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Optimization of sugarcane farming as a multipurpose crop for energy and food production

DAMIEN SABATIER*†, JEAN-FRANÇOIS MARTINÉ*, FRÉDÉRIC CHIROLEU‡, CAMILLE ROUSSEL§, PHILIPPE LETOURMY¶, RIANTO VAN ANTWERPEN†‖, BENOIT GABRIELLE** and BERTRAND NEY**

**CIRAD, UPR102 Systèmes de culture Annuels, Station de la Bretagne, BP 20, Saint-Denis Cedex 9, La Réunion F-97408, France, †SASRI, South African Sugarcane Research Institute, 170 Flanders Drive, Private Bag X02, Mount Edgecombe 4300, South Africa, ‡CIRAD, UMR PVBMT Cirad/Université de La Réunion, 7 chemin de l'Irat, Saint-Pierre 97410, La Réunion, France, §Sugar Processing Department, eRcane, Sainte-Clotilde Cedex, La Réunion Island, BP 315-97494, France, ¶CIRAD, UPR102 Systèmes de culture Annuels, Avenue Agropolis, TA B-102/02, Montpellier Cedex 534398, France, ‖Department of Soil, Crops and Climate Sciences, University of the Free State, P O Box 339, Bloemfontein 9300, South Africa, **AgroParisTech, UMR 1091 EGC (Environnement et Grandes Cultures), INRA-AgroParisTech, Thiverval-Grignon F-78850, France*

Abstract

Sugarcane is a multipurpose crop whose components may be used, in addition to sugar production, for various energy carriers or end-products (electricity, liquid biofuels and heat) which enhance its economic potential. For many years, plant breeders and agronomists have focused on increasing sucrose yields per hectare and millers on increasing recoverable sucrose per ton of sugarcane in sugar mills. Attempting to exploit the energy potential of sugarcane more fully, calls for a more holistic approach focusing on both sucrose and lignocellulosic components of sugarcane biomass, and gaining some insight into the management practices required to optimize sugarcane cropping systems in these respects. Such options include genotype selection, harvest date with respect to the crop's growing cycle, crop type (plant crop vs. ratoon crops) and harvesting systems (mechanical vs. manual). The effects of these factors are strongly modulated by climate and soil properties, and these interactions are overall poorly known. Here, we set out to examine sugarcane infield management × environmental interactions with respect to (i) sugarcane yield and partitioning of the aboveground biomass; and (ii) sugarcane milling products (recoverable sucrose yield and amounts of coproducts) and their derived energy carriers. Three *Saccharum cv.* cultivars (R570, R579 and R585) were planted in three locations on La Reunion Island with contrasting management practices and climatological conditions. Quality characteristics of the samples were assessed by conventional and near infrared spectroscopy methods. Product, coproducts and potential energy production were measured and computed using transfer equations and a mill-operating model. Yields and quality characteristics from cultivars and harvesting systems were affected differently by environmental factors – low temperature and radiation, and water stress. The current study also provides valuable information on how combinations between environments, genotypes and practices affect yield and partitioning of the aboveground biomass, and food and energy production.

Keywords: agro-climatic factor, electricity, energy, ethanol, food, sucrose, sugarcane cropping system, trade-off

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Introduction

Renewables are the world's fastest growing energy source (with an estimated annual growth rate of 15% by 2035) and will play a key role in meeting future energy demands (Gruenspecht, 2011). Biomass is considered as the renewable energy source with the highest potential in this respect, both in industrialized and developing countries worldwide (Demirbas *et al*., 2009). More specifically, global interest in sugarcane (*Saccharum* spp.) has significantly increased in recent years due to the large contribution of sugarcane to bioethanol, heat and electricity production (Cheavegatti-Gianotto *et al*., 2011). In La Reunion Island, following a government plan to reach self-sufficiency in energy consumption by 2030, it was suggested that the dominant cultivars (R570 and R579) be replaced with a new cultivar (R585) producing 20% higher biomass yield and 32% higher fibre concentration than the control cultivar R579 (Dupré, 2011). This study discusses how both sugar and energy production per area can be maximized using the new

Correspondence: Damien Sabatier, tel. + 27 31 508 7526, fax +26 22 625 28001, e-mail: Damien.Sabatier@sugar.org.za
This paper is dedicated to our dear and regretted Professor Bertrand NEY. You were and you will be for ever our mentor.

cultivar. It was based on the local context of La Reunion Island, but its results and approach are relevant to all the major sugarcane-producing areas worldwide.

Sugarcane is recognized as a high potential bioenergy feedstock because of its highly positive energy balance, its photosynthetic efficiency and larger annual biomass yields than most other crops under tropical climatic conditions (Goldemberg, 2008; Waclawovsky *et al.*, 2010; Vermerris, 2011). Sugarcane is also a multipurpose crop whose components may be used to generate various energy carriers (heat, electricity and biofuels) in addition to sugar production (Almazan *et al.*, 1998). Various lignocellulosic fractions may be recovered following harvesting or sugarcane milling to produce these energy carriers. However, total biomass (below- and aboveground) from sugarcane is not currently used to its full potential (Ripoli *et al.*, 2000; Eggleston *et al.*, 2004), as it is estimated that more than 30% of sugarcane aboveground biomass is currently not recovered (Pouzet, 2011). In parallel, mechanical harvesting and green cane harvesting (GCH) are becoming more and more widespread, fostered by the sugar industry in most sugarcane-producing countries (Braunbeck *et al.*, 1999). Such practices have a direct impact on the quantity and quality of the feedstock delivered to sugar mills (Pouzet, 2011), through their blending of leaves and tops with millable stalks compared to burning the sugarcane at harvest which theoretically delivers clean stalks. Thus, GCH has the advantage of potentially increasing the energy recovered from sugarcane fields but it adversely affects the quantity of recoverable sucrose. However, another trade-off occurs with soil quality as the return of crop residues to soils has long-term agricultural benefits (Hassuani *et al.*, 2005; Pankhurst, 2005) that should be weighed against the benefits of using the same residues for energy purposes (e.g. the cogeneration of electricity and/or cellulosic ethanol, in our case).

Fully tapping the energy potential of sugarcane requires a focus on both the sugar and lignocellulosic compounds of sugarcane biomass, and gaining some insight into the management practices available to optimize sugarcane cropping systems in these respects. More specifically, the main quality characteristics of sugarcane relevant to these objectives include harvest index, fibre concentration [because fibre hampers the sugar extraction process (Glaz *et al.*, 2011)], the fraction and biochemical profile of lignocellulosic compounds (Boudet *et al.*, 2003; Burner *et al.*, 2008) and the lower heating value (LHV) and ash concentration (Rhèn, 2004). Studies conducted on wood have shown that aboveground biomass, especially lignocellulosic compounds, can be affected by a number of factors, namely: genotype, region, climate, age and the part of the plant harvested (Han *et al.*, 2007), but little is known on how these factors can simultaneously affect sugarcane aboveground biomass quality characteristics. So far, several studies conducted on sugarcane have confirmed that such characteristics may be modulated by each cultivation practices independently (Banda & Valdez, 1976; Godoy & Elliott, 1981; Kevelenge *et al.*, 1983; Mislevy *et al.*, 1995; Andrade *et al.*, 2003, 2004; Fernandes *et al.*, 2003). However, to our knowledge, no study of this nature has been conducted on different sites simultaneously, to account for genotype, environment and management interactions. Thus, more knowledge on how both climate and management affect the quality characteristics of the aboveground biomass is needed to aid decision-making and optimize cropping systems for multicommodity production, with a focus on the concomitant exploitation of sugarcane biomass for food and energy purposes.

The objectives of this study were twofold. At field level, we aimed at comparing the yield, biomass partitioning and energy outputs of three sugarcane cultivars under various management scenarios (i.e. irrigation and harvesting system) and climatic conditions. At sugar mill and bioenergy plant levels, we aimed at identifying the most interesting combination between genotypes and management options to maximize both food and energy outputs of sugarcane biomass in relation to climatic conditions.

Materials and methods

Field experiments

Field experiments were located in three contrasting regions of La Reunion Island (Table 1). Near-shore experimental sites (control and dry) were situated in 'La Mare' (20°54′S, 55°31′E and 70 m above sea level) and 'Etang Salé' (21°15′S, 55°22′E and 20 m above sea level) localities and were both planted on a nitisol dystric soil (International Union of Soil Sciences, IUSS Working Group WRB, 2007). Intermediate altitude experimental site (cold) was situated in 'Menciol' (20°58′S, 55°36′E and 400 m above sea level) locality and planted on an andosol dystric soil (International Union of Soil Sciences, IUSS Working Group WRB, 2007).

Climatological data were collected from several weather stations located close to the dry and cold experimental sites (in a perimeter of 1.0 km) and on-site for the control experimental site.

