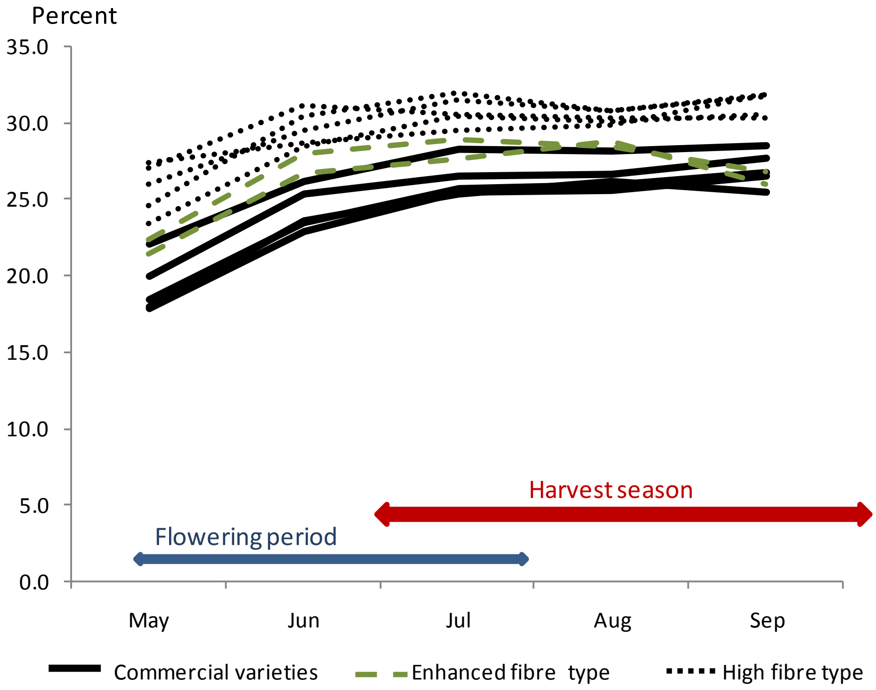


Figure 5-5: Total dry matter accumulation pattern among different types of varieties (combined analysis across locations)

5.3.6 Rank change across sampling periods and genetic parameters

Spearman's rank correlations (Table 5-7) confirmed that changes in rank were highest for sucrose content (Brix % and Pol %) from May to June and minimal thereafter. Most of the commercial varieties had below average sucrose content in May, generally confounded among the low sucrose high fibre canes, and differentiated rapidly and significantly to rank among the top as from June. In addition, the GCVs, as a measure of genetic variance, for Brix % and Pol % were lowest in May (9% and 15% respectively) and progressed to reach their highest levels in September (16% and 19% respectively), a period that coincided with the middle-season harvest (Table 5-7). The heritability estimates for Brix % and Pol % similarly increased from May (*H* values: Brix % = 0.83; Pol % = 0.82) to September (*H* values: Brix % = 0.94; Pol % = 0.92).

Spearman's rank correlations also confirmed that ranking of the genotypes did not change drastically for fibre content across the five pre-harvest sampling dates (Table 5-7). The ρ-values were >0.9***, which supported strongly the high stability of the trait across the pre-harvest to mid-harvest season. The broad sense heritability estimates remained relatively high (0.94-0.97) and the GCV fluctuated in a narrow range of 25-28%.

Table 5-7: Spearman's rank correlations and genetic parameters from combined analyses across locations

		Spearman's rank correlations				**Genetic parameters**			
Variable	**Month**	**May**	**Jun**	**Jul**	**Aug**	$\boldsymbol{\sigma_g^2}$	$\boldsymbol{\sigma_p^2}$	$\boldsymbol{H}$	**GCV %**
Brix %	May					0.68	0.83	0.83	9
	Jun	0.71*				1.89	2.25	0.84	11
	Jul	0.79**	**0.96*****			3.6	3.89	0.92	14
	Aug	0.66*	**0.94*****	**0.95*****		4.26	4.98	0.86	16
	Sep	0.67*	**0.93*****	**0.91*****	**0.96*****	4.35	4.63	0.94	16
Pol %	May					0.67	0.82	0.82	15
	Jun	0.49^{ns}				1.52	2.13	0.71	12
	Jul	0.56*	**0.86*****			3.29	3.81	0.86	17
	Aug	0.35^{ns}	**0.83*****	**0.92*****		3.94	4.83	0.82	18
	Sep	0.43^{ns}	**0.90*****	**0.87*****	**0.92*****	4.45	4.84	0.92	19
Fibre %	May					14.39	14.97	0.96	28
	Jun	**0.94*****				15.54	16.38	0.95	28
	Jul	**0.95*****	**0.99*****			14.58	15.25	0.96	25
	Aug	**0.94*****	**0.99*****	**0.97*****		16.08	17.16	0.94	26
	Sep	**0.90*****	**0.97*****	**0.96*****	**0.95*****	17.99	18.59	0.97	27
DM %	May					10.99	11.68	0.94	15
	Jun	0.74*				6.13	7.88	0.78	9
	Jul	**0.84****	**0.88*****			4.3	5.66	0.76	7
	Aug	0.38^{ns}	**0.80****	0.69**		1.32	3.91	0.34	4
	Sep	0.76*	0.66*	**0.82****	0.54*	4.65	5.99	0.78	8

*: Significant at P=0.05; **: Significant at P=0.01; ***: Significant at P=0.001; ns: non-significant; High ρ-values (in bold) ≈ minimal changes in rank; Lower ρ-values ≈ higher changes in rank

Rank correlation for dry matter content across the sampling dates tended to be more erratic. Relatively high ρ-values were observed from May to July (ρ-values >0.74) and a tendency to be more variable thereafter. This could most probably be due to the maturity behaviour of the clones with respect to sucrose accumulation. Contrary to sucrose content, however, highest heritability and genetic variance (GCV) were observed in May and lowest in August.

5.4 Discussion

In this study, the fresh weight estimates were used and it was assumed that the genotypes were not under water stress conditions. The trial in the dry zone was irrigated. The other trial was in a humid environment where rain water was not limiting. Nayamuth *et al*. (2005) justified the use of dry weights for Pol % to circumvent the confounding effect of moisture content that can vary in different environmental conditions. The dry weight estimates were also reported to bring higher variations in the data and higher precision in data analysis. The authors concluded that in July, early maturing varieties had >53% of Pol % dry matter and late maturing ones <51%. In this experiment, use of dry weight estimates for the cane quality traits were attempted and were found inappropriate for the categorization of varieties. The weaknesses with the dry weight estimates were that fibre content and total dry matter content were assumed to be fixed. This study confirmed that under the same homogeneous conditions fibre content among the varieties varied by around 11% (range during the harvest season: 10-21%) at any given time. The variation for dry matter content was widest in May (18-27%) and smallest in August (25-31%). A simulation study was done to study the impact of varying the fibre content on the rating, as follows:

- Assuming that two varieties, A and B, had the same cane yield, say 100 t ha^{-1}, Pol %, say 13%, and impurity, say 2%, in July. Then, both varieties should theoretically be in the same category with respect to sucrose content and sucrose yield.
- Assuming further that the fibre content of variety A was at 10% and that for variety B was at 14%.
- Then variety A would have 25% (13 + 2 + 10) and variety B 29% (13 + 2 + 14) of dry matter content.
- The Pol % dry matter of variety A would then be 52% (13/25) and that for variety B 45% (13/29).
- The wrong conclusion would be that in spite of the fact that both varieties produced the same amount of sucrose and sugar yield in July, dry matter estimates would have classified variety A as richer in sucrose content than variety B.

The simulation is further supported by a real example from this study. The data from two commercial varieties, M 1400/86 and R 573, are presented in Table 5-8. We support the hypothesis that, notwithstanding the higher precision achievable with dry weight estimates, all classifications of new candidates with those values for cane quality traits should integrate in the formula the varying fibre and total dry matter contents among varieties. To keep the scenario simple, the fresh weight estimates remain good indicators of sucrose and fibre accumulation by acknowledging the fact that those traits do show differential performance across environments. Specific contrasts with appropriate long-term checks with known performance will cater for environment and GEI effects and provide a sound basis for the classification of varieties regarding the most appropriate period of harvest.

All environmental factors were constant during each sampling date for both varieties. Figure 5-6 gives a clear view that variety R 573 was systematically superior to M 1400/86 from May to September not only for sucrose content (Pol %) but also for fibre % and total cane dry matter content fresh weight. However, Pol % dry weight estimates proved the reverse to the fact that variety R 573 had equal to lower sucrose content than M 1400/86 as from June, which is clearly opposite of expected trend. At the MSIRI, R 573 has been correctly characterized for early-middle season harvest and M 1400/86 for middle season harvest only based on fresh weight estimates of sucrose content.

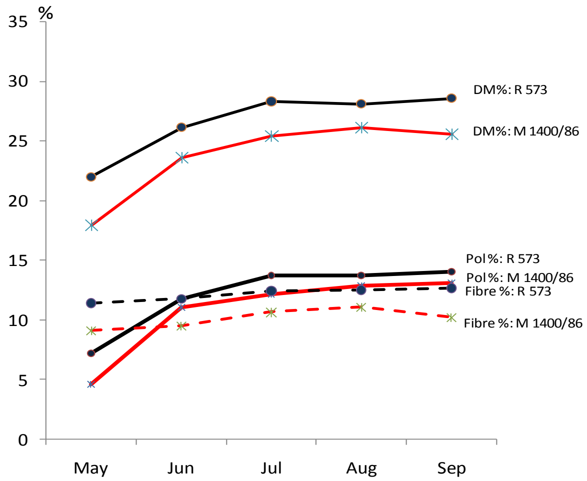


Figure 5-6: Evolution of sucrose and fibre percent fresh weight and dry matter content among two commercial varieties, M 1400/86 and R 573

Table 5-8: Cane quality traits fresh weight of two commercial varieties, M 1400/86 and R 573, across the sampling dates

Variables	**Month**	**R 573**	**M 1400/86**	**Difference**
Pol %	May	7.2	4.6	2.5*
	Jun	11.8	11.1	0.7
	Jul	13.8	12.2	1.6*
	Aug	13.7	12.9	0.8
	Sep	14.1	13.1	1.0*
Fibre %	May	11.4	9.1	2.3*
	Jun	11.8	9.5	2.3*
	Jul	12.5	10.7	1.8*
	Aug	12.5	11.1	1.4*
	Sep	12.7	10.2	2.5*
Dry matter %	May	22.0	18.0	4.1*
	Jun	26.2	23.6	2.6*
	Jul	28.3	25.4	3.0*
	Aug	28.1	26.1	2.0*
	Sep	28.6	25.5	3.1*
Pol % dry matter	May	32.6	25.8	6.8*
	Jun	45.2	46.9	-1.8*
	Jul	48.5	48.0	0.6
	Aug	48.9	49.5	-0.6
	Sep	49.3	51.5	-2.2*

**: Significance at P = 0.05 (see Table 5-4)*

Furthermore, selection is considered most effective when the genetic variance is highest. Sucrose content (Pol %) in this study showed higher genetic variances, heritability and GCV during the harvest season (July to September) than at the pre-harvest season (May). These findings differ from those obtained by Mamet *et al*. (1996), Nayamuth *et al*. (2005) and Badaloo *et al*. (2005). They found highest genetic variation during March to April. This disparity is subject to the type of genotypes used in the population and other unaccounted effects (year, crop cycle, crop age).

While the quoted authors inferred from modern type of varieties and progenies, the population used in this study constituted of a high proportion of early generation hybrids with relatively low sucrose and high fibre. Differences in sucrose content were minimal and not clearly defined among the genotypes (inclusive of commercial varieties) at the ripening phase in early May and widened progressively during the harvest season leading to highest genetic variance and GCV in September. The findings support the assumption that selection for sucrose content among different types of canes will be most effective when done at or near maturity. With a 30% selection rate based solely on sucrose content in May, four of the five sucrose-rich commercial varieties would not have been selected. In contrast, data collected during the early to middle period of the harvest season would ensure that most of the high sucrose genotypes do get screened.

Independent of the genetic variance at any given time, data collected further away from the harvest season is valid only if genotype x time interaction is non-significant and negligible when compared with those taken at harvest date. This will ensure that the high ranking varieties observed during data collection will remain top-ranking at harvest. From this study, Spearman’s rank correlations for Pol % (Table 5-7) confirmed that highest differential performance occurred between May and June. The harvest period starts from mid-June. In consequence, data collected in early May was a poor predictor of varietal performance at harvest in relation to sucrose content. The correlation coefficients for the trait were relatively high (ρ-values >0.83) from June to September, which indicated little changes in rank during the early-harvest to mid-harvest period. As a result, Pol % values collected during the first half of the harvest season had a high predictive power for sucrose level across a longer time span compared to those taken at pre-harvest period in early May.

Another interesting feature clearly observable from this study was that fibre accumulation during the sampling period did not show any marked change in relation to the sharp rise in sucrose content. The partitioning of photosynthates during the pre-harvest to harvest phases was thus in favour of soluble solids. Moreover, the genotypes were already markedly different in terms of fibre in May. These findings confirm that fibre accumulation occurred well before, during the growth phase. As a consequence, in spite of the negative correlations observed between sucrose and fibre content, it should be possible to raise both variables genetically by crossing parents with high fibre and those with high sugar and applying the appropriate selection strategy, as the accumulation pattern of the two traits do not coincide. Still, the physiological limits of the two variables and the total dry matter levels achievable in particular environments cannot be ignored.

This study also showed that, because of the variations in sucrose content across time, categorization of clones into different cane types may change with the period of sampling. At the pre-harvest period in May, the categorization could be erroneous as the check varieties did not accumulate sufficient sucrose content to differentiate from the high-fibre-low-sucrose genotypes.

Moreover, the two enhanced fibre type clones in this study showed high sucrose in June to July only and declined thereafter. They would therefore be categorized as enhanced fibre *Type 2* canes during the early harvest season and, most probably, as multi-purpose *Type 3* canes with lower sucrose and higher fibre at late harvest periods, provided that their biomass yields remain superior to those of the commercial varieties.

5.5 Conclusions

This study provided preliminary indications on the biomass accumulation pattern in terms of sucrose, fibre and total dry matter among the different types of canes. Broadly, for the individual traits, they all follow the same trend as the commercial varieties with a relatively sharp rise in sucrose accumulation at the pre-harvest season of early May to June and a tendency to flatten thereafter. Few genotypes showed high sucrose at early harvest and declined very rapidly. Those clones flowered profusely as from May. They would logically be categorized as early varieties, subject to the level of sucrose produced in relation to commercial varieties. In few others, the sucrose content continued increasing, albeit at a lower rate, across the harvest season. Depending on the period when they would reach their peak level of sucrose, they would be classified as either middle-season or late season-harvest type. Fibre content was generally found to increase marginally but progressively across the sampling period (May to September). While fibre accumulation was significant across month, individual variety x month interaction was found non-significant for the trait. These findings substantiated that fibre accumulation across time was not differentially influenced by the type of varieties. Overall, the study confirmed that, contrary to sucrose accumulation that was reversible (as few varieties showed decreasing trend by end of the sampling period), fibre content accumulated with time and remained stored in the cane stem. The total cane dry matter was found to evolve with time and, as fibre level increased relatively marginally, the changes in dry matter was essentially due to accumulation of soluble solids, mainly sucrose.

Genetic variance, *H* and GCV values for Pol % were lowest in early May and highest in September. Furthermore, the rank change was highest from the pre-harvest season to early harvest season and least during the first half of the harvest period. These findings confirm that sampling for Pol % would be least effective when taken further away than the harvest season. Contrary to sucrose accumulation pattern, fibre content showed least changes in rank across the sampling period. In addition, the GCV for fibre remained nearly constant at around 27%. The *H* values also remained high (>0.94) across the sampling period. These findings confirmed the high stability and repeatability of the trait over time. As a result, sampling for fibre can be done at any time between the pre-harvest to mid-season harvest period. But since both sucrose and fibre contents are determined from the same cane samples, the data collected during the harvest season was more precise than those taken before, for the estimation of cane quality traits.

The study also confirmed that dry weight estimates for Pol % need to integrate the variable fibre content that impacted significantly upon the total dry matter content among different genotypes. In this population, fibre content ranged between 10-21% during the harvest season. The fresh weight estimates for sucrose content (Pol %) were good predictors in spite of the fact that they vary in different environments. Comparison with long term commercial varieties with known performance will help circumvent the effect of both environment and GEI of the cane quality traits.

