Sugarcane as a Feedstock for Biofuels:
An Analytical White Paper

Executive Summary

• Sugarcane (or Sugar cane) is a tall grass that is native to warm temperate and tropical regions. In sugarcane, photosynthesis can utilize high radiation and has lower transpiration per unit of carbon fixation. Sugarcane does not easily produce fertile seeds and commercial propagation must be achieved vegetatively, via stem-cuttings of immature (8-12 month old) canes. Sugarcane begins to decay as soon as it is harvested and must be processed within a day or so, leading to logistical problems for transport and handling with no effective storage.

• By comparison, U.S. corn (or maize) is also a tall warm-season grass but has several important features that differ from sugarcane. For example, corn harvest is in the form of grain which is a condensed package of carbohydrates, protein, oil, and secondary nutritional substances that can be stored (for up to three years) and has good flow characteristics for handling and transport.

• Global total cane production is 1.75 billion tons (1.59 billion metric tonnes) and the 10-year trend has been upward. Brazil and India produce almost 60 percent of all the sugarcane in the world, with Brazil currently producing 35 percent of the global total.

• Sugarcane burning is a major issue. Burning is an effective method to remove the excess crop biomass that arises from the leaves, small tillers, and stalk tips (called trash). This fraction makes up about 14 percent of the sugarcane crop weight in the field. Trash is a restriction at harvest (for both hand-harvesting and mechanical), results in more costly transport, and can absorb the sugar juice during crushing with a negative effect on recoverable sugar.

• Sugarcane processing only occurs for part of the year, depending on the harvest timing for cane lines and regions. Unlike corn, which can be stored for three years, sugarcane must be processed immediately after harvest, especially with mechanical harvesting that damages the cane stalks. Consequently, the mills are closed down for about half of the year.

• One byproduct that is not present in sugarcane but is present in the processing of corn to ethanol is protein. Corn is used to produce ethanol and livestock feed while sugarcane can be used only to generate edible sugar or ethanol, but not both. With the global population expanding and the trend being towards eating more nutritious diets with higher protein, it could be questioned whether using good arable land for any crop that does not contribute protein should be allowed.

• Sugarcane is an old crop that does not have clean germplasm for improvement, does not easily fit mechanical culture practices, does not provide a storable harvest material, does not have a consistent supply, does not yield well in poor soil nor without significant water, does not contribute protein and does not really grow as a perennial. With these factors applied to the assumptions, how can it be considered as a sustainable feedstock for advanced biofuels?
SUGARCANE AS A FEEDSTOCK FOR BIOFUELS

For NCGA by J. McLaren, StrathKirn Inc.

Introduction

Sugarcane (or Sugar cane) is from the genus *Saccharum*, which contains some 30 species of tall grasses (Family: Poaceae, Tribe: Andropogoneae) that are native in warm temperate to tropical regions. Typically the plants are 5-14 ft. in height, with stiff, jointed, fibrous stalks that have a high content of sap sugar, primarily sucrose. Photosynthesis is of the C₄ type which can utilize high radiation and has lower transpiration per unit carbon fixation. Sugarcane does not easily produce fertile seeds and commercial propagation must be achieved vegetatively, via stem-cuttings of immature (8-12 month old) canes (Purseglove, 1979). The geographical range is limited to approximately between 30°S to 37°N, temperatures reflecting frost–free conditions but not above 100°F, and annual rainfall above 24 inches. The time to maturity may last from 270 – 500 days depending on conditions.

All the *Saccharum* species interbreed, and the major commercial cultivars are complex hybrids: although it is typical to have a pedigree with the inclusion of *Saccharum officinarum* (which has varying chromosome numbers: 2n = 70-122). The World collection of sugarcane lines is maintained both at the USDA-ARS Clonal Germplasm Repository, Miami, Fla., and the Sugarcane Breeding Institute, Coimbatore, India (Tai and Miller, 2002). Specific improvements via conventional plant breeding have been difficult because the basic species in the crosses are polyploid (wide range of levels). Also, sugarcane hybrids receive variable numbers of chromosomes from each parent and have variable numbers of copies of each gene (chromosomal mosaicism). Thus, traditional genetics are almost impossible and molecular markers are increasingly being used to help selection for genetic improvement. Transgenic sugarcane is possible and this approach may become more common as the pressure for improved traits increases.

U.S. corn (or maize) is from the species *Zea* and almost all commercially important corn is an annual monoecious-flowering hybrid of *Zea mays*. Like sugarcane, corn is also a tall warm-season C₄ grass but has several important features that differ from sugarcane. For example, corn harvest is in the form of grain which is a condensed package of carbohydrates, protein, oil, and secondary nutritional substances that can be stored (for up to three years) and has good flow characteristics for handling and transport. Conversely, sugarcane begins to decay as soon as it is harvested and must be processed within a day or so, leading to logistical problems for transport and handling with no effective storage.

Corn breeding has been ongoing for over 200 years (with visual selection for thousands of years) with continual improvement in cultural features and useful yield. The introduction of hybrids has allowed the capture of heterosis with associated yield increases, and the development of biotechnology has already added several very beneficial traits. Corn cultivars are widely adapted and can be grown from 0 to 55° latitude, from sea level to 12,000 ft. altitude, and with growing seasons from 42 to 400 days (Farnham *et al*., 2003).
Sugarcane Production in Brazil

The global total for cane production is ~1.75B tons (1.59B metric tonnes) and the 10-year trend has been upward. Brazil and India produce almost 60 percent of all the sugarcane in the world, with Brazil currently producing ~35 percent of the global total.