Sugarcane crops were established in 2008 in all three experimental sites, at the end of the rainfall season for the cold and control experimental sites (on March 21st and April 22nd respectively) and in the middle of the dry and cold season for the dry experimental sites (on July 28th). Each trial was planted to three cultivars (R570, R579 and R585) in randomized subplots which consisted of nine lines of 11 m spaced 1.5 m and each treatment was replicated three times. Trials were fertilized annually with 150 kg, 180 kg and 240 kg of N, P and K ha^{-1}, respectively, in accordance with crop requirements in

Table 1 Crop start date, altitude, daily means of radiation and air temperature, cumulative thermal time, rainfall, irrigation and PET for a first ratoon cane crop cycle (2009–2010) in three contrasted pedoclimatic environments (Control, Dry and Cold) of La Reunion Island

Environment	CSD (dd/mm/yyyy)	Altitude (m)	Radiation (MJ m^{-2})	Air temperature (°C)	Thermal time (°day)	Rainfall (mm)	Irrigation (mm)	PET (mm)
Control	29/10/2009	70	19.0	24.7	9454	1849	1025	1559
Dry	02/11/2009	20	17.0	24.5	9274	981	300	1393
Cold	23/10/2009	400	15.7	21.7	8437	3977	–	1332

CSD, crop start date; PET, potential evapotranspiration.

La Reunion Island (Chabalier *et al.*, 2006). Fertilizer was applied in the furrow and later as a top dressing to provide optimal uptake of N, P and K during the growing season. Irrigation at the control and dry experimental sites was, respectively, managed according weather conditions [rainfall amount and potential evapotranspiration (PET)] and systematically delivered (irrigated with 3 mm daily) except in case of rainfall, while the cold experimental site was rain fed.

The plant crops were harvested within the last week of October 2009 and the ratoon crops were harvested within the last week of November 2010, both at the age of 12 months.

Sampling, treatment and measurement

Each subplot was sampled to quantify aerial biomass over a distance of 1 m. Sugarcane stalks were cut at ground level and removed together with the associated dead leaves on the ground. The biomass samples were partitioned into three components: millable stalk; green leaves and tops; and dead leaves or trash (attached and detached dead leaves were mixed). Based on biomass partitioning, two virtual harvesting systems were created: the clean sugarcane (CC) harvest including only millable stalks, and the whole green sugarcane (WGC) harvest including millable stalks and green leaves and tops. Both could be mechanized in practice. Trash biomass usually stays in the field after harvesting as mulch or can be harvested later for various uses, e.g. as pig litter or as cattle feed, as is frequently the case in La Reunion Island. In Brazil and Cuba, trash biomass has also been used for energy carrier production.

Fresh weights of the overall biomass (Y_B) and of the biomass components were measured (Mg ha^{-1}). Approximately 15 kg of millable stalks was crushed with a cutter grinder (JEFFCO Cutter Grinders, model L118C, JEFFRESS Engineering Pty Ltd, Dry Creek, Australia) to obtain a homogenate sugarcane pulp. A subsample of 1 kg of sugarcane pulp was weighed and pressed for 90 s at 20 000 kPa with a hydraulic press (Pinette Emidecau Industries, hydraulic press model OB-103, Chalon sur Saone, France). Through crushing and pressing, the biomass was split into filter press cake (bagasse) and juice. A subsample of 500 g of green leaves, tops and trash were manually chopped into pieces about 50 mm long in preparation for drying.

Bagasse and subsamples of the plant components were weighed fresh and then dried for 3 days at 70 °C in a ventilated incubator (Lequeux, Paris, France) to obtain dry matter concentration (DMC). Juice was analysed for brix (Br) and pol according to the ICUMSA method (International Commission for Uniform Methods of Sugar Analysis, ICUMSA Method GS 7-31, 2011), and sucrose (Suc) was quantified as shown in the ICUMSA method (International Commission for Uniform Methods of Sugar Analysis, ICUMSA Method GS7/4/8-24, 2011).

Dry samples were analysed according to the sequential method of van Soest *et al.* (1991), as reviewed by Mertens (2002). Neutral detergent fibre (NDF), neutral detergent soluble (*NDSol*), hemicellulose (*Hem*), cellulose (*Cel*), lignin (*Lig*) and ash fractions were determined by mass loss during sequential treatment of samples and combustion (Sabatier *et al.*, 2012). The resulting biochemical fractions (moisture free and ash free) were used as reference data (n = 228) and correlated with near-infrared reflectance (NIR) data to develop a NIR calibration model (Sabatier *et al.*, 2012). After validation, the NIR model was used to estimate the biochemical composition of all of our sugarcane samples (n = 1710).

Energy outputs

At the field processing level, the net energy yield of the aboveground biomass (E_B, in GJ ha^{-1}) was calculated as follows:

$$E_B = \mathrm{LHV}_B \times Y_B \times \mathrm{DMC} \quad (1)$$

where LHV_B is the average lower heating value (MJ kg^{-1} of dry biomass) corresponding to the weighed product of the lower heating values (LHV) of the various plant components and DMC of the aboveground biomass (g 100 g^{-1}). LHV_B was calculated as follows:

$$\mathrm{LHV}_B = ((\mathrm{LHV}_{\mathrm{Br}} \times \mathrm{Br}) + (\mathrm{LHV}_{\mathrm{Hem}} \times \mathrm{Hem}) + (\mathrm{LHV}_{\mathrm{Cel}} \times \mathrm{Cel}) + (\mathrm{LHV}_{\mathrm{Lig}} \times \mathrm{Lig}))/(\mathrm{DMC}) \quad (2)$$

where Br is the fraction of sugars (% of fresh biomass) and $\mathrm{LHV}_{\mathrm{Br}}$, $\mathrm{LHV}_{\mathrm{Hem}}$, $\mathrm{LHV}_{\mathrm{Cel}}$ and $\mathrm{LHV}_{\mathrm{Lig}}$ are the LHV of Br, Hem, Cel (17.5 MJ kg^{-1}) and Lig (26.6 MJ kg^{-1}) respectively. The latter LHV were taken from Sarlos *et al.* (2003).

At the sugar mill processing level, coproducts (bagasse and molasses), product (recoverable sucrose), potential and net electricity production were computed using a mill-operating model (Corcodel, 2011). In this model, sugarcane and juice analyses were used to compute sugar loss in bagasse and reducing sugars (glucose and fructose). Electrical conductivities of juice were used to compute targeted molasses purity and, together with a mass balance, a sugar loss in molasses was calculated. Sugar loss in mud and undetermined losses were set. These computations enabled the calculation of recoverable sucrose and molasses production. The model also predicted the quantity and the composition of bagasse (brix, ash, humidity) that enables the calculation of its LHV (Wienese, 2001). Net electricity production delivered to the grid was then evaluated, with due consideration of the 'sugar mill–power plant' complex steam and electricity consumptions. However, the model was originally designed to simulate the impact of the quality of the biomass delivered to the sugar mill on the production efficiency of the 'sugar mill–power plant' complex, (i.e. recoverable sucrose, bagasse and molasses yields and energy consumption (electricity and steam) of the sugar mill). The model only allows comparisons between different qualities of biomass delivered to the sugar mill (in our case CC vs. WGC) and has no vocation in terms of accurate prediction of coproducts and product yields. As a result, bagasse, molasses, recoverable sucrose, potential electricity production (i.e. production of electricity from a thermal power plant including its conversion efficiency) and net electricity production delivered to the grid (i.e. production of electricity from a thermal power plant including its conversion efficiency and deduction of energy consumption of a sugar mill needed for the overall process) are given for indication purposes only.

The potential energy production of 1G ethanol ($EtOH_{1G}$, in GJ ha^{-1}) from molasses and juice was computed with the method described by Gopal & Kammen (2009) as follows:

$$\mathrm{EtOH_{1G}} = (\mathrm{LHV_{EtOh}} \times \mathrm{ED}_E \times \mathrm{Suc} \times (1 - (J \times (\mathrm{rSuc}/\mathrm{Suc}))) \times (10^6/947.8) \times Y_B)/1000 \tag{3}$$

where Y_B is the fresh biomass yield that would enter the milling process (in Mg ha^{-1}), Suc and rSuc are the sucrose and the recoverable sucrose yields (in Mg ha^{-1}), J is the fraction of sugarcane juice sent to the recovery plant for raw sugar production (in our case 1 or 0), ED_E is the ethanol distillery efficiency (0.51 dry t of ethanol t^{-1} of sucrose) and (10^6/947.8) is coefficients given by Gopal & Kammen (2009) and LHV_{Etoh} is the LHV of pure ethanol (16.65 MJ kg^{-1}) given by the Bioenergy Feedstock Development Programs (Oak Ridge National Laboratory, ORNL, 2012).