Chapter 6

Sugarcane yield estimation at different crop age in marginal environments for the generation of biomass year-round

6 Sugarcane yield estimation at different crop age in marginal environments for the generation of biomass year-round

Abstract

Under the sub-tropical climatic conditions prevailing in Mauritius, the vegetative growth of sugarcane in terms of stalk number per unit area and stalk height is optimal in October to April and sucrose accumulation is favoured by the winter conditions prevailing as from April-May. Availability of biomass for cogeneration is thus limited during the harvest season in the second half of the year. Whether high fibre energy canes maintain their high yields across the year, giving due consideration to the climatic conditions prevailing in Mauritius, has not been studied within the broader perspective of extending the milling activities year-round for the continuous generation of electricity. Four trials with the same set of twelve varieties (nine selected biomass genotypes and three commercial controls) were established in 2014 in the dry zone and the super-humid zone for harvest in June and December. Data were collected from the first ratoon crops in 8-, 10- and 12-months old crops. A split-split-plot model was adopted with location as the whole plot, variety as sub-plot and month of data collection as sub-sub-plot. There were significant differences for all the measured variables among the varieties. Averaged across the four trials, four test genotypes, M 196/07, M 1334/84, M 1395/87 and WI 81456, were the best green biomass yielders. Genotypes M 196/07 and WI 81456 significantly surpassed the average of the commercial varieties by +20%. There were significant interactions of variety with region, harvest date and crop age, which differentially influenced the gains in yield. In the super-humid uplands, WI 81456 was superior with +51% higher dry biomass yields than those of the commercial controls across the year. In the dry zone, M 1334/84 and M 196/07 ranked top in June and December, respectively. Their dry biomass yields were +21% and +31% superior to the average of the commercial varieties. M 1334/84 showed its aptitude for sugar maximization during the end of the harvest season in the dry zone. The remaining three varieties could be cultivated in marginal and abandoned uplands for off-season harvest as from 10-months aged crops with fibre as the main product. WI 81456 also ensured the fastest growth rate in the super-humid region and by 8-months age, its biomass yield doubled those of the commercial varieties. The genotype may be harvested at a younger stage, thereby ensuring three harvests in two years compared to two annual harvests.

Keywords: sugarcane, biomass, bioenergy, year-round harvest, crop age

6.1 Introduction

Sugarcane is recognized worldwide as a potential renewable and environment-friendly bioenergy crop capable of replacing the limiting oil reserve in all energy markets and mitigating the adverse effects of burning fossil fuels on the environment. One key requirement energy-crops should fulfil is the generation of biomass year-round and one weak point with current sugarcane crop ideotype, developed for sugar maximisation, is the seasonality and consequently short lived availability of biomass during the year. In addition, the inability of year-round electricity cogeneration is a significant disadvantage of sugar factories because it impedes obtaining emission reduction credits through Clean Development Mechanism. Storage and handling of the fibre generated by the crop, in the form of bagasse and field residues on a large scale are also a very expensive, difficult, and risky operation of the low density and self-combustion properties of the products. The lack of an alternative energy carrier to electricity with storage capability for use during off-season has to date been an unsolvable question (Alonso-Pippo *et al.*, 2009).

The sugarcane cycle comprises distinct vegetative (tillering and elongation), ripening (sucrose accumulation) and senescence phases (Soopramanien, 1979). During the vegetative phase, dry matter is partitioned in favour of fibre and reducing sugars (glucose and fructose) as opposed to sucrose (Alexander, 1973). Under unfavourable conditions for growth, around 80% of the biomass fixed is deposited as sucrose in mature internodes (Glasziou and Bull, 1967; Soopramanien, 1979). A marked reduction in reducing sugars accompanies this ripening process (Julien and Delaveau, 1977; Mamet, 1992). After peak maturation, in general, very few new leaves are formed whilst older leaves senesce and sucrose storage slows down. The plant uses stored sucrose for maintenance and hence the sucrose concentration declines (Mamet, 1992). The effect is known to vary with normal non-flowering stalks, flowering stalks, flowering stalks that form side shoots and those that do not form side shoots (Van Dillewijn, 1952).

Figure 6-1 broadly illustrates the evolution of dry matter proportion of the above ground biomass across the growth phase of the crop. The development of an adequate production apparatus in the form of leaves and roots is a necessary requisite for the formation of millable cane. This implies that during the early stages of its development, a cane plant consists largely of roots and leaves, the amount of millable canes being practically nil. According to van Dillewijn (1952), the dry weight of the green top remains more or less constant during the entire growing period of the plant, while the root system increases gradually but slightly. The growth of the latter as compared with that of the whole plant is so small that in many cases it may be disregarded. Once the production apparatus has developed to a certain extent, the formation of millable stalks starts. It soon reaches a considerable rate which, with the exception of seasonal fluctuations, is maintained throughout a great part of the growing period. The formation of trash is closely related with cane formation, since the production of each node in the stem is associated with the formation of a leaf.

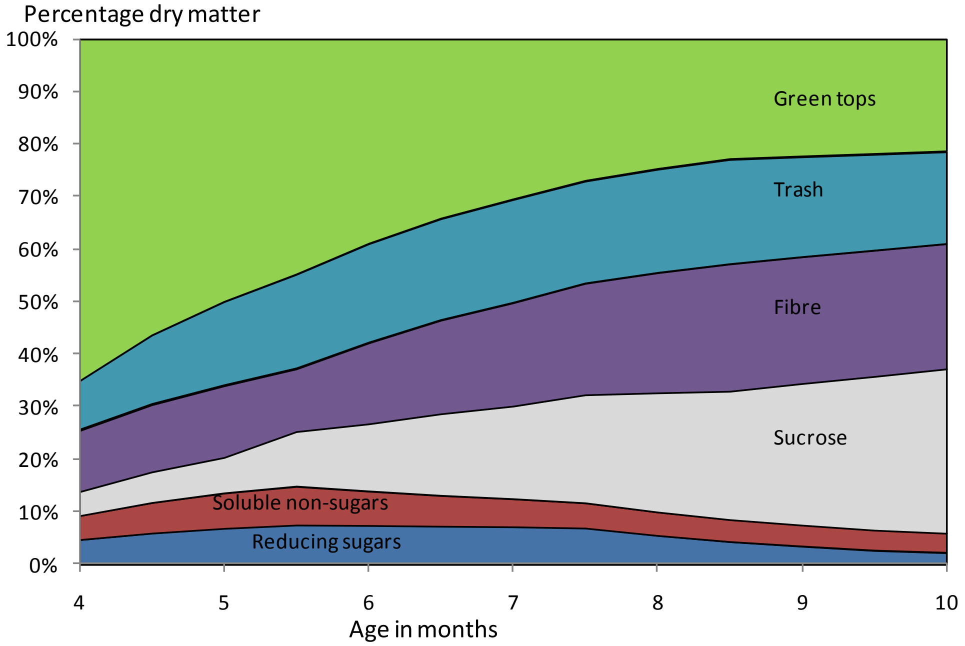


Figure 6-1: Evolution of percentage dry-matter composition of sugarcane across time (adapted from van Dillewijn, 1952)

Generally, only the clean millable stem is cut and sent to the mill. The roots and the stubbles are left behind in the soil for regrowth. The cane tops, leaves (CTL) and trash, commonly termed as sugarcane agricultural residues (SCAR), remain on the field or are used as livestock feed, or as a bagasse mix for the generation of electricity. In Mauritius, with mechanised harvest, they are also used as trash blanketing that controls weed growth and avoids evaporation of moisture content from the soil.

Principal climatic components that control cane growth, yield and quality are temperature, light and moisture availability. Sugarcane thrives best in tropical hot sunny areas. The "ideal" climate for production of maximum sugar from sugarcane is characterized as a long, warm growing season with a high incidence of solar radiation and adequate moisture (rainfall) and a fairly dry, sunny and cool, but frost free season for ripening and harvesting. Optimum temperature for sprouting (germination) of stem cuttings is 32° to 38°c. For ripening, however, relatively low temperatures in the range of 12° to 14° are desirable, since this has a noticeable influence on the reduction of vegetative growth rate and enrichment of sucrose in the cane. At higher temperatures reversion of sucrose into fructose and glucose may occur besides enhancement of photorespiration thus leading to less accumulation of sugars. A total rainfall between 1100 and 1500 mm is adequate provided the distribution is right, abundant in the months of vegetative growth followed by a dry period for ripening. During the active growth period rainfall encourages rapid cane growth, cane elongation and internode formation (URL: http://www.sugarcanecrops.com/climate/).

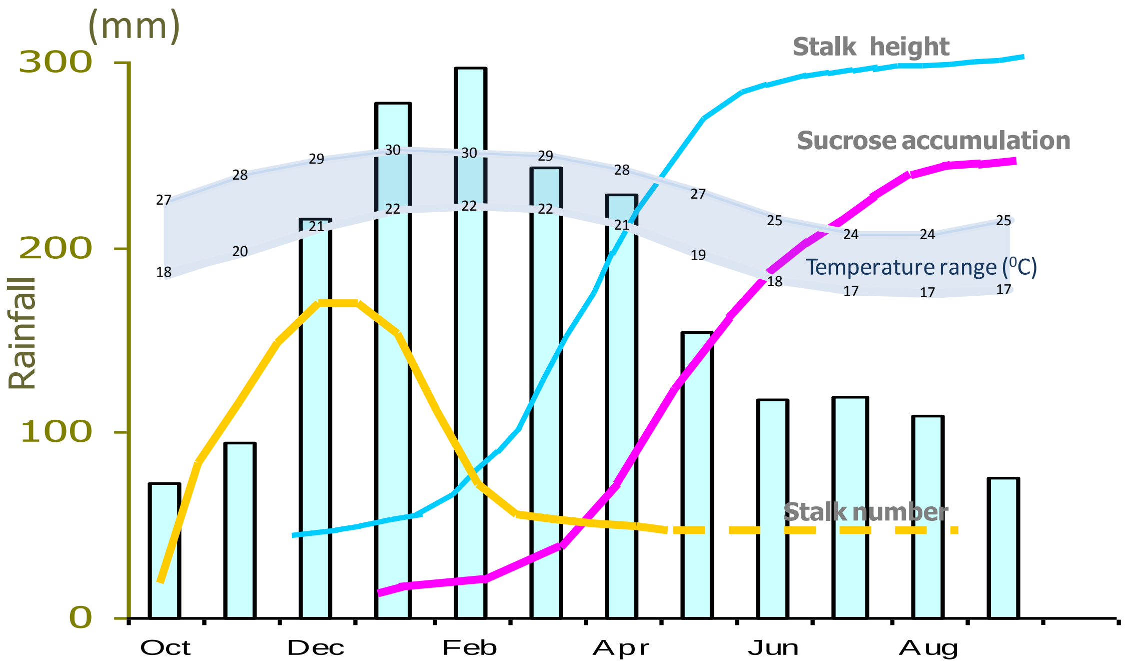


Figure 6-2: Climatic conditions prevailing (Long term means - 1971-2000) in Mauritius and effect on sugarcane growth

Under the sub-tropical climatic conditions prevailing in Mauritius (Oct-Apr: hot and rainy summer; May-Sep: cold and drier winter), the vegetative growth of sugarcane in terms of stalk number per unit area (tillering phase) and stalk height (elongation phase) have been found optimal in October to April. A high number of tillers are formed from October to December and stabilises to a lesser number of millable stalks as from February-March and remains constant until harvest. The elongation of the millable stalks is accentuated by the hot rainy period between February and May (Figure 6-2). Sucrose accumulation is generally favoured by the cooler period at the onset of winter and reaches its peak in August-September. The harvest season spans from mid-June to mid-December.

There is a growing interest among sugarcane stakeholders to extend the harvest season and new precocious types of varieties (high sucrose at pre-harvest season) are being sought (Nayamuth *et al.*, 2005, Badaloo *et al.*, 2005). High fibre varieties offer the possibility of extending the milling activities year-round for the continuous generation of electricity as, contrary to conventional sugarcane where maximum sugar is the main interest, the drive for energy cane is fibre content, or ultimately biomass, and fibre does not vary during the course of the year as is the case with sugar (Matsuoka *et al.*, 2014). However, whether high fibre energy canes maintain their high yields across the year, giving due consideration to the climatic conditions prevailing in Mauritius, has not been studied. The aims of this study were (a) to establish the biomass yield potential of different types of canes in 12-months old crops in June and December in two contrasting environments, super-humid and dry regions of the island, (b) to estimate yields at different crop age, particularly during the off-season (January-June) and (c) to estimate biomass yields in shorter crop cycles. With fibre as the main feedstock, a shorter crop cycle would justify increasing the frequency of harvests in a unit time. Also, careful exploitation of different types of high biomass varieties can provide feedstock for mills to operate year-round.

6.2 Materials and methods

6.2.1 Trials layout

The trial locations, field layout and the type of high biomass genotypes included have been described in Chapter 3. In summary, four trials were established in 2014: two in the dry zone and two in the super-humid zone (Table 3-1). In each location, one trial was meant for harvest in June and one in December. The same set of 12 genotypes, comprising three commercial varieties widely cultivated in Mauritius and nine high biomass clones, was included in all trials and was planted in randomized complete block designs with three replicates. All the trials were rain-fed and harvested at 12-months age in June or December. One genotype, M 1156/00, showed very poor establishment in all trials and was excluded from statistical analyses.

6.2.2 Data collection

Data were collected from the first ratoon crops in 2016 in 8-, 10- and 12-months old crops and consisted of cane quality traits (obtained from laboratory analyses of cane samples), cane morphological parameters (measured from standing canes in the field) and cane biomass variables (obtained and estimated from 12-months old crops weighed at harvest). Aboveground biomass yield, extrapolated to tonnes per hectare (t ha^{-1}), for each genotype constituted of clean cane stems and the sugarcane field residues (SCAR) that consisted of cane tops and leaves (CTL) and clinging trash. The components of cane biomass were fibre yield (FY), sucrose yield (SY) and impurity yield (IMY) and were obtained from the products of cane yield (CY) and laboratory results on fibre %, sucrose % and impurity %, respectively. Impurity % consisted of all soluble solids that were not sugar and was obtained from the difference between Brix and Pol %. Biomass yields in 8- and 10-months old crops were based on measurements of cane yield components (stalk number per unit area, stalk diameter and stalk height) and SCAR weight. The cane stalk was assumed to be a perfect cylinder with specific gravity of 1.00 g cm^{3} (Gravois *et al.*, 1991, De Sousa-Vierra and Milligan, 1999) and cane weight could be estimated using the basic formula:

$$\text{CW (kg)} = nd\pi r^{2}L/1000, \qquad \text{[Eq. 1]}$$

where CW represents cane weight, n equals number of stalks, d is the density at 1.00 g cm^{-3}, r is the stalk radius (cm), and L is the stalk height (cm).

Equation 1 was adopted in comparison to the actual plot weights obtained from the 12-months old crops to derive precise cane yield (CY) estimates in t ha^{-1}, at 8- or 10-months old crops, using the equation:

$$CY_i = n_i/n_{12} \text{ x } d_i/d_{12} \text{ x } r_i^2/r_{12}^2 \text{ x } CY_{12} \quad \text{[Eq. 2]}$$

where CY = cane yield, $i = i^{th}$ month (8 or 10), suffix *12* = measurements made at *12*th month old crop

6.2.3 Data analysis

The first ratoon data were used for the analyses. Data analysis consisted of:

- measuring the actual yields at 12-months old crops in two environments (dry and super-humid) and at two harvest dates (June and December), and
- analyses with estimated yields at 8-, 10- and 12-months old crops.

A split-split-plot model was adopted where location was assigned as whole plot, variety as sub-plot and sampling date as sub-sub-plot. The model formula could be described as follows:

$$Y_{ijkl} = \mu + L_i + R\,(L)_{ij} + G_k + GL_{ik} + RG\,(L)_{ijk} + M_l + ML_{il} + MG_{kl} + GML_{ikl} + \varepsilon_{ijkl} \quad \text{[Eq. 3]}$$

where Y_{ijkl} = observation for Genotype k, in Month l, in Location i, in Rep j nested within Location i, μ = the overall mean, L_i= effect of ith location, $R\,(L)_{ij}$ = the effect of jth replication nested within the ith location, G_k = the effect of the kth genotype, GL_{ik} = the interaction of the kth clone with the ith location, $RG\,(L)_{ijk}$ =the interaction genotype k and replication j nested within location i, M_l = the effect of the lth month, ML_{il}= the interaction of the lth month with the ith location, MG_{kl} = the interaction of the kth clone with the lth month, GML_{ikl} = the interaction term between the kth clone, the lth month and the ith location and ε_{ijkl} = the random residual term associated with Y_{ijkl}.

The biomass yields of the different candidates obtained from shorter crop cycles, particularly 8-months old crops, corresponded to three harvests instead of two in two years. The total biomass produced from each variety with three harvests of 8-months old crops was compared with the conventional two annual harvests and the magnitudes of the differences, in terms of Net Biomass Ratio (NBR) and Net Biomass Balance (NBB), were used to justify the best candidate variety for year-round exploitation with shorter crop cycle. The formulas for NBR and NBB were worked out as follows:

$$NBB = (3 \text{ x } CY_8) - (2 \text{ x } CY_{12}) \quad \text{[Eq. 4]}$$

$$NBR = (3 \text{ x } CY_8) / (2 \text{ x } CY_{12}) \qquad \text{[Eq. 5]}$$

where NBB represents Net Biomass Balance, NBR, the Net Biomass Ratio, CY equals to cane yield fresh weight (t ha^{-1}) and the suffixes 8 and 12 represent the crop age in months.