The potential energy production of 2G ethanol ($EtOH_{2G}$, in GJ ha^{-1}) was estimated using the coefficient of conversion (277 l of ethanol t^{-1} of lignocellulosic biomass) given by Zhang *et al.* (2009), the lignocellulosic biomass yield (in Mg ha^{-1}) and LHV_{EtOh} the LHV of pure ethanol (21.1 MJ l^{-1}) given by the Bioenergy Feedstock Development Programs (Oak Ridge National Laboratory, ORNL, 2012).

Several pathways were defined to represent current trends in the major sugarcane-producing countries and also to explore potential future uses of sugarcane biomass at an industrial scale (Fig. 1). Route 1 is the most widely used option: the process generates bagasse, recoverable sucrose and molasses from sugarcane juice. Bagasse is subsequently used to cogenerate steam and electricity while molasses are usually converted into 1G ethanol. Route 2 is mainly used in Brazil, and its process consists of the cogeneration of steam and electricity from bagasse combustion and the direct conversion of sugarcane juice into 1G ethanol (without prior sugar extraction). It thus provides an alternative to route 1 when sucrose prices are low. Route 3 is more prospective, consisting of the conversion of bagasse and sugarcane juice

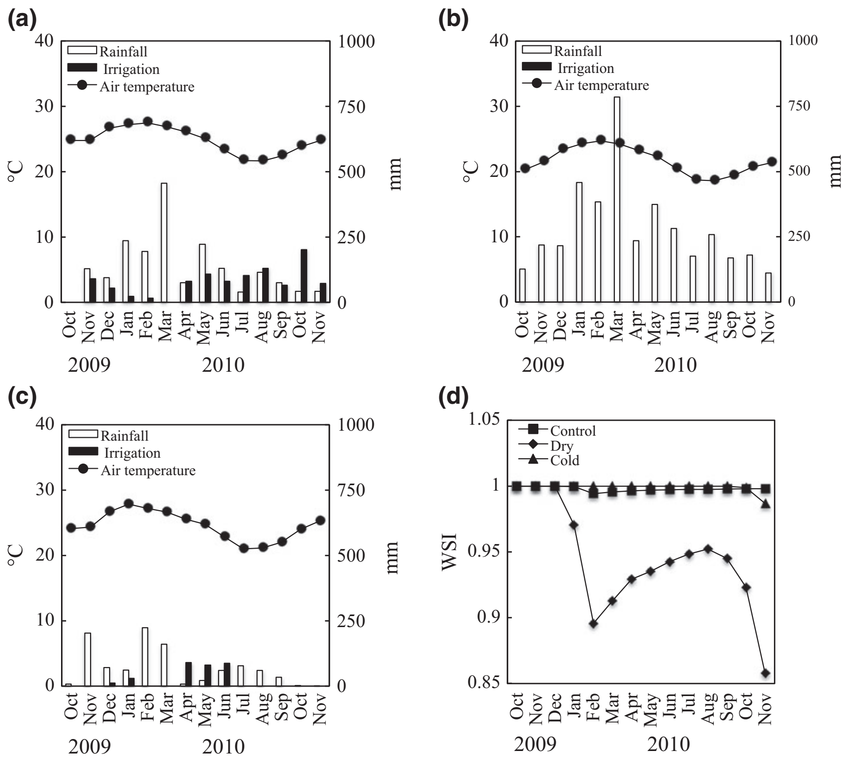

Fig. 1 Climatologic conditions and irrigation for the October 2009 to November 2010 crop cycle of 3 contrasted environments of La Reunion Island, (a) Control, (b) Cold and (c) Dry, and (d) water stress index (WSI) of the 3 contrasted environments for the same time period.

into 2G and 1G ethanol respectively (Marcelli *et al.*, 2012). It could be an interesting alternative route of valorization to use outside the sugarcane harvesting campaign, to exploit other biomass sources such as dedicated lignocellulosic crops or sugarcane grown on contaminated soils that would be unsuitable for food production (Cirad, REBECCA project).

Statistical analysis

Factorial analysis of variance (Chambers *et al.*, 1992) was used to determine the significant differences between genotypes (G), environments (E) and harvesting types (H) and their interactions for the various variables at different processing levels (Table 10). A linear model was used to analyse the data:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \delta_{kl} + \epsilon_{ijkl} \quad (4)$$

where Y_{ijkl} is the analysed variable, μ the grand mean, α_i the G effect, β_j the H effect, γ_k the E effect, $(\alpha\beta)$, $(\alpha\gamma)$, $(\beta\gamma)$ and $(\alpha\beta\gamma)$ are the interactions among G, H and E effects, δ_{kl} the block effect (nested in E) and ε_{ijkl} the residual error. Multiple comparisons of means [low temperature and radiation (cold), and water stress (dry)] were carried out using the Tukey honest significant differences (HSD) test at $P < 0.1$ (Miller, 1981). Statistical analyses were conducted using the R software package (R DevelopmentCore Team, 2013).

Results

Climatologic conditions

Experimental sites were highly contrasted regarding their location and altitudes (range was from 20 to 400 m above the sea level) which gave each environment a unique thermo-radiative profile (Table 1; Fig. 2a–c). Radiation ranged from 15.7 to 19.0 MJ m^{-2}, mean air temperatures ranged from 19 to 24.7 °C and thermal time ranged from 8437 to 9454 day for the experimental sites and followed the same decreasing order: Control ≥ Dry > Cold. Rainfall was highly variable between experimental sites. Cumulative rainfall ranged from 981 to 3977 mm for the experimental sites and was in decreasing order: Cold > Control > Dry. Irrigation was substantial for the control experimental site (1025 mm) and for both control and cold experimental sites the

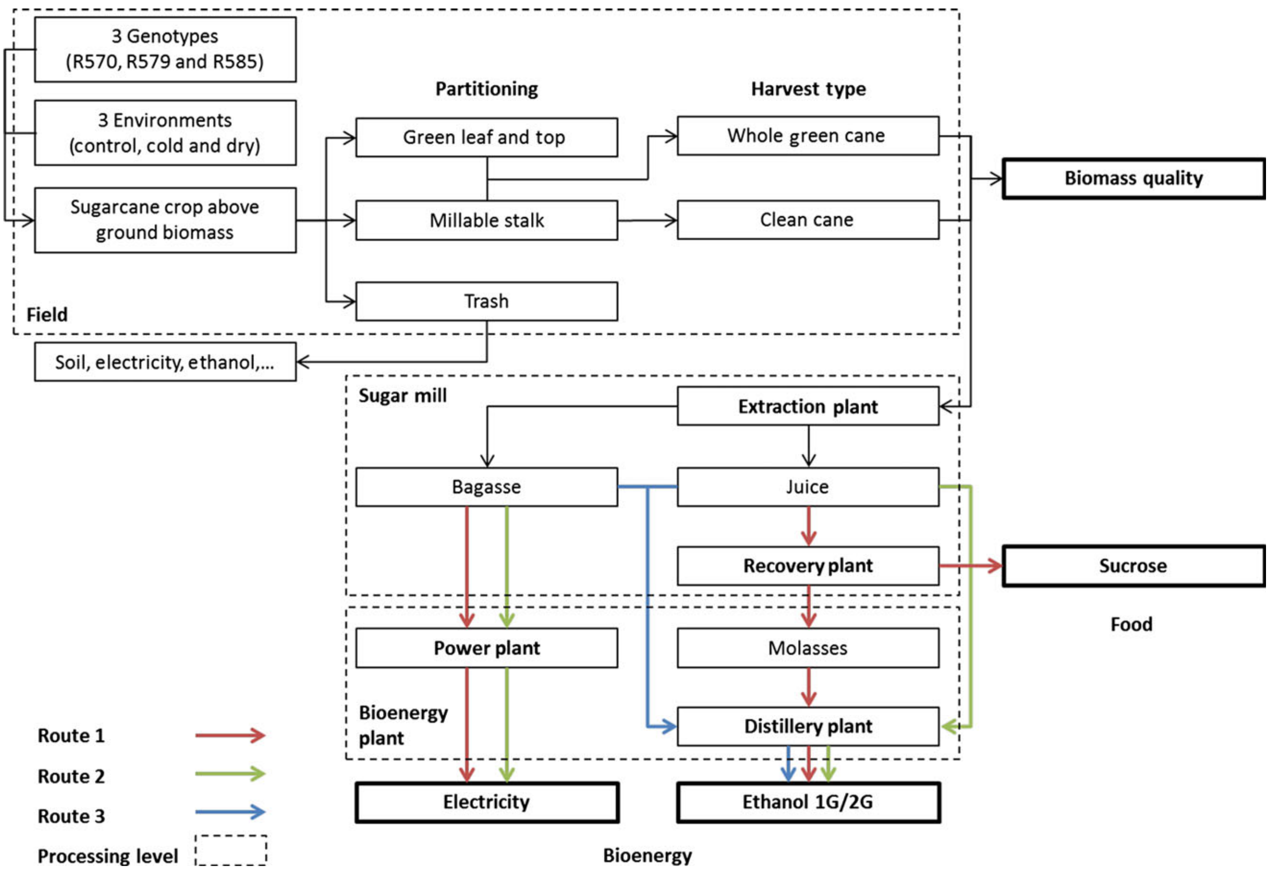

Fig. 2 Diagram of experimental design and approach. Route 1: recoverable sucrose, electricity from bagasse and first generation ethanol (1G) from molasses; Route 2: electricity from bagasse and first generation ethanol (1G) from juice; and Route 3: first generation ethanol (1G) from juice and second generation ethanol (2G) from bagasse.