6.3 Results and discussion

6.3.1 Biomass yields in 12-months old crops in June and December in two environments

Table 6-1 summarises the significance tests obtained from the combined analysis of variances for the important univariate biomass related traits measured at 12-months aged crops in June and December in the two environments.

Table 6-1: F-probabilities (P-values) obtained from 12-month-old trials harvested in the dry and super-humid environments in June and December

Source of variation	Cane yield (FW)	Cane yield (DW)	Fibre yield	Sucrose yield	Fibre %	Pol %	Stalk number	Stalk diameter	Stalk height
Site (S)	0.037	0.023	0.031	0.015	0.01	0.002	0.015	0.488	0.148
Variety (V)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
S x V	<.001	<.001	<.001	<.001	0.345	0.009	0.278	0.006	0.839
Month (M)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
S x M	0.877	0.015	0.005	0.009	<.001	0.001	0.112	0.079	0.416
V x M	<.001	<.001	0.006	<.001	0.035	<.001	0.433	0.567	0.152
S x V x M	0.001	0.004	0.005	0.04	0.262	0.008	0.568	0.783	0.567

P-values: <.001: very highly significant; <.01: Highly significant; <.05: significant; ≥ .05: non-significant
FW: fresh weight; DW: Dry weight

There were significant differences for all the variables among the varieties (V). Site main effect (S) was non-significant at P=0.001 while month of harvest (M), June and December, had a significant impact on all the traits. Aboveground biomass yield dry weight in June (40 t ha^{-1}) was significantly higher than that of December (33 t ha^{-1}) (Figure 6-3). The interaction site x variety (S x V) was significantly high for cane biomass parameters and non-significant for cane quality and morphology traits at P=0.001. This information pertained to differential adaptation of varieties across sites. The interaction variety x month (V x M) of harvest was highly significant for cane yield and sucrose content (Pol %) and non-significant for the rest of variables. The significant interaction for sucrose level related to the differential maturity behaviour of different varieties across time. The second order interaction site x variety x month was non-significant for all the traits at P = 0.001.

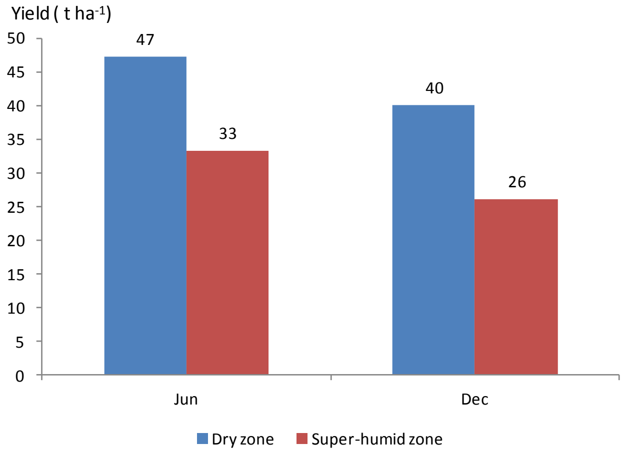
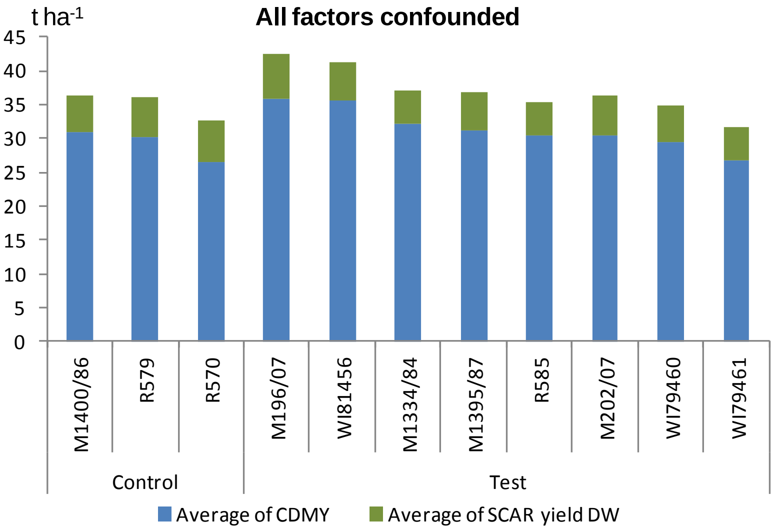


Figure 6-3: Environmental and harvest date effects on total aboveground dry matter mean yields (t ha^{-1})

Subject to the magnitudes of the interactions, general averages may hide intrinsic differences among varieties in specific locations and/or time of harvest. In the following sections, due considerations are given to those interactions in the interpretation of results. Least significant differences (LSDs) were used for all paired contrasts among the means. Variables that were most stable were those that had minimum interactions across locations and harvest dates. Thus, among the 12-months old crops, the cane morphology traits (stalk number, diameter and height) and cane fibre content were most stable.

Varietal effect

Averaged across the four trials, the eight biomass varieties produced equal to significantly higher total aboveground biomass yields on a dry weight basis than those of the commercial varieties (Figure 6-4 and Table 6-2). Generally, aboveground biomass constituted of 77% of cane stalks and 23% of SCAR. The two components roughly consisted of 29% of dry matter and the remaining 71% was water. Variations among the genotypes were significant. WI 79461 had 35% of dry matter and M 1334/84 and R 579 had 30% in the cane stem (Table 6-2). Four test genotypes, M 196/07, M 1334/84, M 1395/87 and WI 81456, had the highest aboveground total dry biomass yield, which comprised cane dry matter yield (CDMY) and the remaining aboveground parts yield dry weight (SCAR yield DW). Genotypes M 196/07 and WI 81456 significantly surpassed the average of the commercial varieties by +20%.



CDMY: Cane dry matter yield; DW: Dry weight; SCAR: Sugarcane field residues (cane tops, leaves and trash)

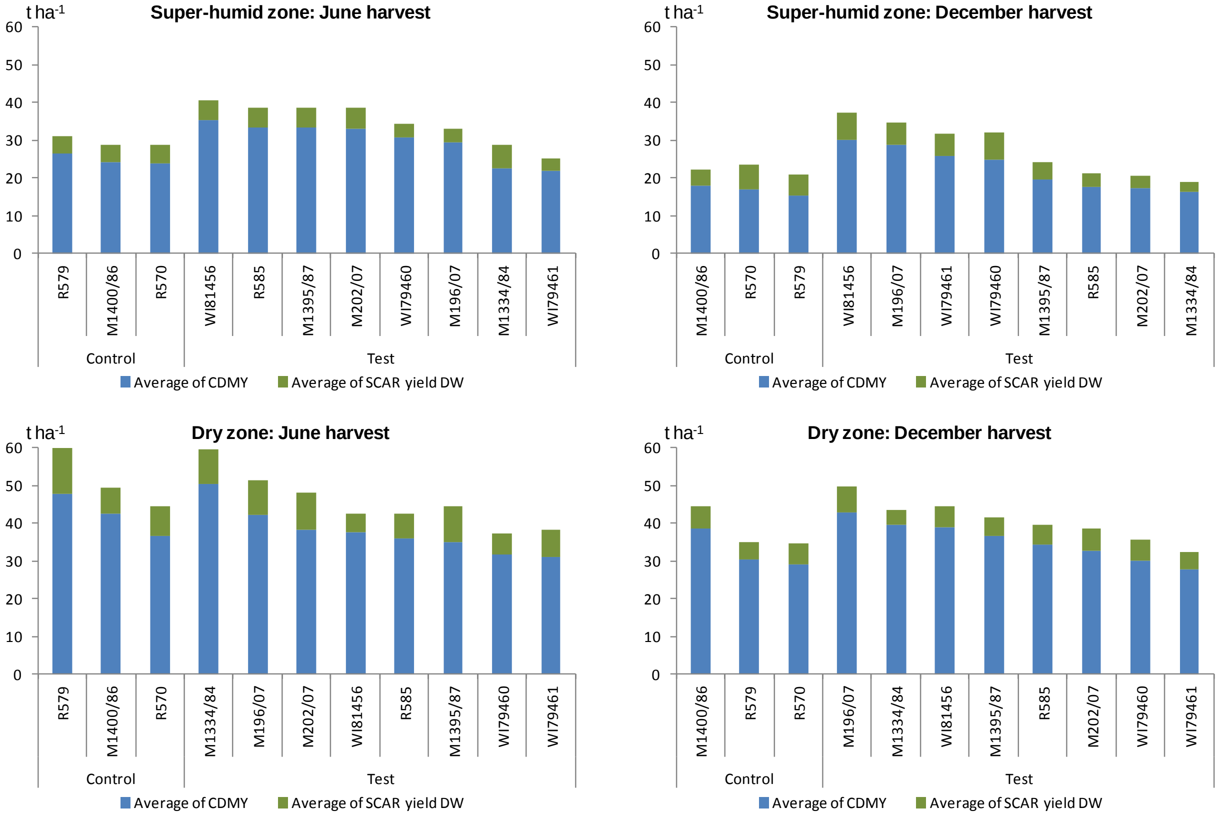
Figure 6-4: Total aboveground dry biomass yield combined across locations and harvest dates

Table 6-2: Performances of genotypes at 12-months age across four trials in first ratoon crop

	Control varieties			*Control*	Test varieties							
Variables	**M1400/86**	**R570**	**R579**	***Average***	**M1334/84**	**M1395/87**	**M196/07**	**M202/07**	**R585**	**WI79460**	**WI79461**	**WI81456**
Cane quality traits												
Brix % Cane	15.5	14.7	15.0	*15.1*	14.0	13.8	14.2	14.9	15.3	12.4	13.6	12.3
Pol % Cane	13.4	12.6	12.9	*13.0*	11.8	11.7	12.0	12.9	13.7	9.8	11.6	9.5
Fibre % Cane	15.6	16.0	15.0	*15.5*	15.2	20.0	19.8	16.9	18.5	21.1	21.5	20.0
DM % Cane	31.1	30.7	30.0	*30.6*	29.3	33.8	34.0	31.8	33.9	33.5	35.0	32.1
Purity %	85.0	84.3	85.8	*85.0*	83.2	83.4	82.0	86.2	88.3	75.1	84.1	74.9
Aboveground biomass traits												
Cane Yield (FW)	99.0	87.5	99.1	*95.2*	108.9	92.8	105.3	94.6	89.5	88.5	76.4	111.5
SCAR yield (FW)	18.8	20.6	20.0	*19.8*	17.5	19.6	22.7	21.1	17.6	19.0	16.9	19.6
Total biomass yield (FW)	117.8	108.1	119.1	*115.0*	126.4	112.4	128.1	115.7	107.1	107.6	93.3	131.2
Cane dry matter yield	30.8	26.6	30.1	*29.2*	32.2	31.1	35.8	30.3	30.3	29.3	26.7	35.5
SCAR yield (DW)	5.5	6.0	5.9	*5.8*	4.9	5.7	6.6	6.1	5.1	5.5	4.9	5.7
Total biomass yield (DW)	36.3	32.6	36.0	*34.9*	37.1	36.8	42.4	36.4	35.4	34.9	31.6	41.2
Sucrose yield	13.0	10.7	12.7	*12.2*	12.7	10.5	12.3	12.1	12.0	8.1	8.8	10.2
Fibre yield	15.6	14.0	15.2	*14.9*	17.0	18.6	21.0	16.3	16.7	18.7	16.4	22.2
Impurity yield	2.2	1.9	2.1	*2.1*	2.5	2.1	2.4	2.0	1.6	2.5	1.6	3.2
Cane morphology traits												
Stalk number (m^{-1})	15.8	13.7	14.3	*14.6*	16.8	24.3	19.8	19.7	13.5	17.4	18.2	20.7
Cane diameter (mm)	28.7	28.5	30.6	*29.3*	31.7	22.4	24.7	25.8	26.5	25.7	24.2	23.0
Cane height (cm)	278.0	266.4	257.8	*267.4*	278.5	319.6	320.4	305.0	321.3	343.3	336.4	358.9

DM %: dry matter %; DW: dry weight; FW: fresh weight

Given the significant interactions of variety with site and harvest date, higher precision in quantum gained were obtainable from within specific environments (Figure 6-5 and Appendixes 6-1 - 6-3). In the super-humid zone, the best candidate WI 81456 produced +51% significantly higher dry biomass (+37% in June and +69% in December) than those of the commercial varieties. In terms of cane fibre yield, it ensured +90% higher yield in the super-humid zone (+74% in June and +118% in December). In the dry zone, the best biomass candidates were M 196/07 and M 1334/84 that together accumulated +15% higher total aboveground dry matter yields than the average of the commercial varieties. In June, M 1334/84 was superior with +21% and in December, M 196/07 was best with +31% higher biomass yield than the average of the control varieties. Compared to the average of the commercial varieties, those differences were significant. Generally, the same varieties were identified from plant cane results (see Chapter 3) although the magnitudes of the differences from the average of commercial varieties are much lesser. Two varieties, R 585 and WI 79461, identified from plant cane crops in 2015 had poorer biomass yields in first ratoon.



CDMY: Cane dry matter yield; DW: Dry weight; SCAR: sugarcane field residues (leaves and trash)

Figure 6-5: Total aboveground dry biomass yield in individual locations and harvest dates

6.3.2 Yield estimations at different crop age

The mass of SCAR (cane tops, green leaves and trash) at 8-, 10- and 12-months old crops were found to be relatively constant and specific to the individual varieties, which supports the findings of van Dillewijn (1952). Major changes were expected from accumulation of biomass in the cane stems in terms of stalk number per unit area, stalk diameter and height. In consequence, in the following section, the changes in yields at different crop age are presented in terms of changes in cane biomass yield. Table 6-3 summarises the F-probabilities of yield estimates from 8-, 10- and 12-months aged crops obtained from the analysis of variances of the different biomass related traits from June and December harvests. The two series of data (harvest in June and harvest in December) were analysed separately.

Table 6-3: F-probabilities (P-values) from 8-, 10- and 12-month-old trials harvested in the dry and super-humid environments in June and December

Source of variation	Cane yield (FW)	Cane yield (DW)	Fibre yield	Sucrose yield	Fibre %	Pol %	Stalk number	Stalk diameter	Stalk height
	Feb-Apr-Jun data (June harvest)								
Site (S)	0.188	0.104	0.147	0.056	0.116	0.057	0.022	0.692	0.269
Variety (V)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
S x V	<.001	<.001	<.001	<.001	0.334	0.051	0.881	0.119	0.03
Month (M)	<.001	<.001	<.001	<.001	<.001	<.001	0.002	<.001	<.001
S x M	<.001	<.001	<.001	<.001	0.137	<.001	0.002	<.001	<.001
V x M	<.001	0.001	0.023	<.001	0.002	<.001	0.033	0.005	<.001
S x V x M	0.002	0.003	0.008	<.001	0.086	0.509	0.033	0.002	0.463
	Aug-Oct-Dec data (December harvest)								
	Cane yield (FW)	Cane yield (DW)	Fibre yield	Sucrose yield	Fibre %	Pol %	Stalk number	Stalk diameter	Stalk height
Site (S)	0.019	0.01	0.01	0.008	0.004	<.001	0.012	0.828	0.094
Variety (V)	0.003	<.001	<.001	0.008	<.001	<.001	<.001	<.001	<.001
S x V	0.017	0.022	0.091	0.001	0.553	<.001	0.171	0.17	0.993
Month (M)	<.001	<.001	<.001	<.001	<.001	<.001	-	<.001	<.001
S x M	0.021	0.334	0.002	<.001	<.001	<.001	-	0.129	<.001
V x M	0.681	0.328	0.371	0.069	0.449	0.001	-	0.139	0.752
S x V x M	0.374	0.195	0.489	0.148	0.157	0.015	-	0.121	0.403

P-values: <.001: Very highly significant; <.01: Highly significant; <.05: significant; ≥ .05: non-significant

Generally, site (S) as main effect was non-significant at P = 0.001 for most traits while varietal (V) and crop age (M) main effects were significant. The interactions S x V, S x M and V x M were significant for most of the yield traits (cane yield, fibre yield, sucrose yield) in the first half of the year (Feb-Apr-Jun), and non-significant in the second half of the year (Aug-Oct-Dec). The interactions for fibre % were generally non-significant at both periods of the years, which indicated its high stability in 8- to 12-months old crops. Differential performance among varieties across crop age for sucrose content (V x M for Pol %) was more significantly pronounced from February to June than from August to December. Stalk number per unit area evolved slightly from February to June (V x M for stalk number) but remained constant at the same crop age from August to December. Stalk diameter generally remained constant across sites (non-significant S x V) but varied across the months (significant M effect). In terms of stalk height, Site and the interactions S x V were generally non-significant. However, the effect of crop age (M) was very highly significant at both periods of harvest. The interaction V x M was very highly significant with February-April-June data and non-significant with August-October-December data.

These results confirmed that higher variability in cane yield and its components across 8-, 10- and 12-months old crops were obtainable from the first half of the year than those made in the second half. This differential performance was undeniably related to the climatic conditions that coincided with the growth phase of the crop. For the harvests made in June, the vegetative phase of the crop coincided with the winter season leading to delayed initial growth. Between February and April (moist summer), the crops accumulated biomass exponentially from an average of 9 t ha^{-1} (29% of annual cane biomass) in 8-months old crop in February to 27 t ha^{-1} in 10-months old crop in April (81% of annual cane biomass) (Figure 6-6 and Appendix 6-4).

For the 12-months old crops harvested in December, tillering and elongation phases coincided with the rainy summer (January to April) and by August (8-months old crops), 78% of biomass obtained in December was already accumulated. The change in biomass between August and October was merely 3 t ha^{-1} (+14%), compared to 21 t ha^{-1} (+52%) between February and April. In addition, higher cross-over type of interactions was observable between February and June than between August and December (Figure 6-6 and Appendix 6-4).

Differential performance among varieties was also evident across regions. The best performing varieties in terms of cane yield dry weight per environment are illustrated in Figure 6-6. In the super-humid region, WI 81456 showed an exceptional growth rate and maintained its superiority in aboveground biomass yield across crop age and harvest date. By 8-months age, the clone had already doubled the biomass accumulated by the commercial varieties, and +65% and +84% of its own annual biomass yield in February and August, respectively. In the dry zone, M 1334/84 showed the best performance in the first part of the year. At 8-months old in February, its cane yield was not remarkably different from the commercial varieties. M 1334/84 was superseded by M 196/07 in the second half of the year. The latter variety showed its superiority from 8- to 12-months old crops.

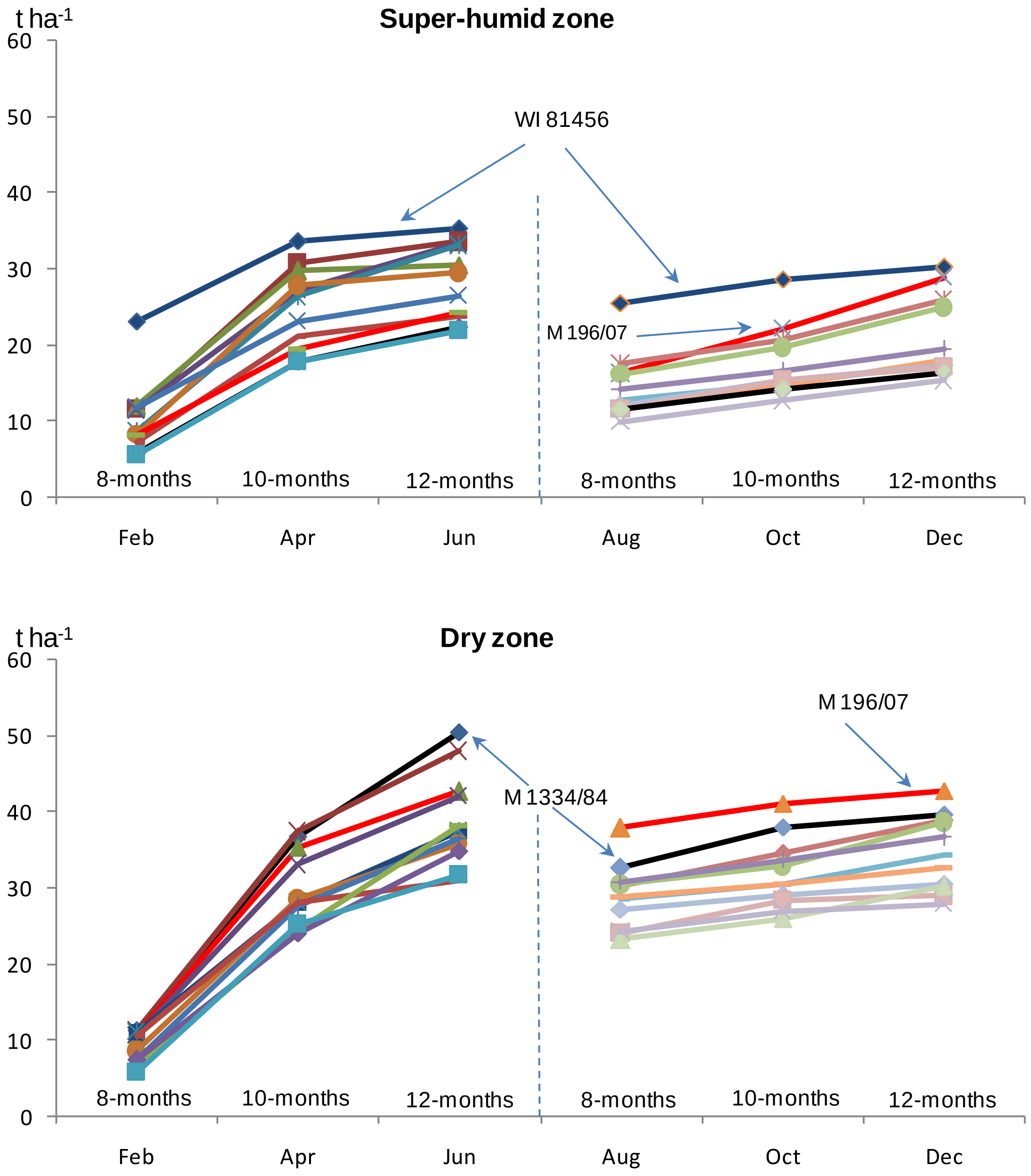


Figure 6-6: Cane yield estimates, dry weight, from 8-, 10- and 12-months old crops harvested in June and December in the super-humid and dry zones

6.3.3 Contributors of cane biomass yield at different crop age

The three main contributors of cane yield were stalk number per unit area, stalk diameter and stalk height. In the 8- to 12-months old crops, stalk number varied slightly in the first half of the year and remained constant in the second half (Table 6-4). The coefficient of determination (r^2: the proportion of variance of one variable that is predictable from another variable) between stalk number and estimated yield was at 0.02. Cane diameter increased slightly across the months and the r^2 was at 0.16. The r^2 value between stalk height and estimated yield was at 0.34, which indicated that biomass yields between 8- to 12-months old crops were highly attributable to cane elongation. The exponential biomass accumulation between February and April coincided with the ideal climatic conditions favouring cane elongation, the cane height increasing at a rate of nearly 2 cm day^{-1} (Table 6-4, Figure 6-6 and Appendix 6-4). For the crops harvested in December, the canes were already appreciably tall at 8-months age (August) and increased relatively marginally and linearly up to December.

Table 6-4: Average of cane morphological traits across crop age in the different environments

Harvest	Cane yield components	Site	February (8-months)	April (10-months)	June (12-months)	August (8-months)	October (10-months)	December (12-months)
June	Stalk number (m^{-1})	Dry zone	12.7	12.3	12.6			
		Super-humid zone	8.7	8.7	8.7			
	Stalk diameter (cm)	Dry zone	2.3	2.8	2.9			
		Super-humid zone	2.5	2.7	2.8			
	Stalk height (cm)	Dry zone	205.0	318.6	347.7			
		Super-humid zone	203.3	303.3	319.6			
December	Stalk number (m^{-1})	Dry zone				14.2	14.2	14.2
		Super-humid zone				11.6	11.6	11.6
	Stalk diameter (cm)	Dry zone				2.4	2.4	2.5
		Super-humid zone				2.4	2.4	2.5
	Stalk height (cm)	Dry zone				274.3	284.3	292.6
		Super-humid zone				234.2	259.7	271.3

6.3.4 Strategies for continuous generation of sugarcane biomass year-round

From the nine highly selected test genotypes evaluated in this study for their biomass potential, four (M 1334/84, M 1395/87, M 196/07 and WI 81456) could be retained for either sugar as the main output and fibre as a by-product, termed here as sugar-model, or fibre as the main feedstock for the generation of bioenergy and the extracted juice to be used for ethanol and other high value products, and termed here as fibre-model. One of them, M 1334/84, suited the sugar-model objectives. It was among the highest total biomass producers in the dry zone with appreciably high sucrose content in December. The remaining three best biomass yielding genotypes were M 196/07, M 1395/87 and WI 81456. Given their significantly higher fibre content and lower sucrose, they fitted best the fibre-model objectives.

With the sugar-model, varieties need to be harvested strictly when sucrose content reaches its peak during the harvest season (June - December). The fibre-model varieties identified in this study offer the possibilities for year-round harvest. They ranked top at both harvest dates (June and December), particularly in the super-humid environment. Also, as their fibre content was already high in the eight to twelve months old crops (Table 6-5), the genotypes may be harvested with a shorter crop cycle. With 8-months old crops, three harvests can be ensured in two years, thereby increasing the total biomass generated in a unit time. The NBBs (Eq. 4) and NBRs

(Eq. 5) with three harvests instead of two in 24 months for the four best genotypes are given in Table 6-5.

Table 6-5: Agronomic characteristics of best biomass genotypes

		Cane quality traits at 12-months crops		Cane yield estimates (t ha^{-1}) fresh weight					
Environment	Variety	Pol %	Fibre %	CY$_8$	CY$_{12}$	8-months crops, three harvests	12-months cops, two harvests	NBR	NBB
Dry zone									
June harvest (12-months crop)	M1334/84	9.95	16.10	69	175	208.3	350.2	0.59	-141.89
	M1395/87	9.91	20.55	33	104	97.8	208.8	0.47	-111.09
	M196/07	8.07	19.48	46	134	138.6	267.3	0.52	-128.67
	WI81456	6.16	20.49	43	123	128.8	245.7	0.52	-116.91
December harvest (12-months crop)	M1334/84	16.13	17.55	101	115	303.9	229.1	1.33	74.85
	M1395/87	16.09	23.07	84	92	253.2	183.7	1.38	69.45
	M196/07	17.06	22.87	103	106	307.7	211.9	1.45	95.80
	WI81456	14.67	23.14	89	100	266.4	200.8	1.33	65.54
Super-humid zone									
June harvest (12-months crop)	M1334/84	8.92	13.57	32	87	97.2	174.2	0.56	-76.98
	M1395/87	7.78	17.88	55	116	163.6	231.5	0.71	-67.92
	M196/07	7.98	18.94	40	96	120.1	192.2	0.62	-72.10
	WI81456	6.30	19.28	105	121	314.4	241.1	1.30	73.28
December harvest (12-months crop)	M1334/84	12.32	13.66	49	59	147.5	118.0	1.25	29.56
	M1395/87	13.03	18.69	48	59	144.9	118.0	1.23	26.96
	M196/07	14.84	17.89	56	86	169.4	171.3	0.99	-1.88
	WI81456	11.03	16.92	89	102	268.3	204.6	1.31	63.67

CY: Cane yield; Suffixes 8 and 12: Crop age in months; NBB: Net Biomass Balance; NBR: Net Biomass Ratio

NBR values less than or equal to one indicated that a shorter crop cycle was not viable. In addition, extra energy will be required for harvesting, transport and milling operations with one additional harvest. At this stage, further economic analyses will be necessary to determine the ideal breakeven point. In the absence of such analyses, a minimum NBR of 1.3 and NBB of 50 t ha^{-1} were arbitrarily set as thresholds to justify harvest in 8-months old crops (shaded cells in Table 6-5). Based on these assumptions, all the selected genotypes qualified for harvest at eight months age in the dry zone in the second half of the year. During the off-season, only one genotype, WI 81456 (NBR: 1.3; NBB: 73 t ha^{-1}) qualified for three harvests in two years in the super-humid zone. The variety maintained the trend in the same environment in the second half of the year as well (NBR: 1.31; NBB: 64 t ha^{-1}) (Table 6-5). Broadly, the average NBB value for WI 81456 could be worked out to 68 t ha^{-1}. The fast growth characteristics of the genotype during the early vegetative phase could explain this demarcation: By February in the uplands, its cane height (312 cm) doubled those of the commercial varieties (~158 cm). Generally, at 10-months aged crops, the genotypes had accumulated the majority of biomass and were exploitable for fibre generation.

6.4 Conclusion

Out of the nine highly selected test genotypes evaluated in this study, four confirmed their high aboveground biomass potential, generally superior to the commercial varieties, in June and December in 12-months old first ratoon crops. Broadly, M 196/07 ranked top and was followed by WI 81456, M 1334/84 and M 1395/87. However, given the significant GEI, ranking changed in different environments. In the super-humid zone, WI 81456 was superior at both harvest dates (June and December), with +51% higher dry biomass yield than those of the commercial controls. In the dry zone, M 1334/84 ranked top in June. Its dry biomass yield was +21% superior to the average of the commercial varieties. It was out yielded by M 196/07 in December, with +31% higher biomass yield than the controls. Although not top-ranking, M 1395/87 remained among the best biomass and fibre yielders.

Of the four best varieties, M 1334/84, with relatively low fibre (15%) and high sucrose (12%) (*Type 1* cane), suited the sugar-model where the main output is sugar and bagasse is a by-product. The variety should be harvested around December in the dry zone to capitalize on both sugar and bagasse yields. M 196/07 showed low sucrose and high fibre at plant cane and was categorized as *Type 3* cane. In the first ratoon crop, its sucrose content (12%) was equivalent to the commercial varieties and its fibre content (20%) remained high. In consequence, the variety can be considered as enhanced fibre *Type 2* cane, where both sugar and fibre are maximized. The remaining two genotypes (M 1395/87 and WI 81456) had fibre content around 20% and lower sucrose content (10%). They suited the fibre-model where bagasse is the main output and the extracted juice a by-product. The fibre-model varieties showed aptitudes for harvest year-round for the continuous generation of biomass. Ideally the high fibre varieties should be cultivated in marginal and abandoned lands for harvests mainly during the off-season, between January and June.

The fibre and biomass yield estimates in 8- and 10-months old crops of the fibre-model varieties were generally appreciable. One exception was in February with 8-months old crops where cane biomass yields dry weight were lowest and around 10 t ha^{-1}. This was mainly due to the cold and dry climatic winter conditions (June - October) prevailing during the early vegetative phase of the crops. Greatest biomass accumulation was observed among the different varieties in the warm rainy climate between February and April. One genotype, WI 81456, ensured the fastest growth rate in the super-humid region and by 8-months age (February and August), its biomass yield doubled those of the commercial varieties. Based on NBB and NBR analyses, WI 81456 was the only genotype that may be harvested at 8-months age, thereby ensuring three harvests in two years and around 68 t ha^{-1} surplus biomass yield fresh weight (~20 t ha^{-1} dry weight) compared to two annual harvests. The remaining clones may be harvested as from 10-months age as the majority of biomass were already accumulated.

The four best varieties were also identified from the plant cane crop in 2015, along with R 585 and WI 79461. The latter two clones showed poorer performance in the first ratoon crop. Also, the magnitudes of the differences between the selectable genotypes and the control varieties stabilized to a lower level in the second harvest. Since sugarcane is planted once and harvested annually over eight or more years, the first ratoon results are expected to be closer to commercial reality. Adoption of the identified promising varieties, and cultivation and harvest strategies described in this study, are expected to increase the total biomass generated for bioenergy production without jeopardizing sugar yield.