water supply was sufficient to avoid water stress during the growing season (Fig. 2d). For the dry experimental site, the cumulative potential evapotranspiration (PET) was higher than the sum of cumulative rainfall and irrigation (Table 1), implying that crops experienced water stress at this site. Even if the water deficit was low (i.e. $100 \times (\text{PET}-(\text{cumulative rainfall} + \text{irrigation}))/\text{PET} = 8\%$), the time distribution of rainfall was erratic over the crop cycle, enhancing the magnitude of water stress (Fig. 2d).

Field processing level – biomass and quality characteristics

Fresh biomass yield increased by 28% on average whereas the dry matter concentration decreased by 1% on average from CC to WGC harvests (Table 2). Fresh biomass yields were significantly higher for CC harvest and cultivar R570 in the control environment (170.0 Mg ha^{-1}) than in the cold and dry environments (109.3 and 106.7 Mg ha^{-1} respectively), and WGC harvest and cultivar R585 in the control environment (236.2 Mg ha^{-1}) compared to the dry environment (148.0 Mg ha^{-1}). The other differences between cultivars and environments were not significant according Tukey HSD test ($P < 0.1$).

whole green sugarcane (WGC) harvesting increased fibre concentration by 13% and decreased brix and sucrose concentration by 8 and 12%, respectively, on average, compared to CC harvesting (Table 3). Fibre concentrations were significantly higher for CC and WGC, and cultivar R570 and R579 in the cold environment (42.6 and 51.5 g 100 g^{-1} for R570 and 39.8 and 47.3 g 100 g^{-1} for R579) compared to the other environments. For cultivar R585 the control environment presented higher fibre concentration than the dry environment for both harvesting type. Brix concentration for CC harvest and cultivars R570 and R579 was higher in the dry environment (56.1 and 59.6 g 100 g^{-1} respectively) compared with the other environments and differed only from the control environment for the cultivar R585. For the WGC harvest, the brix concentration of the cultivars R585 and R579 was higher in the dry environment (49.0 and 57.8 g 100 g^{-1}) than in the other environments and differed only from the cold environment for the cultivar R570. Sucrose concentration for CC harvest of cultivars R579 and R585 was higher in the dry environment (53.8 and 45.4 g 100 g^{-1} respectively) compared to the cold and control environments (48.2 g 100 g^{-1} and 39.5 g 100 g^{-1} respectively). For the WGC harvest, the sucrose concentrations of cultivar R579 differed significantly between each environment. Cultivars R570 and R585 were higher in the dry environment (47.2 and 42.4 g 100 g^{-1} respectively) compared to the cold and control environments (37.7 g 100 g^{-1} and 32.5 g 100 g^{-1} respectively).

Hemicellulose, cellulose and lignin concentrations increased by 19, 10 and 2%, respectively, from CC to WGC harvests (Table 4). Hemicellulose concentrations were significantly higher in the cold environment for both type of harvest and all cultivars (range was from 15.9 to 21.4 g 100 g^{-1}) compared to the dry environment (range was from 13.9 to 16.4 g 100 g^{-1}). It was the same for cellulose concentrations (range was from 18.8 to 24.7 g 100 g^{-1} for the cold environment and from 15.9 to 20.1 g 100 g^{-1} for the dry environment) except for the CC harvest and cultivar R585 in the control environment where cellulose concentrations were higher than in the other environments. Lignin concentrations were significantly higher in the cold environment for both type of harvest of cultivar R579 only (4.1 and 4.2 g 100 g^{-1}) compared to the dry environment (3.5 and 3.6 g 100 g^{-1}).

Trash biomass yield did not differ between environments (Table 5). Trash biomass of control and cold environments and cultivar R585 had lower dry matter concentration (77.1 and 80.6 g 100 g^{-1} respectively) compared to the dry environment (88.3 g 100 g^{-1}). In the cold environment trash biomass of all cultivars had higher fibre concentrations (range was from 75.0 to 77.7 g 100 g^{-1}) compared to the other environments (range was from 70.2 to 75.6 g 100 g^{-1}). Trash hemicellulose concentrations of all cultivars were always

Table 2 Aboveground biomass yield (Mg ha^{-1}) and dry matter concentration (g 100 g^{-1} of fresh matter) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Yield (Mg ha^{-1})		Dry matter (g 100 g^{-1})	
Cultivar	Environment	CC	WGC	CC	WGC
R570	Control	171.0a	212.1	30.5b	30.5B
	Cold	109.3b	170.1	31.3ab	29.6B
	Dry	106.7b	122.7	34.1a	34.5A
R579	Control	143.1	172.1	29.7b	29.4B
	Cold	156.3	211.9	27.6c	27.1C
	Dry	127.5	145.1	32.0a	32.2A
R585	Control	180.9	236.2A	30.9b	31.0B
	Cold	140.9	202.6AB	32.3ab	31.0B
	Dry	132.7	148.0B	34.1a	34.5A

CC, Clean Cane; WGC, Whole Green Cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

Table 3 Fibre, brix and sucrose concentrations (g 100 g^{-1} of dry matter) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Fibre (g 100 g^{-1})		Brix (g 100 g^{-1})		Sucrose (g 100 g^{-1})	
Cultivar	Environment	CC	WGC	CC	WGC	CC	WGC
R 570	Control	40.8ab	45.0B	53.0ab	48.5AB	47.5	42.2AB
	Cold	42.6a	51.5A	51.4b	45.6B	46.0	37.7B
	Dry	37.4b	42.0B	56.1a	52.8A	51.1	47.2A
R 579	Control	37.5b	41.6B	56.7b	53.4B	51.6 a	47.1B
	Cold	39.8a	47.3A	55.5b	49.9C	48.2 b	40.6C
	Dry	35.0c	39.0C	59.6a	57.8A	53.8 a	50.3A
R 585	Control	46.5a	50.6A	45.9b	40.3C	39.5 b	32.5B
	Cold	42.8b	50.2A	50.1a	46.0B	44.6 a	37.4AB
	Dry	41.1b	43.9B	51.8a	49.0A	45.4 a	42.4A

CC, Clean cane; WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

Table 4 Hemicellulose, cellulose and lignin concentrations (g 100 g^{-1} of dry matter) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Hemicellulose (g 100 g^{-1})		Cellulose (g 100 g^{-1})		Lignin (g 100 g^{-1})	
Cultivar	Environment	CC	WGC	CC	WGC	CC	WGC
R 570	Control	14.8ab	17.4B	20.3a	21.4B	5.0	5.0
	Cold	15.9a	20.9A	21.2a	24.7A	5.2	5.2
	Dry	13.9b	16.4B	18.2b	20.1B	4.5	4.6
R 579	Control	14.9b	17.4B	17.7b	19.0B	4.0 ab	4.1 AB
	Cold	16.2a	20.3A	18.8a	21.9A	4.1 a	4.2 A
	Dry	14.4b	16.5B	15.9c	17.7C	3.5 b	3.6 B
R 585	Control	17.7a	20.6A	22.8a	23.6A	5.1	5.1
	Cold	17.4a	21.4A	20.7b	23.4A	4.4	4.7
	Dry	15.8b	17.4B	19.9b	20.8B	4.7	4.7

CC, Clean cane; WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

significantly higher in the cold environment (range was from 31.7 to 32.3 g 100 g^{-1}) than in the dry environment (range was from 30.2 to 31.3 g 100 g^{-1}). There were no significant differences between cultivars and environments for trash cellulose concentrations (range was from 31.5 to 35.9 g 100 g^{-1}). Trash lignin concentrations of all cultivars were always significantly higher in the cold environment (range was from 7.3 to 8.5 g 100 g^{-1}) than in the control environment (range was from 6.1 to 7.1 g 100 g^{-1}).