Appendix 6-1: Performance of high biomass canes in 1st ratoon crop in the dry zone at 12-months aged crops (averaged across harvest dates)

		Control varieties			***Control***	**Test varieties**							
SITE	**Variables**	**M1400/86**	**R570**	**R579**	***Average***	**M1334/84**	**M1395/87**	**M196/07**	**M202/07**	**R585**	**WI79460**	**WI79461**	**WI81456**
Dry zone	**Cane quality traits**												
	Brix % Cane	16.8	16.0	16.0	*16.3*	15.0	14.8	14.7	15.4	16.5	13.1	13.7	13.2
	Pol % Cane	14.9	14.4	14.4	*14.6*	13.0	13.0	12.6	13.5	15.0	10.6	11.7	10.4
	Fibre % Cane	17.1	17.2	16.2	*16.8*	16.8	21.8	21.2	17.8	20.0	22.9	22.3	21.8
	DM % Cane	33.9	33.2	32.2	*33.1*	31.8	36.6	35.8	33.2	36.5	36.0	36.0	34.6
	Purity %	87.6	89.1	89.4	*88.7*	85.9	86.8	82.8	87.3	90.3	78.2	84.7	75.6
	Aboveground biomass traits												
	Cane Yield (FW)	122.3	101.6	123.1	*115.7*	144.8	98.1	119.8	106.2	97.4	86.8	82.7	111.6
	SCAR yield (FW)	21.6	23.0	28.9	*24.5*	22.9	25.1	27.9	27.4	20.2	19.3	20.1	18.3
	Cane dry matter yield	40.6	32.8	39.2	*37.5*	45.1	35.8	42.5	35.5	35.1	30.9	29.5	38.2
	SCAR yield DW	6.3	6.7	8.4	*7.1*	6.4	7.3	8.1	7.9	5.9	5.6	5.8	5.3
	Sucrose yield	17.5	13.9	17.1	*16.2*	17.9	12.6	14.5	14.4	14.3	8.8	9.5	11.1
	Fibre yield	20.5	17.1	19.9	*19.2*	24.2	21.4	25.2	19.0	19.2	19.8	18.3	24.2
	Impurity yield	2.5	1.8	2.2	*2.2*	3.1	1.8	2.7	2.0	1.6	2.3	1.8	3.3
	Cane morphology traits												
	Stalk number (m^{-1})	19.7	15.3	16.6	*17.2*	20.2	28.5	22.1	20.8	14.9	19.6	19.8	23.9
	Cane diameter (mm)	29.8	29.3	32.2	*30.4*	32.3	22.2	23.3	25.3	26.5	26.2	23.3	23.8
	Cane height (cm)	291.3	279.8	273.5	*281.6*	299.3	329.2	328.3	312.0	336.7	360.8	336.3	374.0
Super-humid zone	**Cane quality traits**												
	Brix % Cane	14.2	13.4	14.0	*13.9*	13.1	12.8	13.7	14.4	14.2	11.8	13.4	11.4
	Pol % Cane	11.9	10.9	11.5	*11.4*	10.6	10.4	11.4	12.4	12.3	9.0	11.4	8.7
	Fibre % Cane	14.1	14.7	13.8	*14.2*	13.6	18.3	18.4	15.9	17.1	19.3	20.7	18.1
	DM % Cane	28.3	28.2	27.7	*28.1*	26.7	31.1	32.1	30.3	31.3	31.1	34.1	29.5
	Purity %	82.4	79.5	82.3	*81.4*	80.6	80.0	81.3	85.1	86.3	72.0	83.4	74.2
	Aboveground biomass traits												
	Cane Yield (FW)	75.6	73.4	75.1	*74.7*	73.0	87.4	90.9	83.0	81.7	90.3	70.2	111.4
	SCAR yield (FW)	14.8	19.4	15.8	*16.7*	15.3	17.3	16.5	15.2	15.2	18.7	15.2	20.9
	Cane dry matter yield	21.1	20.4	20.9	*20.8*	19.4	26.4	29.1	25.2	25.5	27.7	23.9	32.8
	SCAR yield DW	4.3	5.6	5.0	*5.0*	4.4	5.0	4.8	4.4	4.4	5.4	4.4	6.1
	Sucrose yield	8.6	7.5	8.4	*8.2*	7.5	8.4	10.2	9.8	9.6	7.5	8.1	9.4
	Fibre yield	10.6	10.8	10.5	*10.6*	9.9	15.7	16.8	13.5	14.2	17.5	14.5	20.3
	Impurity yield	1.9	2.1	2.0	*2.0*	1.9	2.3	2.2	1.9	1.7	2.8	1.3	3.2
	Cane morphology traits												
	Stalk number (m^{-1})	11.9	12.0	12.0	*12.0*	13.5	20.0	17.5	18.6	12.2	15.3	16.5	17.5
	Cane diameter (mm)	27.5	27.7	29.0	*28.1*	31.0	22.7	26.0	26.3	26.5	25.2	25.0	22.2
	Cane height (cm)	264.7	253.0	242.2	*253.3*	257.7	310.0	312.5	298.0	305.8	325.8	336.5	343.8

DW: Dry weight; FW: Fresh weight; DM: Dry matter; SCAR: Sugarcane agricultural residues (cane tops, green and clinging dry leaves)

Appendix 6-2: Performance of high biomass canes in 1st ratoon crop in the dry zone in June and December at 12-months aged crops

	Harvest		**Control varieties**			*Control*	**Test varieties**							
SITE	date	**Variables**	**M1400/86**	**R570**	**R579**	*Average*	**M1334/84**	**M1395/87**	**M196/07**	**M202/07**	**R585**	**WI79460**	**WI79461**	**WI81456**
Dry zone	Jun	**Cane quality traits**												
		Brix % Cane	14.6	13.6	14.7	*14.3*	12.8	12.8	11.8	15.0	15.1	11.0	12.5	10.8
		Pol % Cane	11.5	11.1	12.5	*11.7*	10.0	9.9	8.1	12.3	12.7	6.8	9.4	6.2
		Fibre % Cane	15.3	15.7	16.1	*15.7*	16.1	20.6	19.5	17.7	18.1	21.2	20.8	20.5
		DM % Cane	29.9	29.2	30.8	*30.0*	28.9	33.3	31.3	32.7	33.2	32.3	33.3	30.6
		Purity %	78.9	81.8	84.7	*81.8*	78.0	77.7	68.0	81.9	84.1	60.8	74.6	56.8
		Aboveground biomass traits												
		Cane Yield (FW)	142.6	124.9	155.5	*141.0*	175.1	104.4	133.6	116.4	108.2	97.7	93.2	122.8
		SCAR yield (FW)	23.1	26.9	42.4	*30.8*	31.5	33.8	31.9	34.0	23.1	19.3	24.8	16.9
		Cane dry matter yield	42.6	36.6	47.9	*42.4*	50.5	34.9	42.1	38.3	35.9	31.7	31.1	37.5
		SCAR yield DW	6.7	7.8	12.3	*8.9*	9.1	9.8	9.2	9.9	6.7	5.6	7.2	4.9
		Sucrose yield	16.3	13.9	19.5	*16.6*	17.3	10.3	10.9	14.4	13.7	6.7	8.7	7.5
		Fibre yield	22.0	19.6	25.0	*22.2*	28.3	21.5	26.2	20.8	19.6	21.0	19.4	25.2
		Impurity yield	4.4	3.1	3.5	*3.6*	4.9	3.0	5.0	3.1	2.6	4.1	3.0	5.8
		Cane morphology traits												
		Stalk number (m^{-1})	18.3	15.5	16.0	*16.6*	18.7	27.0	19.3	21.3	16.2	18.0	19.3	18.8
		Cane diameter (mm)	31.7	30.7	35.0	*32.4*	35.3	24.3	26.0	26.7	29.0	27.7	24.0	25.7
		Cane height (cm)	325.0	304.7	290.0	*306.6*	331.7	361.0	350.0	363.3	353.3	388.3	362.7	394.3
	Dec	**Cane quality traits**												
		Brix % Cane	19.1	18.4	17.3	*18.2*	17.2	16.8	17.5	15.8	18.0	15.2	14.9	15.5
		Pol % Cane	18.4	17.7	16.3	*17.4*	16.1	16.1	17.1	14.7	17.4	14.5	14.1	14.7
		Fibre % Cane	18.8	18.8	16.4	*18.0*	17.6	23.1	22.9	18.0	21.8	24.5	23.8	23.1
		DM % Cane	37.8	37.2	33.7	*36.2*	34.7	39.8	40.3	33.8	39.8	39.7	38.7	38.7
		Purity %	96.2	96.4	94.0	*95.6*	93.8	95.9	97.6	92.8	96.5	95.6	94.7	94.4
		Aboveground biomass traits												
		Cane Yield (FW)	101.9	78.4	90.7	*90.3*	114.5	91.9	106.0	96.0	86.5	75.8	72.1	100.4
		SCAR yield (FW)	20.1	19.2	15.3	*18.2*	14.2	16.5	23.9	20.8	17.4	19.2	15.3	19.7
		Cane dry matter yield	38.5	29.0	30.5	*32.7*	39.7	36.6	42.8	32.6	34.4	30.2	27.9	38.8
		SCAR yield DW	5.8	5.6	4.4	*5.3*	3.7	4.8	6.9	6.0	5.0	5.6	4.4	5.7
		Sucrose yield	18.7	13.8	14.8	*15.8*	18.5	14.8	18.1	14.4	15.0	11.0	10.2	14.7
		Fibre yield	19.1	14.6	14.9	*16.2*	20.0	21.2	24.3	17.2	18.9	18.6	17.2	23.2
		Impurity yield	0.7	0.5	0.9	*0.7*	1.2	0.6	0.4	1.0	0.5	0.5	0.6	0.9
		Cane morphology traits												
		Stalk number (m^{-1})	21.0	15.2	17.2	*17.8*	21.7	30.0	24.8	20.2	13.7	21.2	20.3	29.0
		Cane diameter (mm)	28.0	28.0	29.3	*28.4*	29.3	20.0	20.7	24.0	24.0	24.7	22.7	22.0
		Cane height (cm)	257.7	255.0	257.0	*256.6*	267.0	297.3	306.7	260.7	320.0	333.3	310.0	353.7

DW: Dry weight; FW: Fresh weight; DM: Dry matter; SCAR: Sugarcane agricultural residues (cane tops, green and clinging dry leaves)

Appendix 6-3: Performance of high biomass canes in 1st ratoon crop in the super-humid zone in June and December at 12-months aged crops

	Harvest		**Control varieties**			***Control***	**Test varieties**							
SITE	date	**Variables**	**M1400/86**	**R570**	**R579**	***Average***	**M1334/84**	**M1395/87**	**M196/07**	**M202/07**	**R585**	**WI79460**	**WI79461**	**WI81456**
Super-humid zone														
	Jun	**Cane quality traits**												
		Brix % Cane	12.6	11.7	13.3	*12.5*	12.2	11.0	11.7	13.2	13.1	9.3	11.1	10.2
		Pol % Cane	9.4	8.1	10.1	*9.2*	8.9	7.8	8.0	10.5	10.4	4.9	8.2	6.3
		Fibre % Cane	14.2	14.9	14.7	*14.6*	13.6	17.9	18.9	17.0	18.0	19.9	21.0	19.3
		DM % Cane	26.7	26.7	28.0	*27.1*	25.7	28.9	30.6	30.2	31.1	29.2	32.1	29.5
		Purity %	74.8	69.2	75.8	*73.3*	73.3	70.7	68.3	79.3	80.0	52.6	73.4	61.1
		Aboveground biomass traits												
		Cane Yield (FW)	90.2	89.4	94.5	*91.4*	87.1	115.8	96.1	109.4	107.5	105.0	68.3	120.6
		SCAR yield (FW)	15.7	17.0	12.4	*15.0*	21.6	18.6	12.7	19.2	17.4	12.8	10.6	17.5
		Cane dry matter yield	24.1	23.8	26.5	*24.8*	22.4	33.3	29.4	33.1	33.5	30.6	21.9	35.4
		SCAR yield DW	4.6	4.9	4.4	*4.6*	6.3	5.4	3.7	5.6	5.0	3.7	3.1	5.1
		Sucrose yield	8.5	7.3	9.5	*8.4*	7.8	9.1	7.7	11.6	11.2	5.1	5.6	7.5
		Fibre yield	12.8	13.4	13.9	*13.4*	11.8	20.5	18.2	18.5	19.5	20.8	14.4	23.2
		Impurity yield	2.9	3.2	3.0	*3.0*	2.8	3.7	3.5	3.0	2.8	4.6	2.0	4.7
		Cane morphology traits												
		Stalk number	10.0	9.2	9.7	*9.6*	11.5	18.8	13.5	15.0	11.8	13.0	14.7	15.8
		Cane diameter	28.7	30.0	30.7	*29.8*	32.0	25.0	27.3	27.3	28.0	26.7	25.7	23.0
		cane height	277.7	282.7	257.0	*272.4*	280.0	335.0	336.0	326.7	316.7	362.7	384.0	357.7
	Dec	**Cane quality traits**												
		Brix % Cane	15.9	15.2	14.6	*15.2*	14.0	14.6	15.7	15.6	15.3	14.2	15.7	12.6
		Pol % Cane	14.3	13.6	13.0	*13.6*	12.3	13.0	14.8	14.2	14.2	13.0	14.7	11.0
		Fibre % Cane	14.0	14.5	12.8	*13.8*	13.7	18.7	17.9	14.8	16.1	18.7	20.3	16.9
		DM % Cane	29.9	29.7	27.4	*29.0*	27.7	33.3	33.6	30.4	31.4	32.9	36.0	29.6
		Purity %	90.0	89.8	88.7	*89.5*	87.9	89.3	94.3	90.9	92.5	91.3	93.5	87.3
		Aboveground biomass traits												
		Cane Yield (FW)	61.1	57.3	55.6	*58.0*	59.0	59.0	85.6	56.6	55.8	75.6	72.0	102.3
		SCAR yield (FW)	13.9	21.9	19.2	*18.3*	9.1	16.0	20.3	11.1	13.0	24.5	19.9	24.3
		Cane dry matter yield	18.0	17.0	15.3	*16.8*	16.3	19.5	28.8	17.3	17.6	24.8	25.9	30.2
		SCAR yield DW	4.0	6.4	5.6	*5.3*	2.6	4.6	5.9	3.2	3.8	7.1	5.8	7.0
		Sucrose yield	8.7	7.8	7.2	*7.9*	7.3	7.7	12.7	8.1	7.9	9.8	10.5	11.3
		Fibre yield	8.4	8.3	7.1	*7.9*	8.0	11.0	15.3	8.4	9.0	14.2	14.7	17.3
		Impurity yield	1.0	0.9	0.9	*0.9*	1.0	0.9	0.8	0.8	0.6	0.9	0.7	1.6
		Cane morphology traits												
		Stalk number (m^{-1})	13.8	14.8	14.3	*14.3*	15.5	21.2	21.5	22.2	12.5	17.5	18.3	19.2
		Cane diameter (mm)	26.3	25.3	27.3	*26.3*	30.0	20.3	24.7	25.3	25.0	23.7	24.3	21.3
		Cane height (cm)	251.7	223.3	227.3	*234.1*	235.3	285.0	289.0	269.3	295.0	289.0	289.0	330.0

DW: Dry weight; FW: Fresh weight; SCAR: Sugarcane agricultural residues (cane tops, green and clinging dry leaves)

Appendix 6-4: Cane yield dry weight estimates in 8-, 10- and 12-months old crops harvested in June and December

Harvest	Region	Variety	February 8-months	April 10-months	June 12-months	August 8-months	October 10-months	December 12-months
June	Dry zone	M1400/86	10.7	35.3	42.6			
		R570	7.3	27.5	36.6			
		R579	11.2	37.4	47.9			
		Control Average	***9.8***	***33.4***	***42.4***			
		M1334/84	11.3	36.8	50.5			
		M1395/87	7.4	24.1	34.9			
		M196/07	10.6	33.1	42.1			
		M202/07	6.6	24.4	38.3			
		R585	8.5	28.5	35.9			
		WI79460	5.7	25.2	31.7			
		WI79461	10.5	28.1	31.1			
		WI81456	11.0	28.2	37.5			
	Super-humid zone	M1400/86	8.1	19.5	24.1			
		R570	7.2	21.1	23.8			
		R579	11.7	23.1	26.5			
		Control Average	***9.0***	***21.3***	***24.8***			
		M1334/84	5.7	17.8	22.4			
		M1395/87	11.4	27.1	33.3			
		M196/07	8.2	27.7	29.4			
		M202/07	8.6	26.4	33.1			
		R585	11.5	30.8	33.5			
		WI79460	12.1	29.7	30.6			
		WI79461	5.5	17.8	21.9			
		WI81456	23.1	33.6	35.4			
December	Dry zone	M1400/86				30.4	32.8	38.5
		R570				24.1	28.4	29.0
		R579				27.1	29.0	30.5
		Control Average				***27.2***	***30.0***	***32.7***
		M1334/84				32.6	38.0	39.7
		M1395/87				30.7	33.7	36.6
		M196/07				37.9	41.0	42.8
		M202/07				28.7	30.6	32.6
		R585				28.5	30.4	34.4
		WI79460				23.2	26.0	30.2
		WI79461				24.2	26.9	27.9
		WI81456				30.2	34.7	38.8
	Super-humid zone	M1400/86				12.0	14.7	18.0
		R570				11.5	15.2	17.0
		R579				9.9	12.6	15.3
		Control Average				***11.1***	***14.2***	***16.8***
		M1334/84				11.5	14.0	16.3
		M1395/87				14.1	16.7	19.5
		M196/07				16.2	22.1	28.8
		M202/07				11.9	15.4	17.3
		R585				12.6	15.0	17.6
		WI79460				16.2	19.6	24.8
		WI79461				17.4	20.6	25.9
		WI81456				25.5	28.6	30.2

Chapter 7

Further investigations on selected high biomass varieties

7 Further investigations on selected high biomass varieties

Abstract

In this study, a selected group of biomass varieties implemented in the four trials in the sub-optimal environments were retained for analyses on their energy equivalences, the creation of an economic selection index (ESI) and on the determination of the most appropriate harvesting method. The gross calorific values (GCVs) in terms of kilojoules per kilogram (KJ kg^{-1}) of different cane components dry weight, were obtained using a boom calorimeter. The values were used to estimate the net energy output of the different varieties in terms of gigajoules per hectare per year (GJ ha^{-1} yr^{-1}). The ESI for each variety was based on the products of economic weights of sugar and bagasse with their corresponding yields obtainable from the different varieties. Economic weights were the actual price per tonne paid to sugarcane growers for the different components. The ease of manual harvesting the different varieties with variable fibre content was measured using a five-point-scale-index. Strategies for mechanical harvesting were also investigated from available literature. The GCVs of bagasse and cane trash were comparable and nearly the same for the different varieties, while those for cane juice were more variable. The net energy outputs of the different varieties generally showed nearly the same relative differences from the commercial varieties as those of total aboveground dry matter yields in t ha^{-1} yr^{-1}. However, ranking changed drastically with the ESI, which favored varieties rich in sucrose content at the expense of high fibre canes. Those energy canes were also found most difficult to harvest manually. Further research strategies on mechanized whole cane harvesting were elucidated.

Keywords: energy canes, net energy output, economic selection index, whole cane harvesting

7.1 Introduction

The different types of new high biomass varieties identified from the trials implemented in two marginal environments in 2014 were M 1334/84 as *Type 1* cane (high sucrose low fibre), R 585 as *Type* 2 cane (high sucrose high fibre) and, M 196/07, M 1395/87 and WI 81456 as *Type 3* canes (low sucrose high fibre). Out of the three, M 196/07 had relatively higher sucrose content and was at the margin of *Type* 2 and *Type* 3 canes. Given its high fibre content and its morphological attributes, a conservative approach was adopted in this study by considering the clone as a *Type 3* cane. M 1156/00 was the only pure fibre *Type 4* energy cane with negligible sucrose and very high fibre. However, its poor germination in the trials was a point of concern and an area of further investigations. Nevertheless, some information could be made available from the sporadically germinated stools. In this study, we focused on three main objectives, namely:

a) the energy equivalence of the selected best biomass varieties identified from the trials implemented in marginal environments,
b) the creation of a simple economic selection model that will be helpful in screening high biomass varieties with maximum profit, and
c) the different harvesting scenarios of the different cane components.

For more precise information, the three objectives require large scale industrial cultivation, milling and processing at the factory, and experts from diverse sources (sugarcane technologists, economists, agronomists and mechanization scientists). These were beyond the scope of this study as the trials implemented consisted of relatively small plots of 65 m^2 each. The findings from this study are, nevertheless, expected to contribute towards more intensive future research focal areas.

7.2 The energy equivalence of selected biomass varieties

A major bottleneck with the generation of biofuels currently is related to the gain in terms of net energy output to input ratio (NER- net energy input divided by net energy output). To be a viable alternative, a biofuel should provide a net energy balance (NEB – net energy output minus net energy input) over the energy required to produce it (Hill *et al.*, 2006). Quantifying the energy output value of an energy crop is measuring the quantity of energy content of the biofuels produced in terms of Gigajoules per hectare per year (GJ ha^{-1} yr^{-1}). Obtaining the value of energy input is more complex and involves the assignment of an energy value to all the inputs in producing the crop and processing it to energy (Hill *et al.*, 2006). In this sub-section, we focused on the total aboveground energy equivalence (energy output) of selected biomass varieties with variable sucrose to fibre ratios.

7.2.1 Materials and methods

The varieties retained for this study were M 1400/86 (control variety), M 1334/84, M 196/07, M 1395/87, WI 81456 and M 1156/00. The first two were of commercial type with high sucrose and low fibre. The next three had lower sucrose and higher fibre. The last candidate, M 1156/00, is known to have negligible sucrose and very high fibre. Six cane samples were taken in October 2015 from each replicate in the late-season trial implemented in the dry zone. The canes were trashed and topped. The non-millable parts (CTL) were chopped to about a cm length and collected in bags, weighed and oven-dried at 105 ^{0}C for 48 hours. The dried trash from the three replicates were ground into tiny particles and thoroughly mixed together. Sampling procedure was adopted that consisted of separating the sample into two equal halves. A half was discarded and the second half was thoroughly mixed again. The sampling procedure was repeated three to four times until a uniform quantity of 100 g of ground thoroughly mixed dry trash were left for each variety. The latter were kept sealed in plastic containers. A boom-calorimeter was used to determine the gross calorific value (GCV_{trash}), in Mega-Joule per kilogram (MJ kg^{-1}), of each variety from the sealed sample.

The clean cane stalk samples taken from the field were shredded into tiny particles. Part of each sample was used to determine the cane quality traits as per the methods described in page 31. The oven-dried clean fibre obtained through the process was used to determine the GCV_{fibre} for each variety. The remaining shredded and unwashed cane sample that contained the cane juice and fibre was oven-dried similarly for each variety. The dried samples were subjected to sampling procedure, sealed and used for the determination of the corresponding $GCV_{fibre + juice}$ values.

Overall, the energy equivalence of three aboveground components, namely cane fibre (GCV_{fibre}), cane juice (GCV_{juice}) and trash (GCV_{trash}) were derived. GCV_{fibre} and GCV_{trash} were obtained directly from the calorimeter readings. GCV_{juice} for each variety was determined indirectly using the proportion of Brix and fibre in the dried unwashed samples and the formula described below:

$$GCV_{juice} = (GCV_{fibre + juice} - (\text{Fibre DW \% x } GCV_{fibre}))/(\text{Brix DW\%}) \qquad \text{Eq. 1}$$

where the suffixes represent the different cane components from the same field sample and DW% is the dry weight percentage of fibre or Brix from the corresponding cane sample.

These values were used to determine the energy equivalence in GJ ha^{-1} yr^{-1} based on the yields per hectare of the individual varieties from 12-months old crops. The net energy equivalences were determined by the sum total of the simple products of individual components yields in dry weight and their corresponding GCVs.

7.2.2 Results and discussion

The dry weight GCVs in KJ kg^{-1} of the selected biomass varieties are given in Table 7-1. Generally, GCV of dried bagasse averaged 19200 KJ kg^{-1} and all the varieties showed nearly the same energy equivalence. The pure fibre type energy cane M 1156/00 was top-ranking with 20783 KJ kg^{-1}. The GCV of dried trash averaged 16700 KJ kg^{-1} and, similar to bagasse, the varieties did not show any marked differences. For cane juice dry weight, however, the pure fibre type cane M 1156/00 showed much less energy equivalence (6985 KJ kg^{-1}), while the remaining varieties fluctuated in the range of 12000-17000 KJ kg^{-1}. Highest juice calorific value was obtained from variety WI 81456 (16857 KJ kg^{-1}).

Table 7-1: The dry weight GCVs of different aboveground components of selected varieties

Cane type	Variety	Dry weight proportions		GCV (KJ kg^{-1}) on dry weight samples		
		Juice % (Brix)	Fibre %	Juice only	Bagasse only	Trash (CTL)
Type 1	**M 1400/86**	**49.24**	**50.76**	**13453**	**20260**	**17490**
Type 1	M 1334/84	48.98	51.02	11996	18450	16820
Type 3	M 196/07	40.16	59.84	13759	17462	16816
Type 3	M 1395/87	38.01	61.99	12732	20156	16545
Type 3	WI 81456	33.89	66.11	16857	18218	16010
Type 4	M 1156/00	20.81	79.19	6985	20793	16438

In bold: Commercial control variety; GCV: Gross calorific value

The dry matter yields in t ha^{-1} yr^{-1} of the different components were derived from the first ratoon crop, as given in Table 6-2, page 99, and the Chapter 6 appendixes, pages 108-111. The overall performance of the selected high biomass varieties, averaged across the four trials implemented in 2014 in marginal areas, are given in Table 7-2.

Table 7-2: Yield per hectare and energy equivalence of selected high biomass varieties across four trials combined (broad inference)

	Yield dry weight (t ha^{-1} yr^{-1})				Energy equivalence (GJ ha^{-1} yr^{-1})				
Varieties	Brix (Juice)	Fibre (bagasse)	Field residues (SCAR)	Total yield	Brix (Juice)	Fibre (bagasse)	Field residues (SCAR)	Total energy	Difference from M 1400/86
M 1400/86	15.4	15.4	5.5	36.3	207.1	312.8	95.6	615.5	
M 1334/84	15.5	16.8	4.9	37.1	185.6	309.5	81.6	576.7	94%
M 1395/87	12.7	18.4	5.7	36.8	161.3	371.4	94.2	626.9	102%
M 196/07	14.9	20.9	6.6	42.4	205.5	364.1	110.9	680.5	111%
WI 81456	13.6	22.1	5.7	41.2	229.5	402.4	91.2	723.1	117%

Compared to the commercial control variety M 1400/86, test candidates M 1334/84 and M 1395/86 showed nearly the same overall net energy equivalence in GJ ha^{-1} yr^{-1}. WI 81456 showed +17% higher energy than that of M 1400/86 and was followed by M 196/07 with +15%.

As observed in the previous chapters, differential performance of varieties across locations for yield parameters was highly significant. In consequence, higher precision was expected from evaluations in individual locations (Table 7-3).

Table 7-3: Yield per hectare and energy equivalence of selected high biomass varieties in individual locations

	Yield dry weight (t ha^{-1})				Energy equivalence (GJ ha^{-1} yr^{-1})				
Varieties	Brix (Juice)	Fibre (bagasse)	Field residues (SCAR)	Total yield	Brix (Juice)	Fibre (bagasse)	Field residues (SCAR)	Total energy	Difference from M 1400/86
Super-humid zone									
M 1400/86	10.6	10.5	4.3	25.4	142.6	212.5	75.2	430.2	
M 1334/84	9.5	9.9	4.4	23.8	113.8	182.0	74.8	370.6	86%
M 1395/87	10.9	15.6	5.0	31.4	138.5	313.5	82.9	534.9	124%
M 196/07	12.4	16.7	4.8	33.9	170.9	291.5	80.5	542.9	126%
WI 81456	12.7	20.1	6.1	38.9	214.0	366.5	96.9	677.5	157%
Dry zone									
M 1400/86	20.2	20.4	6.3	46.9	271.2	414.0	109.6	794.7	
M 1334/84	21.3	23.9	6.4	51.6	254.9	440.6	108.0	803.5	101%
M 1395/87	14.4	21.3	7.3	43.0	183.9	429.6	120.5	734.0	92%
M 196/07	17.4	25.1	8.1	50.5	238.9	438.1	135.9	812.9	102%
WI 81456	14.5	24.1	5.3	43.5	244.9	438.3	85.0	768.2	97%

In the super-humid environment at Valetta, WI 81456 had the highest energy equivalence (677.5 GJ ha^{-1} yr^{-1}) that was +57% superior to that of M 1400/86. M 196/07 followed with 542.9 GJ ha^{-1} yr^{-1} (+26%). In the dry non-irrigated zone of Ferret, the differences were much reduced and negligible compared to the commercial variety M 1400/86.

Overall, then, it could be confidently stated that two varieties, namely M 196/07 and WI 81456 represented the best biomass varieties in terms of total aboveground energy equivalence. WI 81456 was top-ranking in the super-humid environment. The energy equivalence of fibre derived from the pure fibre cane M 1156/00 was also highly appreciable (Table 7-1), although its yield per hectare could not be determined for reasons explained earlier.

7.3 Economic selection index

The different components of aboveground biomass of sugarcane (cane juice, bagasse and field residues) have different economic values. In order to create new varieties with maximum profit, an economic weight needs to be applied to each of the different components. Economic selection indexes in sugarcane have been devised with a sugar maximization perspective (Simmonds and Walker, 1986, Deren *et al.*, 1995, Alvarez *et al.*, 2009). Wei *et al.* (2007) attempted a model that included economic weights for fibre as well but were limited with the lack of information on the income and cost structures for the entire production, processing and marketing chain, thereby encompassing the crop production, milling and marketing costs and revenues. In this study, we attempted a simple economic selection index based on the revenue paid to farmers in Mauritius for every tonne of the different components obtained from sugarcane.

7.3.1 Materials and methods

The full model of the economic selection index for screening the most profitable biomass varieties could be written as follows:

$$ESI = (EW_{sugar} \text{ x } SY) + (EW_{bagasse} \text{ x } BY) + (EW_{trash} \text{ x } TY) + (EW_{molasses} \text{ x } MY) \qquad \text{Eq. 2}$$

where ESI represents Economic Selection Index, EW is the economic weight and the suffixes represent the corresponding sugarcane aboveground components. SY stands for sugar yield, BY for bagasse yield, TY for trash yield and MY for molasses yield in t ha^{-1}.

The economic weights are represented here as the actual price paid to sugarcane growers for every tonne of the respective products. These are clearly defined for sugar and molasses, indirectly for bagasse and not at all for trash left in the field. The estimated price per tonne of sugar for the year 2016 is MUR15600.00 (Pers. Com. Mauritius Sugar Syndicate, 2017). Planters are being paid MUR 2074.58 per tonne of molasses. The price of bagasse has recently been raised from MUR 125.00 to MUR 1225.00 per tonne of sugar for planters producing up to 60 tonnes of sugar. Those producing beyond 60 tonnes are receiving MUR 300.00 for every additional tonne of sugar. Extrapolating from the proportions of the different components worked out by Beeharry (1996) (see Figure 2-3, page 12), for every tonne of sugar produced from conventional varieties, 3 tonnes of bagasse at 50% moisture content are obtainable. The upper limit revenue from a tonne of bagasse (with 50% moisture content) would be (MUR 1225.00 ÷ 3 =) MUR 408.00. Roughly, bagasse dry weight would double the amount. This would summarize to MUR 15600.00, MUR 816.00 and MUR 2074.00 for every unit tonne of sugar, bagasse dry weight and molasses, in the ratio of 38:2:5, respectively. In this study, the amount of molasses obtainable from milling and processing of high fibre energy canes could not be estimated. The only way to get that information would be through real processing of the variety at the mill, which was not possible in this study. Sugarcane trash (the price of which is not established) and molasses from the different varieties were thus assumed to be constant and, in consequence, dropped from the full model. The reduced simplified model, comprising sugar yield and cane fibre yield, could then be written as follows:

$$\text{ESI} = (38 \times \text{SY}) + (2 \times \text{BY}) \qquad \text{Eq. 3}$$

where ESI represents Economic Selection Index, SY sugar yield and BY bagasse yield in t ha^{-1}.

Sugar yield was determined as the product of cane yield and industrially recoverable sucrose content (IRSC), as follows:

$$\text{SY} = \text{Cane yield} \times \text{IRSC, and} \qquad \text{Eq. 4}$$

$$\text{IRSC} = (0.85 \times \text{Pol \%}) - 1.65 \qquad \text{Eq. 5}$$

where 0.85 is the correction factor for the presence of extraneous matter sent to the mill and 1.65 is the loss at the mill. IRSC is generally used to estimate the maximum extractible sugar from the canes reaching the mill.

The ESI formula (Eq. 3) was applied to the corresponding yields obtained from the different varieties at the first ratoon crop in 2016 (as given in Table 6-2, page 99 and the annexed Chapter 6 appendixes) and the most profitable varieties, from the farmers' perspective, were identified.

7.3.2 Results and discussion

Table 7-4 summarizes the first three most profitable varieties from the combined and individual trial analyses. Overall, two commercial varieties (M 1400/86 and R 579) and one high fibre variety (M 196/07) were best ranked. M 196/07, generally categorised as *Type 3* cane, had relatively high sucrose and was top-ranking in terms of ESI in the super-humid environment. In the dry zone, M 1334/84, another commercial type variety, was classified best. The highest energy output variety (WI 81456) in the super-humid environment (see Table 7-3), was superseded by varieties with higher sucrose content in all trials.

In general, with the existing cane payment system, the ESI favoured the sucrose rich varieties (M 1400/86, M 1334/84 and R 579). M 196/07 was the only high fibre variety with relatively high sucrose level among the *Type 3* canes and it was effectively screened by the ESI. The other high fibre energy canes with lower sucrose content (M 1395/87 and WI 81456) were less remunerative.

Table 7-4: Three best ranked varieties using ESI from individual and combined trials analyses

Ranking	Variety	Sugar yield	Fibre yield	ESI
Overall (all trials combined)				
1	**M 1400/86**	9.6	15.6	397.1
2	M 196/07	9.0	21.0	383.9
3	**R 579**	9.3	15.2	382.7
Dry zone (harvest dates combined)				
1	M 1334/84	13.7	24.2	567.4
2	**M 1400/86**	13.5	20.5	554.2
3	**R 579**	13.0	19.9	534.2
Super-humid zone (harvest dates combined)				
1	M 196/07	7.3	16.8	311.5
2	M 202/07	7.4	13.5	306.6
3	R 585	7.2	14.2	301.9
Dry zone - June harvest				
1	**R 579**	13.9	25.0	579.1
2	M 1334/84	11.9	28.3	509.7
3	**M 1400/86**	11.6	22.0	484.7
Dry zone - December harvest				
1	**M 1400/86**	14.2	19.1	578.6
2	M 196/07	13.6	24.3	566.0
3	M 1334/84	13.8	20.0	564.8
Super-humid zone - June harvest				
1	M 202/07	8.0	18.5	340.1
2	R 585	7.8	19.5	334.3
3	**R 579**	6.5	13.9	276.0
Super-humid zone - December harvest				
1	M 196/07	9.4	15.3	387.6
2	WI 81456	7.9	17.3	335.0
3	WI 79461	7.8	14.7	325.6

In bold: sucrose rich commercial varieties; ESI: Economic Selection Index

7.4 Harvesting strategies of high fibre canes

Considering the exploitation of the whole of the aboveground parts requires exploration on the different harvesting techniques. While high fibre canes provide a significant alternative to increase bagasse, sugar cane field residues (SCAR) collection and burning in boilers provide an additional source of biomass as a bagasse-mix for cogeneration (Panray Beeharry, 2001; Hassuani *et al.*, 2005; Franco *et al.*, 2013; Antonio Bizzo *et al.*, 2014; Smithers, 2014). Different scenarios exist in collecting the whole of the aboveground biomass. In this study, we focused on the level of difficulties observed from harvesting different types of high biomass canes and identify strategies that would be most appropriate.