Net energy increased by 26% from CC to WGC harvests (Table 6). Net energy was higher in the control environment for CC harvest and cultivar R570 (892.7 GJ ha^{-1}) and for WGC harvest and cultivar R585 (1256.3 GJ ha^{-1}) compared to the cold and dry environments (589.0 and 877.3 GJ ha^{-1} respectively). There were no other significant differences between cultivars and environments. Net energy of trash was higher only in the dry environment for cultivar R585 (224.1 GJ ha^{-1}) compared to cold environment (157.0 GJ ha^{-1}). The energy content of millable stalks (sucrose included) made up on average 67% (in% of aboveground biomass net energy) of the aboveground biomass net energy, with 34% share from fibre (i.e. fibre energy content = $E_B/(E_B \times (\mathrm{NDF}/(Y_B \times \mathrm{DMC})))$ and 33% share from sugars (i.e. sugars energy content = $E_B/(E_B \times (Br/(Y_B \times \mathrm{DMC}))))$. Energy content of green leaves and tops accounted for on average 17% of the net energy of the aboveground biomass and trash for on average 16%. Energy content of green leaves and tops of

Table 5 Trash yield (Mg ha^{-1}) and trash dry matter (g 100 g^{-1} of fresh matter), fibre, hemicellulose, cellulose and lignin (g 100 g^{-1} of dry matter) concentrations of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry)

		Trash					
Cultivar	Environment	Yield (Mg ha^{-1})	Dry matter (g 100 g^{-1})	Fibre (g 100 g^{-1})	Hemicellulose (g 100 g^{-1})	Cellulose (g 100 g^{-1})	Lignin (g 100 g^{-1})
R 570	Control	20.3	83.7	74.4b	30.9a	33.3	7.0b
	Cold	12.1	80.8	77.7a	31.8a	35.9	8.5a
	Dry	14.1	88.3	75.6b	30.2b	35.1	8.6a
R 579	Control	10.2	77.1	71.4b	30.7ab	32.3	6.1b
	Cold	10.7	84.4	75.0a	31.7a	34.2	7.3a
	Dry	10.3	87.0	70.2b	30.3b	31.5	6.5ab
R 585	Control	14.6	77.1b	73.5b	31.0b	33.4	7.1b
	Cold	11.3	80.6b	76.4a	32.3a	33.3	8.4a
	Dry	14.7	88.3a	74.2b	31.3ab	32.2	7.6b

Means with no letters and same letter for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

Table 6 Net energy (GJ ha^{-1}) and energy content (% of aboveground biomass net energy) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Net energy (GJ ha^{-1})			Energy content (%)		
Cultivar	Environment	CC	WGC	Trash	Millable stalk	Green Leaf and Top	Trash
R570	Control	892.7a	1092.2	287.5	64.7a	14.5B	20.8ab
	Cold	589.0b	864.9	169.4	56.9b	26.7A	16.4b
	Dry	629.5ab	732.3	217.3	66.3a	10.8B	22.9a
R579	Control	731.7	868.8	134.8	72.9a	13.7B	13.4
	Cold	738.5	981.1	156.4	64.9b	21.3A	13.7
	Dry	698.2	799.3	153.2	73.3a	10.6B	16.1
R585	Control	963.9	1256.3A	194.0ab	66.5b	20.2A	13.4b
	Cold	784.3	1081.1AB	157.0b	63.3b	24.0A	12.7b
	Dry	778.5	877.3B	224.1a	70.7a	9.0B	20.3a

CC, Clean cane; WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

all cultivars were significantly higher in the cold environment (range was from 21.3 to 26.7%) than in the dry environment (range was from 9.0 to 10.8%). The cold environment showed lower energy content for trash biomass (in% of aboveground biomass net energy) of cultivars R570 and R585 (16.4 and 12.7% respectively) compared to the dry environment (22.9 and 20.3% respectively).

Sugar mill processing level – coproducts and product yields

Bagasse, molasses and recoverable sucrose yields can increase by on average 57, 58 and 4%, respectively, from CC to WGC harvests (Table 7). Bagasse yields were higher in the control environment for CC and cultivar R570 (43.6 Mg ha^{-1}) and for both harvesting systems and cultivar R585 (55.4 and 88.6 Mg ha^{-1} respectively) compared to the dry environment (28.4, 39.1 and 48.3 Mg ha^{-1} respectively). There were no differences between environments for the bagasse yields of cultivar R579. Molasses yields were higher in the cold environment for WGC harvest and cultivar R579 (10.5 Mg ha^{-1}) compared to the control and dry environments (5.9 and 6.3 Mg ha^{-1} respectively). Molasses yields were higher in the control environment for both types of harvest and cultivar R585 (6.8 and 10.4 Mg ha^{-1} respectively) compared to the cold environment for CC harvest (4.5 Mg ha^{-1}) and to the dry environment for WGC harvest (6.3 Mg ha^{-1}). Recoverable sucrose yield was only higher in the control environment for cultivar R570 compared to the cold environment, and there were no

Table 7 Bagasse, molasses and recoverable sucrose yields (Mg ha^{-1}) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Bagasse (Mg ha^{-1})		Molasses (Mg ha^{-1})		Recoverable sucrose (Mg ha^{-1})	
Cultivar	Environment	CC	WGC	CC	WGC	CC	WGC
R570	Control	43.6 a	65.6	5.6	7.9	21.5 a	22.4
	Cold	29.8 ab	63.4	3.4	7.6	14.0 b	15.2
	Dry	28.4 b	37.4	3.4	4.3	16.9 ab	17.8
R579	Control	34.8	49.6	4.0	5.9 B	19.8	20.9
	Cold	37.3	64.6	6.0	10.5 A	17.9	18.4
	Dry	33.2	42.9	4.3	6.3 B	19.5	20.4
R585	Control	55.4 a	88.6 A	6.8 a	10.4 A	18.9	19.0
	Cold	43.4 ab	81.8 A	4.5 b	9.7 A	18.0	19.0
	Dry	39.1 b	48.3 B	5.5 ab	6.3 B	17.8	18.4

CC, Clean cane; WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

Table 8 Potential electricity energy production (GJ ha^{-1}) and net electricity energy production (GJ ha^{-1}) for route 1 and for routes 2 and 3 of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		Potential electricity energy (GJ ha^{-1})			Net electricity energy for route 1 (GJ ha^{-1})		Net electricity energy for routes 2 and 3 (GJ ha^{-1})	
Cultivar	Environment	CC	WGC	Trash	CC	WGC	CC	WGC
R 570	Control	92.0 a	121.5	52.8	56.2 a	75.5	67.1a	89.1
	Cold	63.7 ab	110.2	31.7	40.1 ab	71.2	47.1ab	82.1
	Dry	60.4 b	71.2	41.5	37.3 b	44.1	44.1b	51.9
R 579	Control	68.2	87.3	21.6	39.4	51.6AB	48.5	62.6AB
	Cold	71.0	105.5	27.8	40.4	62.2A	50.4	75.7A
	Dry	59.5	69.7	26.8	33.7	39.7B	41.8	48.9B
R 585	Control	115.9a	161.6A	30.0b	75.2a	106.4A	86.7a	121.4A
	Cold	83.1b	130.3AB	26.9b	52.2b	83.4AB	61.1b	96.3AB
	Dry	82.5b	93.2B	40.1a	52.7b	59.6B	61.2b	69.0B

CC, Clean cane; WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).

differences between environments for the other cultivars and harvesting types.

Bioenergy plant processing level – energy carriers yields

Potential electricity energy yield, net electricity energy yield for route 1 and for routes 2 and 3 can increase on average by 36, 39 and 37%, respectively, from CC to WGC harvests (Table 8). Potential electricity energy yields were higher in the control environment for CC harvest and cultivar R570 (92.0 GJ ha^{-1}), and for both harvesting systems and cultivar R585 (115.9 and 161.6 GJ ha^{-1} respectively) compared to the dry environment (60.4, 82.5 and 93.2 GJ ha^{-1} respectively). There were no other significant differences between cultivars and environments. Potential electricity energy yields of trash biomass were lower in the control and cold environments for cultivar R585 (30.0 and 26.9 GJ ha^{-1} respectively) compared to the dry environment (40.1 GJ ha^{-1}). Net electricity energy yields for route 1 were higher in the control environment for CC harvest and cultivar R570 (56.2 GJ ha^{-1}) and for WGC harvest and cultivar R585 (75.2 and 106.4 GJ ha^{-1}) compared to the dry environment (37.3, 52.7 and 59.6 GJ ha^{-1}). That was different for cultivar R579 with the net electricity energy yields for route 1 which were

Table 9 Potential 1G ethanol energy production from molasses and juice (GJ ha^{-1}), and potential 2G ethanol energy production from bagasse or trash (GJ ha^{-1}) of three cultivars (R570, R579 and R585) cultivated in three contrasted environments (Control, Cold and Dry) and for two virtual harvesting systems

		1G* ethanol energy from molasses (GJ ha^{-1})		1G* ethanol energy from Juice (GJ ha^{-1})		2G† ethanol energy from bagasse or trash (GJ ha^{-1})		
Cultivar	Environment	CC	WGC	CC	WGC	CC	WGC	Trash
R 570	Control	25.8	36.1	221.8a	239.8	254.6a	383.6	118.6
	Cold	15.8	33.7	143.0b	172.4	174.0ab	370.3	70.4
	Dry	16.9	21.7	170.5ab	183.7	166.1b	218.6	82.5
R 579	Control	20.1	27.5B	200.4	217.3	203.7	290.1	59.5
	Cold	25.2	43.6A	188.0	211.3	217.9	377.5	62.8
	Dry	22.1	27.8B	199.6	213.7	194.3	250.4	59.9
R 585	Control	29.7a	44.0A	202.0	217.3	323.9a	517.6A	85.1
	Cold	22.1b	42.4A	186.0	215.7	253.4ab	478.3A	65.8
	Dry	24.3ab	28.8B	186.5	196.4	228.5b	282.1B	85.8

CC, Clean cane, WGC, Whole green cane.
Means with no letters and same letter (lower case for Clean Cane and capitals for Whole Green Cane) for each variety are undifferentiated ($P < 0.1$) by Tukey's honest significant differences (HSD).
*1G = first generation.
†2G = second generation.

higher in the cold environment (62.2 GJ ha^{-1}) than in the dry environment (39.7 GJ ha^{-1}). The same differences as previously mentioned were observed for the net electricity energy yields for routes 2 and 3.

1G ethanol from molasses and juice and 2G ethanol from bagasse yields can increase by on average 51, 10 and 57%, respectively, from CC to WGC harvests (Table 9). 1G ethanol from juice yields were higher in the control environment for the CC harvest and cultivar R570 (221.8 GJ ha^{-1}) than in the cold environment (143.0 GJ ha^{-1}) and there were no differences between environments for the other cultivars and harvesting types. Similar differences were noted between environments for 1G ethanol energy yields from molasses and juice and for 2G ethanol energy yields from bagasse compared to molasses, recoverable sucrose and bagasse yields, respectively, which was expected as we only used a transfer equation Cf. Eqn (2) to extrapolate from mill products to 1G and 2G ethanol. Similarly, there were no differences between environments for the 2G ethanol energy yields from trash biomass, as we used only a conversion factor (Zhang *et al*., 2009) to estimate potential ethanol energy yields from trash biomass yields.

Relationships and trade-offs

Statistical comparisons (Tukey's HSD, $P < 0.1$) showed no significant effect of the environment on LHV_B (data not shown). The relative difference between the LHV_B of the CC and WGC harvests was very low (<1%). These results were both emphasized by the strong relationship found between E_B and the fresh ($R^2 = 0.91$) and dry ($R^2 = 0.99$) aboveground biomass, and strongly suggest that LHV_B remain constant even across a wide range of variations (Fig. 3a and b).

At field processing level, the sucrose yields (in Mg ha^{-1}) increase simultaneously with the fresh biomass yield (Fig. 3c). Cultivar R570 was the most affected by environments and presented the largest variation in sucrose yield (coefficient of variation (CV) was 58%). The sucrose yields were always higher in the control and dry environments (range was from 18.6 to 27.3 Mg ha^{-1}) than in the cold environment (range was from 15.7 to 23.3 Mg ha^{-1}) except for the sucrose yield of WGC harvest and cultivar R585 with the cold environment (23.5 Mg ha^{-1}) which was higher than the dry environment (21.7 Mg ha^{-1}).

At sugar mill processing level, the bagasse yield was – as previously mentioned for the sucrose yield – driven by the fresh biomass yield (Fig. 3d). Bagasse yield was lower for cultivar R579 compare to the other cultivars which is consistent with the lower fibre concentration exhibited by cultivar R579.

At sugar mill and power plant processing level, there was a trade-off between the energy recovered in the various carriers produced and the extra energy needed to extract sugar in the WGC compared to CC harvests (Fig. 3e). This trade-off was modulated by G, E and H effects and their interactions. Cultivar R570 was the most affected by environments regarding both recoverable sucrose and potential electricity yields (CVs were 60 and 88% respectively). Compared with the other

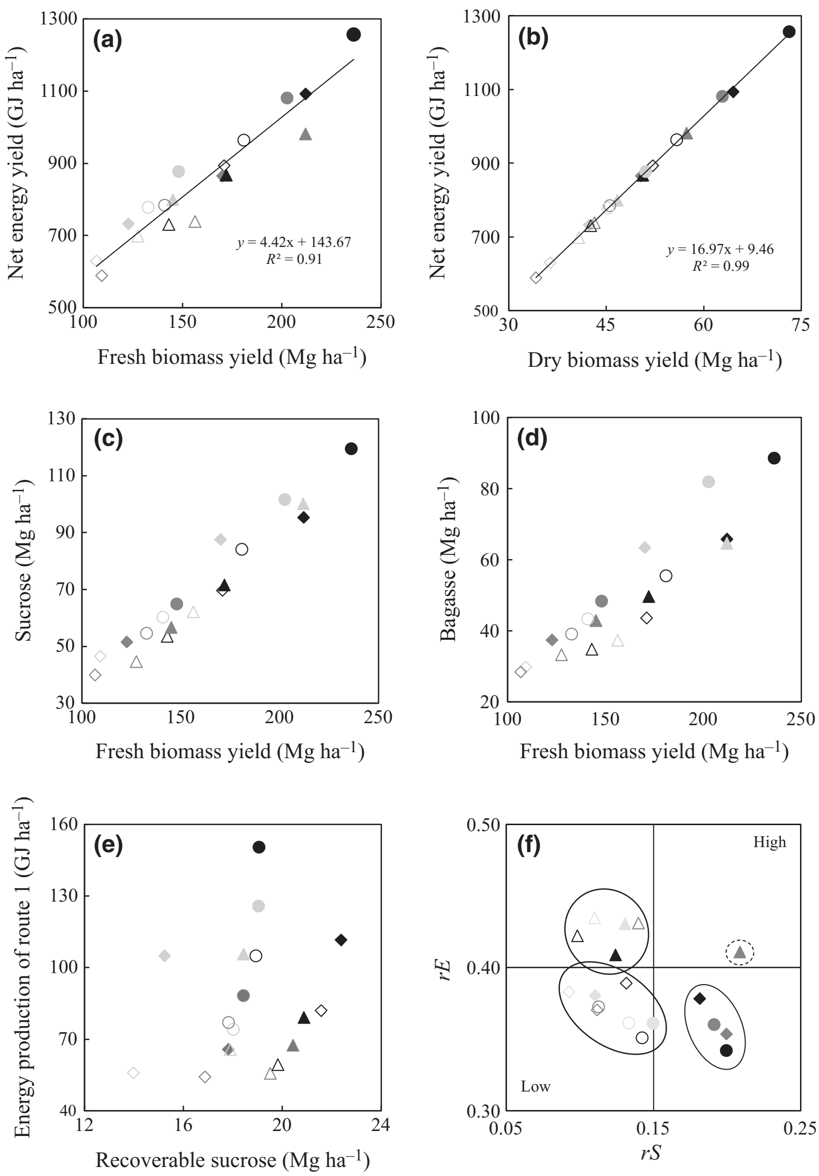

Fig. 3 Relationships between above-ground biomass net energy and (a) fresh and (b) dry above-ground biomass yields, (c) brix and fresh above-ground biomass yields, (d) bagasse and fresh above-ground biomass yields, (e) net electricity energy and recoverable sucrose yields, and (f) ratio of sugar mill energy consumption to net energy production (*rE*) and ratio of sucrose losses to sucrose entering the sugar mill (*rS*) of three cultivars (R570 = ♦, R579 = △ and R585 = ○), for two virtual harvesting systems (Clean Cane = empty markers and Whole Green Cane = solid markers) and three contrasted environments (black = Control, light grey = Cold and grey = Dry).

cultivars, R570 also performed best in the control environment (21.5 and 22.4 Mg ha^{-1}), but was out-performed in the cold environment for recoverable sucrose yield by the other cultivars. Cultivar R579 was affected to a lesser extent by the environments compared to cultivar R570 (CV was 17%), and out-performed the other cultivars in the dry environment for recoverable sucrose yield (19.5 and 20.4 Mg ha^{-1}). Cultivar R585 was less affected by environments regarding recoverable sucrose yield (CV was 7%), and out-performed the other cultivars in all environments regarding electricity yields (range was from 52.7 to 106.4 GJ ha^{-1}). The change in harvesting system predominantly affected potential electricity energy production and to a lesser extent the recoverable sucrose yields.