7.4.1 Materials and methods

The four trials in the marginal areas were harvested manually. Labourers were asked to rate the level of difficulty in harvesting the different types of canes on a five-point scale index, where 1 =

very easy, 2 = fairly easy, 3 = fairly difficult, 4 = difficult and 5 = very difficult. Furthermore, a survey was carried out in 2015 at Terragri Ltd. where cane trash is collected after harvest of cane fields. The findings were compared with available literature to identify the best harvesting approach of high fibre energy canes.

7.4.2 Results and discussion

The average ratings of labourers on the level of difficulty observed at harvest are presented in Table 7-5. The commercial type varieties (*Type 1* canes - M 1400/86, M 1334/84), with relatively thick and short cane stalks and low fibre content, were easiest to harvest manually. The enhanced fibre type canes (*Type 2* canes – M 196/07 and R 585) were rated as fairly difficult to cut. The higher fibre *Type 3* canes (M 1395/87 and WI 81456) that were also thinner and taller were found tough and difficult to cut manually. The pure fibre *Type* 4 cane, M 1156/00, was considered most difficult as several knife strikes were necessary to cut one stalk.

Table 7-5: Level of difficulty with manual harvest of different high biomass canes

Varieties	Cane Type	Difficulty rating at harvest	Description
M 1400/86	*Type 1*: High sucrose low fibre	1	Very easy
M 1334/84	*Type 1*: Average sucrose low fibre	1	Very easy
R 585	*Type 2*: High sucrose high fibre	3	Fairly difficult
M 196/07	*Type 3*: Lower sucrose high fibre	3	Fairly difficult
M 1395/87	*Type 3*: Lower sucrose higher fibre	4	Difficult
WI 81456	*Type 3*: Lower sucrose higher fibre	4	Difficult
M 1156/00	*Type 4*: Negligible sucrose, very high fibre	5	Very difficult

In bold: Commercial control varieties

Labourers also argued that high fibre energy canes, that are generally lighter than commercial varieties, would not be remunerative when paid on a tonnage basis. As such, mechanized harvest of energy canes is fundamental.

Currently, mechanized harvest of commercial fields is a common practice in Mauritius. The sugarcane field residues (SCAR) are being collected after harvest by sugar estates and burnt in boilers as a bagasse-mix for cogeneration. The methodology adopted is one alternative and involves leaving the trash in the field for a few days after harvest to decrease its water content through natural drying. Tractor mounted windrowing equipments gather around 50% of the field residues and a baler collects and compresses them (Figure 7-1). The bales are transported by trucks to the industry. The trash is de-compacted and used along with bagasse for co-generation. A range of costs is associated with bale handling, transportation and storage.

Figure 7-1: Trash collection, baling and use as bagasse mix for electricity production in Mauritius

Another alternative, not yet adopted in Mauritius, involves "integral harvesting system" where the whole aboveground canopy is mechanically harvested, chopped and transported together with the sugarcane trash without laying it down to the ground for natural drying. At the mill, trash is separated from stalks using an air separation system (Hassuani *et al.*, 2005). Harvesting whole cane, however, results in a significant increase in the total mass of product to be harvested and transported (McGuire *et al.*, 2010). Additionally and more significantly, it also results in a considerable decrease in the bulk density of the transported material. The bulk density of the cane/trash mix has a significant impact on whole cane harvest and transport costs and so strategies are being identified worldwide that would increase bulk density (Inderbitzin and Beattie, 2013).

A third alternative is a "harvester-mounted trash shredder and collection system", which involves cane trash to be shredded and collected separately from the cane during the harvesting process (Figure 7-2). Two tractors mounted with bins run in parallel with the sugarcane harvester. Chopped clean canes are collected in the first and the trash is blown in the second. The development of such a harvester-mounted cane trash shredder and collection system has been achieved but the economics of this approach

Source: Spinaze et al (2002)

Figure 7-2: Harvester-mounted trash shredder and collection require further evaluation (Zafar, 2015).

The fourth alternative remains to investigate on a range of small to mini sugarcane harvesters capable of cutting the canes at the base in small and undulating marginal lands (Figure 7-3) and sending the whole aboveground parts to the mill. Various models have been developed that have the potential to adapt to various agro-climatic conditions, including under wet conditions caused by frequent rain during the harvesting season (Shinzato *et al.*, 2015).

Source: https://www.youtube.com/watch?v=pcah0HevSVU

Figure 7-3: A small sugarcane harvester

7.5 Conclusion

The diffferent components of selected varieties showed variable energy equivalences. The dry weight GCVs of bagasse and trash were nearly the same and fluctuated around 17000 to 19000 KJ kg^{-1}. The GCVs for cane juice that were worked out by difference were more variable among the varieties with the lowest (6985 KJ kg^{-1}) obtained from the pure fibre type cane, M 1156/00 and the remaining varieties ranged between 12000 and 17000 KJ kg^{-1}. Extrapolated to GJ ha^{-1} yr^{-1} from the field results, the varieties generally showed nearly the same relative differences from the commercial varieties as those of total aboveground dry matter yields in t ha^{-1} yr^{-1}. WI 81456, that showed 51% higher biomass yield in t ha^{-1} yr^{-1} in the super-humid zone, had 57% higher energy equivalence in GJ ha^{-1} yr^{-1} than the commercial variety M 1400/86.

However, profitability from sugar and bagasse components worked out using ESI had a serious impact on the ranking of the varieties. Those with high sucrose content were largely favoured at the expense of high fibre energy canes. Among the high biomass test candidates, M 1334/84 and M 196/07 were found most remunerative. The current cane payment system does not favour exploitation of fibre as farmers are paid for bagasse in terms to tonnes sugar produced. Evidently, exploitation of energy canes requires a different payment system that directly valorises fibre content and fibre yield.

Furthermore, although the price of sugarcane trash has not been established, exploitation of energy canes involves devising methodologies for harvesting and transporting the whole of the aboveground parts to the mill. This study made it clear that manual harvest of high fibre energy canes was inappropriate, essentially due to the relatively thin, tough and tall cane stalks that were generally lighter than those of the commercial varieties. With mechanized harvest, different alternatives exist. Harvesting energy canes necessitates further research on whole cane harvesting, the bulk density of cane/trash mix, compaction and transport. The “integral harvesting system” or the “harvester-mounted trash shredder and collection system” may prove most effective in already rehabilitated lands and entail in-depth analyses. The difficulty of mechanized whole cane harvesting in Mauritius can get further compounded if energy canes are to be cultivated in marginal and abandoned lands that have not been prepared to accept large and heavy machineries. The adoption of small or mini sugarcane harvesters capable of adapting to harsh agro-climatic conditions needs further investigations.

Chapter 8

General discussion

8 General discussion

8.1 Selection of high biomass canes

Selection of new sugarcane varieties is a lengthy process (12-15 years) whereby various key sugar and yield related parameters from individual varieties need to be assessed thoroughly. Selection of high biomass varieties entails additional measurements related to fibre content and total biomass yield. Moreover, sugarcane is a perennial crop that is planted once and harvested over several years (ratoons). Thus ratooning ability (performance in yield across successive annual harvests) needs to be evaluated. Ultimately, the selected elite genotypes need to be assessed in several environments to determine the best regions where they can be exploited commercially.

Although studies on energy canes started in Mauritius in the mid-1980s with the assessment of basic species and early generation interspecific hybrids, selection of high biomass varieties for commercial exploitation objectively began in 2007 with the evaluation of a 100 varieties (59 locally bred and 41 imported genotypes) at an intermediate selection stage (first replicated clonal stage) and in a sub-humid partially irrigated environment. The study allowed the pioneering definition of four types of high biomass canes that could be cultivated for different end-uses (Santchurn *et al*., 2014), as follows:

Models	**Cane types**	**Categorization**	**Cane components**
Sugar-model	*Type 1*	Existing commercial type	High sucrose, low fibre
Sugar-model	*Type 2*	Enhanced fibre type	High sucrose, high fibre
Fibre-model	*Type 3*	Multi-purpose type	Lower sucrose, higher fibre
Fibre-model	*Type 4*	Pure fibre type	Negligible sucrose, very high fibre

Type 1 and *Type 2* canes represented the sugar model where the main feedstock remained sugar and the fibre generated could be used for bioenergy production. *Type 3* and *Type 4* canes represented the fibre model where the main feedstock was bagasse and the derived juice could be used for ethanol or other high value products. A selection model was developed that could screen the four types of varieties simultaneously. Fourteen best candidates from the 2007 trials were retained for more intensive analyses with higher precision (in larger plots) in a second series of trials (2009-2014) in multiple environments (METs). The clones were evaluated for adaptation to middle season harvest (mid-August to Mid-October) and over plant cane and three ratoons. Data from those trials were used in this study to evaluate the adaptation and stability of high biomass canes across the island and years, and to establish biomass accumulation pattern among the different types of high biomass varieties (Chapters 4 and 5). Five best biomass yielders from those trials, along with four new entries, were implemented in 2014 in four trials to study their performances in two marginal environments (super-humid and dry rain-fed zones) and at contrasting harvest dates, June (early-season harvest) and December (late-season harvest).

The overall approach in this study reflected the true lengthy selection scenario in sugarcane breeding whereby breeders most often need to deal with unbalanced trials (Patterson, 1997; Piepho and Eeuwijk, 2002; Balzarini *et al.*, 2002), as observed with the METs data (Chapter 4), and, at times, even the most balanced trials become unbalanced, as the 2014 trials, due to missing plots caused by mortality or poor germination. As a result, genetic analyses become too complex with the conventional ANOVA techniques. Recent statistical packages, capable of fitting linear mixed models (LMMs) using Residual Maximum Likelihood (REML) algorithm, provide reliable and flexible tools for genetic analyses using unbalanced data (Gilmour *et al.*, 2009; Piepho, 2005; Smith *et al.*, 2005). These techniques, representing an innovative approach in the MSIRI varietal evaluation programme, were used in this study wherever necessary (Chapters 3, 4 and 6) to obtain pertinent and reliable results from the trials. The LMM approach was also highly informative on the heritability of the traits, genetic gains and on genotype-environment interactions (GEIs).

Generally, the cane quality traits (sucrose and fibre content) were more heritable than the cane biomass parameters, mainly cane yield (see Table 3-4). There was also good evidence that in 12 months old crops, certain varieties that had high sucrose in June were superseded by others in December. For fibre accumulation, however, the interactions between early (June) and late (December) harvests were of lower magnitude. Fibre content was most heritable and stable, with minimum changes in rank, across the two extreme harvest periods in the two locations. These findings confirm that fibre content, once produced, remains fixed in the cane stem and can be stored in the field. For cane biomass parameters, the variety x location interactions were more pronounced and significant than variety x harvest date interactions. These results pertained to the adaptation of genotypes across environments.

The significant GEIs (see Table 3-4) for biomass yield urged for closer investigations on the interactions using statistical tools designed for the purpose. AMMI (Gauch, 1992; Zobel *et al.*, 1988) and GGE (Yan *et al.*, 2000; Gauch *et al.*, 2008) represent the two most advanced multivariate linear-bilinear models, associated with simple graphical displays, currently adopted worldwide in multi-environment trials analyses. Two main differential performances, namely variety x location and variety x year (crop cycle) interactions, were elucidated using data made available from the second series of trials (2009-2014). A total of 14 high biomass varieties were evaluated in five different regions (representing five distinct major soil types) of the island over plant cane and two ratoons. Two of the trials were in extreme environments: one at Mon Desert Alma (super-humid) and one at Belle Vue (dry and non-irrigated). The multivariate models produced visual biplot displays that were very instructive and easy to grasp on the stability and adaptation of the genotypes under evaluation. The various trends were confirmed using basic statistics, ANOVA analyses and appropriate correlations. With both models, the same conclusions were reached. GGE analysis also pointed to the presence of two mega-environments (humid and dry zones) in Mauritius and confirmed that the best high fibre clones were mainly adapted to the more humid regions of the island. The commercial type high sucrose varieties were high biomass producers in the drier areas. These results were confirmed from the trials evaluated in marginal environments (2014-2017).

The analyses also established that yields at plant cane were least representative of the performance of varieties in successive years. Ranking of genotypes and yield changed more drastically between plant cane and ratoon crops than between first and second ratoon crops. Since sugarcane is planted once and harvested over several years, the biomass yields in ratoons were considered closer to the commercial reality. In the trials implemented in marginal environments, plant cane results were obtained in 2015. As mentioned in section 3.4 (page 45), year 2015 was abnormally wet and growth, particularly of commercial control varieties, were below expectation in the upland trials. The relative differences of individual best biomass varieties with the commercial controls for cane yield were >125%. Those differences were effectively reduced to around +50% (see section 6.4, page 106) in the first ratoon crop in 2016 and reflected closely the differences observed from previous trials (see yields at MDA in Table 4-4, page 57). Preliminary raw data obtained from second ratoon harvests, taken in June-July 2017 (early harvest) concur well with the first ratoon results (Table 8-1).

Table 8-1: Raw data obtained from the harvest of second ratoon crops in June-July 2017

Variety	Pol % (sucrose)	Fibre %	Cane yield (t ha^{-1})	Difference from control average for cane yield
Super-humid environment				
M 1400/86	8.46	11.58	58.77	+1%
R 570	7.67	11.96	61.32	+6%
R 579	8.97	11.56	54.07	-7%
Control average	*8.37*	*11.70*	*58.05*	*0%*
M 1156/00	3.18	19.67	-	-
M 1334/84	7.73	11.64	78.68	+36%
M 1395/87	9.03	17.01	75.39	+30%
M 196/07	8.50	16.97	71.93	+24%
M 202/07	9.79	16.45	55.23	-5%
R 585	9.51	16.62	65.93	+14%
WI 79460	7.68	18.21	85.19	+47%
WI 79461	9.89	18.15	75.31	+30%
WI 81456	8.31	18.40	87.33	+50%
Dry rain-fed environment				
M 1400/86	9.94	13.19	109.88	+5%
R 570	9.17	13.41	94.75	-9%
R 579	9.87	12.70	109.47	+5%
Control average	*9.66*	*13.10*	*104.70*	*0%*
M 1156/00	3.91	22.38	-	-
M 1334/84	8.52	12.11	123.66	+18%
M 1395/87	8.64	15.24	81.38	-22%
M 196/07	7.51	16.28	106.48	+2%
M 202/07	10.29	13.96	92.90	-11%
R 585	11.54	16.32	86.42	-17%
WI 79460	8.25	18.49	77.06	-26%
WI 79461	8.98	18.15	70.58	-33%
WI 81456	7.07	18.93	79.32	-24%

Commercial varieties in bold; DW: dry weight

In the super-humid zone, WI 81456 maintained the same +50% superior cane yield than the average of controls as obtained in first ratoon. These findings point to the higher predictive power obtainable from ratoon results.

With the sugarcane cropping system adopted in Mauritius, availability of sugarcane biomass for cogeneration is limited during the harvest season in the second half of the year (June - December). The Independent Power Producers use coal as an alternative to continuously produce electricity during the off-season (January-June). However, the dangers of using coal on environment and health are well known. Whether high fibre energy canes maintain their high yields across the year for the continuous generation of an environment-friendly electricity, giving due consideration to the climatic conditions prevailing in Mauritius, was another major scope of this study. Pre-harvest data were collected in 8- and 10-months old crops from the trials established in the marginal environments. The results were conclusive with respect to few high fibre clones that could be harvested as from 10-month old crops (around April). One candidate, WI 81456, also ensured the fastest growth rate in the super-humid region and by 8-months age (around February) its biomass yield doubled those of the commercial varieties. The genotype may be harvested at a younger stage, thereby ensuring three harvests in two years compared to two annual harvests.

Studies on biomass accumulation also confirmed that energy canes followed the same general patterns as those of the commercial varieties with respect to sucrose and fibre accumulation (Chapter 5). Sucrose accumulation showed a sharp rise at the pre-harvest season (April-June) and a tendency to flatten thereafter. Few profusely flowered clones showed significant reductions in sucrose content by August to September. Fibre content, on the other hand, was highly stable and increased marginally and linearly across the sampling period. The genotypes were already markedly different for fibre content at the pre-harvest season and they did not show significant differential performance across time. The results confirm that fibre accumulation occurs mainly during the growth phase and sucrose accumulates mainly during the ripening phase (pre-harvest to harvest season). Notwithstanding the negative correlations between the two variables (Bakshi and Shanker, 1997; Badaloo and Ramdoyal, 2003; Santchurn *et al.*, 2012), it should then be possible to improve both variables in a single variety, as the accumulation patterns of the two traits do not coincide. Kennedy (2008) worked with early generation hybrids and made similar remarks. Regarding sucrose content, higher genetic variances were observed during the harvest season (June to September) than at the pre-harvest season (May). Furthermore, the highest differential performance was observed between May and June, which indicated that clones showing high rank during the pre-harvest season may not necessarily be the best in mature canes at harvest. There is a need to be cautious with data collected further away (particularly before the harvest season) from the scheduled harvest date. Overall, when sugar is the main output, a combined effect of period of maximum sucrose accumulation and cane yield would determine the best time of data collection and harvest. When fibre is the main feedstock, on the other hand, only the biomass yield in different regions (adaptation) would be appropriate for recommendation to farmers.