The assessment of a sugar mill efficiency is feasible by determining (i) the sucrose losses (rS = 1 - (recoverable sucrose yield/sucrose yield)), which could be expressed as the ratio of sucrose losses to sucrose entering the sugar mill; and (ii) the energy consumption needed to process the sugarcane entering the sugar mill [$rE = 1 -$ (net electricity energy production/potential electricity energy production)] which could be expressed as the ratio of sugar mill energy consumption to net energy production (Fig. 3e). It appears that rE remains constant by switching from CC to WGC harvesting (0.38–0.39 on average for route 1 and 0.27 on average for routes 2 and 3 respectively). This means that the extra amount of biomass entering the sugar mill and the increase in electricity energy consumption to process this larger amount of biomass are overwhelmingly compensated by the extra amount of electricity produced from this biomass itself. Cultivar R585 (high yield and fibre concentration) performed the best in this respect followed in descending order by cultivars R570 (intermediate fibre and sucrose concentrations) and R579 (low fibre and high sucrose concentrations). Concerning rS, it increased by switching from CC to WGC harvesting (from 0.12 to 0.17) which means that, as currently observed, sucrose losses increase when leaves and tops blend with millable stalks. For CC harvesting, cultivar R570 performed the best (lower sucrose losses) followed in descending order by R579 and R585 (higher sucrose losses), and for WGC harvesting, cultivar R579 performed the best followed in descending order by R570 and R585.

Influence of agro-climatic factors

The environment significantly affects both aboveground biomass yield and dry matter concentration (Table 10). Aboveground biomass yield was significantly affected by the type of harvesting ($P < 0.001$) as well as by genotypes but to a lesser extent ($P < 0.1$). Significant genotype–environment (G × E) and environment–harvesting system (E × H) interactions ($P < 0.05$ and 0.01 respectively) were also found. Genotypes, environments and harvesting systems effects (G, E and H respectively) significantly affect dry matter concentration and a significant E × H interaction ($P < 0.1$) was found. Fibre concentration was significantly affected by G, E and H effects as well as interactions between all these effects. Brix and sucrose concentrations were significantly affected by G, E and H effects as well as G × E and E × H interactions. G, E and H effects significantly affected hemicellulose and cellulose concentrations and significant interactions between all these effects were also found. Lignin concentration was affected by G, E and H effects and a significant E × H interaction was found. Energy yield was significantly affected by G, E and H effects and significant G × E and E × H interactions were found.

G, E and H effects significantly affected bagasse and molasses yields with also significant G × E and E × H interactions. Recoverable sucrose yield was only significantly affected by the environment.

G, E and H effects significantly affected potential electricity energy and 2G ethanol energy from bagasse yields with also significant interactions among all these effects. Net electricity energy for route 1 and routes 2 and 3, and 1G ethanol from molasses were affected by

Table 10 Analysis of variance (ANOVA) of the response variables at different processing levels

		Effect/Interaction						
Processing level	Variable	G	E	H	G × E	E × H	G × H	G × E × H
Field	Yield	.	***	***	*	**	ns	ns
	Dry matter	*	***	***	ns	.	ns	ns
	Fibre	***	***	***	***	***	***	.
	Brix	***	***	***	***	.	ns	ns
	Sucrose	***	***	***	***	*	ns	ns
	Hemicellulose	***	***	***	.	***	**	*
	Cellulose	***	***	***	***	***	***	ns
	Lignin	***	***	***	ns	***	ns	ns
	Net energy	**	***	***	*	*	ns	ns
Sugar mill	Bagasse	***	***	***	*	**	ns	ns
	Molasses	**	**	***	**	*	ns	ns
	Recoverable sucrose	ns	*	ns	ns	ns	ns	ns
Bioenergy plant	Potential electricity energy	***	***	***	**	**	***	ns
	Net electricity energy for route 1	***	***	***	*	*	ns	ns
	Net electricity energy for routes 2 and 3	***	***	***	*	*	ns	ns
	1G ethanol energy from molasses	**	**	***	*	**	ns	ns
	1G ethanol energy from juice	*	ns	.	ns	ns	ns	ns
	2G ethanol energy from bagasse	***	***	***	*	***	**	ns

G, genotype; E, environment; H, harvesting system; ns, nonsignificant. Significance ·$P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

G, E and H effects with also significant G × E and E × H interactions. 1G ethanol energy from juice was only affected by G and H effects.

The ANOVA analysis showed that the variables studied are affected by a complicated interaction between effects and G, E and H interactions which made interpretation too complicated to present relevant discussions in this study.

Discussion

Biomass production, quality characteristics and net energy

The control environment had the best potential climatologic conditions to meet sugarcane crop requirements for an optimal growth with higher mean radiation and thermal time, and no water stress over the growing season (Table 1; Fig. 2). Indeed, according to Inman-Bamber (1994) warm temperature without water stress will promote leaf appearance and at the same time interception efficiency which will finally result in a high conversion rate of radiation into biomass. Compared with the cold and dry environments, the mean radiation was 17 and 11% lower, the thermal time was 11 and 2% lower and the water deficit was 0 and 7% lower than at the control environment respectively.

Water stress appeared to be the most influential factor for yield and can cause reduction in yield of 18–38% for CC harvest and of 32–42% for WGC harvest (Table 2), in line with results showed in previous studies (Inman-Bamber *et al.*, 2002; Singels & Bezuidenhout, 2002). Cooler temperature and lower amount of radiation affected yield but to a lesser extent compared to water stress. Surprisingly, the yield of the cultivar R579 in the cold environment appears to be on average higher than in the control environment but, this difference was not significant according to the Tukey HSD test ($P < 0.1$). However, we assume that this could derive from the sampling method as the field trials presented heterogeneity in regard to their stalks density. Results from the ANOVA (Table 10) suggest that yield was strongly modulated by environmental conditions and management options rather than genotypes as mentioned by Jackson (2005). This trend can be illustrated, e.g. by a much higher variability in the yield between environments for the cultivar R570 (CV was 38%) compared to the yield variability between cultivars in the control environment (CV was 16%). An option to increase yields that aims at compensating for unfavourable climatologic conditions would be to extend the duration of the growing season (i.e. the period between two harvests). Thus, later harvests specifically in the highlands (e.g. cold environment) could become an interesting alternative to ensure a year-round stabilized supply of biomass to power plants (Paturau, 1982), especially if their feedstock supply area include zones with contrasting climatological conditions and management practices, as it is the case in La Reunion Island [i.e. irrigated crops in the coastal areas (higher temperature) and rain-fed crops in the highlands (low radiation and cooler temperature)].

The dry matter concentration was clearly enhanced by water stress and as a result was higher in the dry environment for all cultivars and harvesting systems compared to the other environments (Table 2). This result highlighted the fact that dry matter concentration was clearly promoted under water stress conditions as shown in similar conditions by Martiné & Lebret (2001). The ANOVA (Table 10) showed that dry matter concentration was affected by genotype as well. DRY matter concentration of cultivar R579 was obviously lower than for the other cultivars. This observation can be confirmed by the fact that cultivar R579 has high sucrose content and the inhibition of the photosynthesis (growth) due to sucrose accumulation (Ebrahim *et al.*, 1998).

Fibre concentration differed between environments (Table 3), being highest when climatological conditions were optimal for crop growth (control environment), and lowest when stresses occurred (dry environment), in particular water-related stress as mentioned in several studies (Martiné & Lebret, 2001; Inman-Bamber *et al.*, 2002; Singels & Bezuidenhout, 2002). Cultivars seemed to exhibit a different response to water stress regarding their fibre concentration. This may be explained by (i) innate differences in fibre concentration between cultivars as observed by Andrade *et al.* (2003) on a wide range of genotypes; and by (ii) genetic traits such as biomass partitioning dynamics, temperature threshold, water requirement of the physiological processes involved in biomass partitioning promotion or inhibition and drought tolerance.

Brix and/or sucrose accumulations in millable stalks were clearly enhanced by water stress (Table 3), as mentioned by several authors (Inman-Bamber *et al.*, 2002; Singels *et al.*, 2005). This phenomenon has originally been shown by Ebrahim *et al.* (1998) and these authors explained that water stress affects root and leaf expansion rate before it affects photosynthesis. Accordingly, under water stress conditions sugarcane stops organ growth and gives a higher priority to the accumulation of sucrose in millable stalks (culm). The significant interactions (Table 10) point out that sucrose accumulation can be modulated by environmental and practice changes and also that genotypes can be affected differently by these changes. Brix concentrations globally follow the same trends as sucrose concentrations.

Lignocellulosic compounds concentrations were affected by genotypes, environments and harvesting systems (Table 4). At first sight, hemicellulose, cellulose and lignin concentrations were enhanced by cooler temperature and low radiation conditions (cold environment) and reduced by water stress (dry environment). These assumptions worked out well for cultivars R570 and R579 and both harvesting systems but not for cultivar R585 (high yield and fibre concentration). Indeed, hemicellulose, cellulose and lignin concentrations were higher for cultivar R585 in the control environment. Cultivar R585 has higher fibre and lower sucrose concentrations which would mean that sucrose concentration could play a key role in the regulation phenomenon of lignocellulosic compounds synthesis pathway. However, all these results regarding lignocellulosic compounds concentrations must be balanced by the fact that LHV remained roughly constant across a wide range of cultivars and biomass components as was reported in previous work (Don *et al.*, 1977; Burner *et al.*, 2008), and environments as was the case in this study. As a result, lignin becomes a key compound for biomass quality improvement in regard to the net energy content. Change in harvesting system might also provide an easy means to modulate the profile of lignocellulosic compounds (especially the hemicellulose and cellulose fractions) of harvested biomass, and can be done in accordance with a specific end-use of the lignocellulosic biomass (pulping, cattle feed, bio-based material, 2G ethanol, etc.).

Climatologic conditions lead to large differences in net energy yield (Table 6). These observations are supported by the strong relationship between biomass and energy yields (Fig. 3a and b), and imply that aboveground biomass yield accounts to a large extent for the variability in the biomass energy yield across environments, genotypes and harvesting systems. Energy content of the millable stalk (% of aboveground biomass net energy) of cultivars R570 and R579 was more affected by low temperatures than the cultivar R585, but conversely cultivar R585 was more sensitive to water stress than the other two cultivars. A possible explanation of this observation could be that cultivar R585 is a hybrid from a crossing between two varieties, one of which was native to Hawaii and presented some cold tolerance (personal communication).

Energy carriers and trade-off with sucrose yields

Harvesting systems have a direct impact on the qualitative characteristics (e.g. fibre and brix concentrations) of the biomass delivered to the mill as each biomass component has variable concentration of fibre as mentioned by Pouzet (2011) and differs in their concentrations of soluble carbohydrates (sucrose, reducible sugar, etc.). Indeed, switching from CC to WGC harvest allowed substantial increase in bagasse (57% on average) and molasses (58% on average) yields (Table 7). Notwithstanding, in real conditions (sugar mill process) and based on the equation given by Legendre (1992), the increase in fibre concentration caused by change in harvesting system (13%) could lead to a decrease in recoverable sucrose yield of about 10–20 kg sucrose Mg^{-1} sugarcane reaching the mill. Conversely, in the current study, the model used showed that switching from CC to WGC harvesting can, at the same time, potentially improve the yields of coproducts (by 23–113% for bagasse and by 15–119% for molasses) as well as that of recoverable sucrose. This unexpected recoverable sucrose yield result can be explained by (i) an overestimation of the amount of sucrose contained in the top of the stalks by the model; and (ii) the model design that does not cater for accurate quantification but mainly to simulate the impact of biomass quality delivered to the sugar mill on the production efficiency of the 'sugar mill–power plant' complex.

The harvesting system is one of the most important management factors that can be manipulated to maximize energy (Table 6) and electricity (Table 8) yields. The potential electricity energy production could be increased by 36% by changing from CC to WGC harvests, and by 51% by changing from CC to overall aboveground biomass. Similar to studies conducted in Brazil, Mauritius and Cuba (Ripoli *et al.*, 2000; Beeharry, 2001; Alonso Pippo *et al.*, 2007; respectively), it appeared that GCH (unburned sugarcane) allows the use of green leaves and tops as a source of energy to massively increase the electricity production. Besides, GCH is also responsible for reducing air pollution (Ripoli *et al.*, 2000) due to reduced sugarcane burning at harvest and for increasing organic matter storage in soils and improving biodiversity thanks to the presence of a trash blanket (Pankhurst, 2005).

The choice of the genotype can affect the efficiency of the 'sugar mill–power plant' complex (Fig. 3). It appears that the electricity yields for the various valorization routes of cultivar R579 presented differences between environments, which was not the case for the bagasse yield. This suggests that the energy consumption of the milling process was lower for cultivar R579 compared to the other cultivars. A possible explanation is that cultivar R579 was designed to meet the sugar industry's demands in the early 1990s for high sucrose and low fibre concentrations. Thus, increasing fibre concentration of the load entering the mill will logically be associated with more coproducts and energy yield, although decreasing fibre concentration could also reduce energy consumption of the sugar mill and create a trade-off between the energy recovered and the energy needed to process the sugarcane entering the mill.

Finally, in addition to management options, proper combinations of agro-climatic conditions and cultivars can act as leverages to improve energy carriers' yields. As an example, the potential electricity energy production and 1G ethanol energy production from molasses can increase by 47–171% and by 27–178%, respectively, from the worst to the best combinations. At this stage, analysing the trade-off between food and energy production regarding genotypes, environments and management options is needed to simultaneously maximize biomass production and optimize the valorization of sugarcane biomass.

Analysing the trade-off between food and energy production

Overall, the choice of cultivars appears to be the quickest way to improve sustainability of the sugar industry (sucrose production) and to contribute towards increasing the substitution of finite resources (bioenergy production). Indeed, for both harvesting systems, the simple fact to recommend the best combination between cultivars and environments may allow increase by 14–29% of recoverable sucrose, by 33–60% of 1G ethanol from molasses and by 18–85% of potential electricity energy yields.

At field processing level, sucrose concentration and energy of the biomass were clearly negatively correlated, exhibiting a correlation coefficient of −0.78. According to a previous study (Sunil & Lawrence, 1996), it is well known that the accumulations of sugar and structural compounds are antagonistic physiological processes. As in the current study, earlier studies (Clarke & Giamalva, 1986; Clarke & Keenliside, 1986) showed that increases in both sugar and biomass yields per hectare are possible, however, the biomass quality is not always compatible with sugar mill processing constraints because of the large fibre concentration contained in the biomass delivered to the mill. Accordingly, the change from CC to WGC harvesting leads to a decrease in sucrose concentration (g 100 g^{-1}) mainly due to the dilution of the initial amount of sucrose in a larger amount of biomass and increase in fibre concentration. Therefore, there is a trade-off between the sugar mill's objective to maximize recoverable sucrose and the quest for multicommodity production (sucrose, energy or feed).

At sugar mill and bioenergy plant processing level, harvesting system (i.e. switching from CC to WGC) is a major avenue to increase energy outputs (by 13–73% of potential electricity energy and by 19–113% of 1G ethanol energy productions) as mentioned by Beeharry (2001), but to a lesser extent for recoverable sucrose yield (1–9%). According to the model, the change from CC to WGC harvesting allowed a potential increase in net energy (GJ ha^{-1}) and surprisingly in recoverable sucrose (Mg ha^{-1}) yields which is, respectively, due to the extra amount of coproducts generated and probably because of the sucrose contained in tops. Notwithstanding what is usually observed in reality, the addition of green leaves and tops to the load delivered to the sugar mill results in increased losses in recoverable sucrose for various reasons (e.g. low purity, dextran content, low coefficient of extraction, etc.) that have not been implemented in the operating model used in this study. A solution to ward off these types of issues would be to set up a cleaning station to send clean sugarcane material (CC) to the mill. Nonetheless, a prerequisite cost-benefit analysis to evaluate cost-effectiveness of such investments is needed to estimate the extra amount of energy produced.

Finally, we should be careful not to overshadow the trade-off between sugarcane cropping systems potential benefits and drawbacks that could ensue from trash biomass removal from fields (Hassuani *et al*., 2005; Pankhurst, 2005). In the short term, an important question to address is the amount of crop residue to be removed from the field that will affect the natural balance (i.e. soil organic C content, water retention and weed control) and sustainability (yields) of the sugarcane cropping systems. Recently, a study conducted by Cerri *et al.* (2011) on a wide selection of soil types in Brazil showed that crop residue retention in the fields lead to an accumulation of organic C in soils. According to an earlier study by Wiedenfeld (2009), effects due to green sugarcane harvesting (GCH, comparable with WGC in this study) on soil properties and crop growth were relatively minor (probably because such a change in soil organic C can take decades to manifest); nevertheless, the study also mentioned that the residue remaining on the soil presents considerable challenges in cultivation, weed control and irrigation. With regard to this work, a life cycle assessment of the sugar industry in La Reunion Island is recommended to fully establish services and impacts of current practices in sugarcane cropping systems from both environmental and economic points of view. The current study provides a basis on which optimal combinations between genotypes, environments and management options (ideotypes) may define food and energy production from sugarcane cropping systems.

Sugarcane cropping systems are exclusively optimized for sucrose production (Jackson, 2005). Thus, design, assessment and optimization of new cropping systems aiming at multicommodity production (e.g. food and energy) are needed but require decision-making tools and support. Among these tools, use of ecophysiological growth models, which are able to predict aboveground biomass, sucrose and energy carriers' yields according to a wide range of management options (cultivars, environments and irrigation), is of primary importance.

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