This study also elucidated the intrinsic complexities and inaccuracies involved in categorization of varieties for sucrose content based on dry weight. Those values can be reliable only if fibre content is constant. In this study, for the same amount of sucrose content, fibre content varied significantly among genotypes, thereby affecting the total dry matter content and the corresponding dry weight estimates (see section 5.4, page 84).

8.2 The selected best biomass varieties

From the plant cane results (year 2015) of the four trials established in the sub-optimal areas, six biomass varieties (M 1334/84, M 196/07, M 1395/87, R 585, WI 79461 and WI 81456) were found selectable for multiple end-uses. Two of them, namely R 585 and WI 79461, showed poorer performance in first ratoon crop in 2016. This trend was confirmed for R 585 with data obtained in June 2017 (Table 8-1). As observed earlier, plant cane yield results are less representative of performance of varieties across ratoons. Thus, the dataset obtained from year 2016 (1st ratoon) were considerably more reliable. As a result, four biomass varieties (M 1334/84, M 196/07, M 1395/87 and WI 81456), showing good stability across ratoons, could be retained for multiple end-uses. Overall, genotypes M 196/07 and WI 81456 significantly surpassed the commercial varieties by +20% in terms of total dry biomass yield (Table 6-2). There were significant interactions of variety with region and variety with harvest date, which differentially influenced the gains in yield. In the super-humid uplands, WI 81456 was superior with +51% higher dry biomass yields than those of the commercial controls across the harvest dates. This difference was also obtained from the recently harvested second ratoon crop (Table 8-1). In the dry zone, M 1334/84 and M 196/07 ranked top in June and December, with +21% and +31% superior dry biomass yields to the average of the commercial varieties, respectively (see section 6.4, page 106). Although not top-ranking, genotype M 1395/87 ensured stable and high fibre yield across the different environments. The selected varieties could be classified into either the sugar-model or the fibre model.

M 1334/84 suited the sugar-model high biomass cane. The variety had 1.2% lower sucrose content than the average of the commercial controls (Table 6-2, page 99). Nevertheless, the genotype ensured significantly higher total aboveground biomass dry weight (+20%) and sugar yields (+11%) than those of the commercial varieties in the dry zone. Latest results obtained at second ratoon crop confirmed its higher cane biomass yield potential (Table 8-1). Its juice purity was above 85% in December and its fibre content was equivalent to those of the commercial varieties. Although the variety showed similar energy equivalence in terms of GJ ha^{-1} yr^{-1} to control variety M 1400/86, it ranked top in the dry zone in terms of economic selection index (ESI). The morphological attributes of the genotype are very interesting with non-flowering erect canes of good diameter and height, which are highly appreciated characteristics by growers. Overall, M 1334/84 represents a good candidate in the dry zone for increasing the total biomass without jeopardizing sugar yield. It should be harvested when it sucrose accumulation peaks, which is around November-December.

M 1334/84, a sugar-model high biomass cane

Genotypes M 196/07, M 1395/87 and WI 81456 fitted the fibre model with relatively high fibre (~20%) and low sucrose content (~10%) while those of the commercial controls averaged 15% and 13%, respectively (see Chapter 6 Appendixes, pages 108-111 and Table 6-2, page 99) in the four trials established in marginal environments. The three energy canes were generally highly vigorous with fast canopy cover. This feature is highly desirable for more efficient weed control. However, the clones flowered profusely in May, which demarcated the end of their growth phase. Few side-shoot leaves with narrow blades were observed thereafter and the older ones gradually started senescing, thereby causing more light to penetrate the canopy. Generally, energy canes are expected to have excellent ratooning ability (Matsuoka *et al.*, 2014; Carvalho-Netto *et al.*, 2014). The fibre-model energy canes evaluated in this study responded similarly to the stable commercial varieties across ratoons. Data from more crop cycles will certainly shed more light to their behaviour across older ratoons. This study also confirmed that the energy canes produced a high density of relatively thin, tall and erect canes that were about 26% lighter than those of the commercial varieties. Per metre length of cane stalk, the clones weighed about 60% of those of the commercial varieties.

M 196/07: A fibre-model high biomass cane with relatively moderate sucrose

Of the three fibre-model varieties, M 196/07 had the highest level of sucrose content (12% vs. 13% for controls) and, at times, equivalent to those of the commercial varieties. This variation rendered its classification rather ambiguous between enhanced fibre *Type* 2 canes and multi-purpose *Type 3* canes. Its fibre content was high (19.8% vs. 15.5% for controls) and its morphological attributes were characteristic of high fibre energy canes, with relatively thin and tall cane stalks that flowered profusely as from May. We adopted a conservative approach to maintain it among *Type 3* canes with fibre as the main feedstock. Broadly, the variety ensured high total biomass dry weight (+20%

of controls) and fibre yield (+41% of controls). Its best performance was in the dry environment in December where it produced +31% and +41% of dry biomass and fibre yields superior to those of commercial controls, respectively. Those differences were significant at 95% probability. In 12-months old crops, its juice purity was 82%. The energy equivalence of M 196/07 was superior to the control variety M 1400/86, particularly in the super-humid environment (+26%), where it also ranked top with the ESI model adopted. The variety is a good candidate for increasing bagasse yield and subject to the level of sucrose content and purity, its cane juice can be used to produce sugar or ethanol.

M 1395/87, a fibre-model variety with high proportion of trash

M 1395/87 is a variety with high fibre (20% vs. 15% of controls), low sucrose content (11.7% vs. 13.0% of controls) and low juice purity (83% vs. 85% of controls). Its biomass yield generally equalled those of the commercial varieties. It produced high density of very thin and erect canes that flowered profusely as from May. Its fibre yield was +25% higher than the commercial varieties. M 1395/87 also produced high proportion of cane tops and leaves (30% vs. 26% of controls). In terms of energy equivalence, its aboveground dry matter yield was superior to that of the commercial control variety M 1400/86 by +26% in the super-humid environment. However, because of its low sucrose content, it was not screened by the ESI model in any of the four sub-optimal environments. Still, M 1395/87 remained among the most stable varieties across locations and may be cultivated for the generation of green biomass for bioenergy production. The extracted juice can be used for ethanol production.

WI 81456: A high ranking fibre-model variety with low sucrose

WI 81456 was the overall best ranking fibre-model variety with high fibre (20% vs. 15% of controls) and low sucrose (9.5% vs. 13.0% of controls). Broadly, its total aboveground biomass yield dry weight surpassed the commercial varieties by +20% and performed best in the super-humid environment where the gain in biomass and fibre yields were +51% and +92% to those of the commercial controls, respectively. Latest results obtained at second ratoon crop confirmed the observations (Table 8-1). In terms of total aboveground dry biomass, WI 81456 overall showed +17% superior energy equivalence than M 1400/86 and +57% in the super-humid environment. However, with the ESI model, it was not screened in any environment, except in December in the super-humid region where it ranked second. Its poor juice quality (purity: 75% vs. 85% of controls) prohibits its cultivation for sugar production. The variety suits best in the super-humid environment where it can be exploited for its fibre as a feedstock for cogeneration and the extracted juice for the production ethanol and other high value products.

8.3 Future outlook

The economic selection index (ESI) model adopted in this study was based on the revenue obtained by sugarcane producers per tonne of the sugar and fibre produced. The model favoured sucrose rich varieties at the expense of high fibre energy canes. This could not be otherwise as the current price of a tonne of sugar (MUR 15600.00 for the year 2016) largely overshadows that of a tonne of bagasse at 50% moisture content (MUR 408.00). The new official price of sugar for the year 2017 has gone down to around MUR 13000.00. Still, it is not expected to make a significant impact on the most profitable type of varieties selectable by the ESI model. Moreover, in this study, the upper limit price of bagasse (MUR 1225.00 for every tonne of sugar) was used in the development of the model. Planters producing more than 60 tonnes of sugar are receiving MUR 300.00 for every additional tonne of sugar. The lower revenue for bagasse puts even higher emphasis on sucrose rich varieties for larger planters. Most importantly, the current cane payment system where sugarcane producers are paid for bagasse subject to tonnes sugar produced goes against the interest in high fibre canes exploitation. The very first step towards the economics of energy cane cultivation is to compensate sugarcane producers directly for the amount of bagasse produced. This remains one major future research focus area towards successful exploitation of energy canes in Mauritius.

In addition, so far sugar remains more profitable than fibre all diversifications within the sugarcane industry should not be at the expense of sugar yield. It is envisaged that all fertile sugarcane lands need to be exploited for sugar maximisation. Biomass yield in those areas can be increased by adopting higher yielding sugar-model biomass varieties namely, *Type 1* and *Type 2* canes. Higher fibre *Type 3* and *Type 4* canes (with lower sucrose content) may be cultivated in sub-optimal regions and abandoned lands for the continuous generation of biomass year-round. From this study, it became clear that manual harvest of the tougher cane stalks of energy canes will accentuate the difficulties at the production level. Unless cheap labour is made available, energy canes will be more effectively harvested mechanically. Various alternatives are being investigated worldwide for whole cane mechanical harvesting, bulk density improvement and transport. Another major research focus area, under local conditions, pertains to the introduction of mechanised harvest of high biomass canes in marginal lands.

Moreover, as energy cane production is fundamentally a reorientation of cane sugar planting and management, a concerted effort integrating agronomic practices, harvesting, transport and processing of the high fibre varieties is fundamental. Renouf *et al.* (2010) found major differences between the classical high-intensity farming production systems and the more modern low-energy-input farming systems and reported savings of more than 25% when a new low-energy-input sugarcane farming system was applied. The lowest inputs represent systems involving manual labour rather than mechanization, no irrigation, and only low inputs of agricultural chemicals including synthetic fertilizers. In this study, the recommended agronomic practices for sugarcane cultivation were adopted and all varieties in the trials were treated as conventional sugarcane varieties. There is a need to establish the yield potential of the selected best biomass energy canes with low-energy-input and sparse agronomic practices. To achieve sustainability, energy crops should not require extensive use of prime agricultural lands, and they should have low cost of energy production from biomass. Basically, the crop energy output must be more than the fossil fuel energy equivalent used for its production (Matsuoka *et al.*, 2014). Globally, energy output:input analyses through life cycle assessment with high biomass energy canes are lacking.

Chapter 9

General conclusions

R 579
Control variety

M 1334/84
Sugar model HBC

WI 81456
Fibre model HBC

Sugar- and fibre-model high biomass canes (HBC) showing differences in height at same crop age in the super-humid zone

9 General conclusions

In this study, the main focus was on screening high biomass sugarcane varieties that can be exploited in marginal environments and determine the quantum gains with different types of biomass varieties in terms of sugar, fibre and total dry matter yields. Twelve highly selected early and advanced generation hybrid varieties were concurrently planted in four trials in 2014. Two trials were in the central super-humid environment at Valetta and two in dry rain-fed zone at Ferret in the North. In each location, one trial was harvested in June and the other one in December. Contrary to the general trend, the holistic approach was not only on early generation hybrids with high fibre as the sole biomass varieties but also on those advanced generation candidates, inclusive of commercial varieties, that can generate high total biomass with high sugar yield. Various statistical tools, both conventional and latest ones available, were found necessary to obtain pertinent and reliable inferences from the huge datasets generated from the trials. The initially set objectives were attended and the overall results could broadly be summarised as follows:

- Four varieties with variable sucrose to fibre ratios were identified as the best biomass yielders in the marginal environments.
- The interactions for cane quality traits (sugar and fibre content) were more important with harvest periods than with locations. For aboveground biomass yields, the varieties showed higher interactions with locations than with harvest dates. These results confirmed that the varieties in the population had different maturity behaviour in terms of sucrose accumulation across time. Also, different varieties performed best in the two contrasting locations.
- High fibre energy canes showed good adaptation and stability in the super-humid environment of the island. The high sucrose type varieties adapted well in the drier areas.
- High fibre energy canes showed similar trends across ratoons as those of the commercial varieties. Plant cane results were less representative of performance across ratoons.
- The biomass accumulation pattern in relation to sucrose and fibre in the cane stem was highly informative on the best period for data collection and harvest of the different types of canes.
- Unlike sucrose accumulation pattern, fibre accumulated with time and remained stored in the stem. Generally, the selected high fibre varieties can be harvested outside the harvest season to ensure availability of biomass year-round.
- The high fibre energy canes showed vigorous growth habit and could be harvested at younger crop ages. One variety accumulated enough biomass at 8-months age to warrant three harvests in two years.
- The high fibre varieties produced high density of thin, tall and tough cane stalks that were, per unit length, about 40% lighter than those of the commercial varieties. These morphological attributes impacted upon the manual harvest efficiency. The different alternatives of mechanized whole cane harvesting were elucidated.

- The energy equivalences in terms of GJ ha^{-1} yr^{-1} of the selected best biomass varieties were determined. Bagasse and cane tops and leaves had nearly similar energy equivalences among the different types of canes on a dry weight basis. Cane juice, however, showed variable energy equivalences among the varieties.
- An economic selection index was developed and was based on revenues obtainable from sugar and fibre yields. The index favoured sucrose rich varieties at the expense of higher fibre energy canes.

From the plant cane results obtained in year 2015, six biomass varieties (M 1334/84, M 196/07, M 1395/87, R 585, WI 79461 and WI 81456) were found suitable for multiple end-uses. Two of them, namely R 585 and WI 79461, showed poorer performance in ratoon crops. As a result, the four best biomass varieties were M 1334/84, M 196/07, M 1395/87 and WI 81456. They could be categorized into either the sugar-model or fibre-model with main feedstock being sugar or fibre, respectively.

- M 1334/84 suited the sugar-model varieties with around 1.2% lower sucrose content than that of the average of the commercial varieties. Its significantly high aboveground dry biomass (+20% of commercial controls) compensated for the low sucrose level and ensured +11% higher sucrose yield than those of the commercial varieties in the dry zone.
- M 196/07 was essentially a fibre-model variety with appreciable amount of sucrose content (12% vs. 13% for controls) and high fibre (19.8% vs. 15.5% for controls). At times, its sucrose content was equivalent to those of the commercial varieties, upgrading it to “enhanced-fibre type” sugar-model variety. However, its morphological attributes were typical of high fibre energy canes. Broadly, M 196/07 ensured significantly high total biomass dry weight (+20% of controls) and fibre yield (+41% of controls). Its best performance was in the dry environment in December (+31% and +50% of dry biomass and fibre yields of controls).
- M 1395/87 suited the fibre-model with high fibre (20% vs. 15% of controls) and low sucrose content (11.7% vs. 13.0% of controls). Although its total biomass yield was equal to those of the commercial varieties, its fibre yield was +25% higher than the controls. The variety also produced a high proportion of cane tops and leaves (30% vs. 26% of controls).
- WI 81456 was the overall best ranking fibre-model variety with high fibre (20% vs. 15% of controls) and low sucrose (9.5% vs. 13.0% of controls). With combined analysis across the four trials, its total aboveground biomass yield dry weight surpassed the commercial varieties by +20%. It performed best in the super-humid environment where the gain in biomass and fibre yields were +50% and +90% to those of the commercial controls, respectively.

In the short term, in a small country like Mauritius, where land is limited, sugar-model varieties that comprise *Type 1* (high sucrose low fibre) and *Type 2* (high sucrose high fibre) canes can bring immediate success by maximizing on biomass without impacting on sugar yield. By being less stringent on the sucrose content, many more candidates can become exploitable without loss in total sugar. M 1334/84 is a typical example where, by relaxing the stringency on sucrose level, the total biomass and sugar yields exceed those of existing commercial varieties in the dry zone. The variety needs to be harvested by the end of the harvest season (November-December) in the dry zone to ensure maximum gains in terms of sugar and total biomass yields.

The fibre-model *Type 3* (lower sucrose higher fibre) and *Type 4* (negligible sucrose very high fibre) energy canes can be cultivated in the marginal environments for the generation of biomass year-round. They ensured fast growth rate allowing harvest at younger crop ages. WI 81456 accumulated enough biomass by 8-months age in the super-humid environment to justify three harvests in two years. Successful exploitation of energy canes requires further investigations on the economic aspects of cane fibre payment system, the best alternative for mechanized harvest and processing efficiency of the harder canes at the mill.

As sugarcane breeding is a lengthy process (12-15 years) the decision on the type of variety that will be most remunerative by 2030 should be taken now. With the imminent rise in petroleum prices and technological breakthroughs in cane processing and cellulosic ethanol conversion, high fibre energy canes are deemed to become a viable source of environment-friendly and renewable energy in the very near future. Of volcanic origin, Mauritius has no coal or natural oil reserve. Its fuel reserve lies on the sugarcane crop that covers about 85% of agricultural land. Continued investments on breeding for high biomass and on further research towards the successful exploitation of energy canes should lead to increased sustainability and resilience of the local sugarcane industry and an important lifeline for the national energy security. The varieties identified, findings and algorithms defined and developed in this study are all expected to contribute towards paving the way forward.

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