![Pie chart showing global sugarcane production distribution.](Chart1)

Fig. 1: The global distribution of production for 2007 and the trend of increasing production in Brazil. Source: UN-FAO; UNICA

The large increase in Brazilian production has occurred in the past 4-5 years (Fig. 1), and seems to be driven by the Brazilian government desire to export more ethanol (derived from processed cane juice). The higher output of sugarcane could have arisen from higher yields and/or an increase in the area of land used for sugarcane.

![Bar chart showing sugarcane yields for top countries.](Chart2)

Fig. 2: Sugarcane yields for the top countries using the mean of 2004-2006 to smooth out annual variations. Source: UN-FAO.

The Brazilian yields for 2008 were ~79 MT/Ha. Using that number the yield change accounts for only 14 percent of the overall sugarcane production increase, when comparing 2008 with 1998.
Data on the area of sugarcane harvested per year (Fig. 3) shows a large increase in the land used for sugarcane over the 10-year period, since 1998.

![Fig. 3: Area of harvested sugarcane in Brazil](source: UN-FAO; UNICA)

The trends in production (Fig. 2) and land area used (Fig. 3) are similar with the largest increase occurring over the past four to five years. The increase in land area used accounts for almost 70 percent of the production increase over the period.

While the sugarcane growing area (Fig. 4) is a considerable distance from the Amazon rainforest, the question must be raised as to where the land area increase came from. Brazilian-based reports attempt to make several points concerning the land use issue: e.g. sugarcane is a relatively small area so it doesn't have an impact, new cane land is taken from pasture not forest, etc. (BNDES/CGEE, 2008; UNICA2, 2009). These seem to miss the point that has been used to attack corn, based on indirect land use change (ILUC) and a convoluted argument about roll-on effects from the MidWest all the way to the Amazon. In addition, it is widely recognized that most deforested land in the Amazon basin is first used for grazing – i.e. pasture replacement. These reports do not mention the coastal Atlantic rainforest.

![Fig. 4: Sugarcane growing areas in Brazil. Showing distance to the Amazon and proximity to the Atlantic rainforests.](source: Goldemberg, 2008)
Comparing this situation with that of corn shows a different pattern of events, in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Sugarcane</th>
<th>Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MM acres</td>
<td>tons/acre</td>
</tr>
<tr>
<td>1996-98 base period</td>
<td>12.0</td>
<td>30.5</td>
</tr>
<tr>
<td>Aver 2008-09</td>
<td>20.6</td>
<td>35.5</td>
</tr>
<tr>
<td>Delta</td>
<td>8.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Delta as % base</td>
<td>72%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Using the average data for 1996-98 as a baseline and comparing the current data, we can see that sugarcane area harvested increased by over 70 percent while corn area harvested increased by only 7 percent. Alternatively, when we look at the yield increase data corn yield increased considerably more than sugarcane – especially considering that the yield data is the average national yield over 78 MM acres. It is unclear whether such data have been included in the modeling used for environmental aspects such as LCAs, but we propose that these effects should be taken into consideration when making decisions about ILUC, emissions, and sources of ethanol for U.S. consumption.

Examining the impact of sugarcane area expansion from another perspective shows that, had some technical progress not been achieved in sugarcane yield, then the current level of production would require 2.9 MM acres more than is harvested today. In the case of corn, had technical progress and biotechnology not contributed to a large increase in corn yield then the current level of production would require 18 MM acres more than is harvested today (Fig. 5). Thus, progress in corn has effectively “saved” 18 MM acres: which is almost as much as all the sugarcane grown in Brazil today.

Fig. 5. Yield increases in sugarcane and corn, respectively, in recent times. Data sources: UN-FAO, UNICA, USDA-NASS

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While the sugarcane growing area continues to be enlarged, mainly to generate more ethanol for export (see table below), corn yield improvement is saving millions of acres that would otherwise be required to meet internal ethanol needs. This relationship is clear and shows a large advantage for existing corn acres in the U.S., yet this factor does not seem to be taken into account in the Life Cycle Analysis (LCA) modeling used by the EPA and others.

It should also be noted that if we take the differential in yield changes, over the past 10 years, and convert that production difference into potential ethanol, then corn yield increase accounts for almost 80 percent of the U.S. ethanol produced today. It seems that corn should perhaps be credited with saving acres, either directly or indirectly, rather than being accused of being a major factor in causing ILUC in Brazil.

Future projections concerning Brazilian sugarcane, made by UNICA, Copersucra and Cogen in 2007, are shown in the following table:

This data from the Brazilian sugar organizations clearly shows that they are planning by 2020 to export 63 percent more sugar and export 336 percent more ethanol – all at the expense of increasing the land area required for sugarcane by 78 percent. These factors should have more accounting in the comparison of cane and corn ethanol by the U.S. agencies.

Government data from Brazil (MAPA, 2009) indicates that in 2008, the sugarcane industry was:
- Planted area = ~9 MM Ha (22.2 MM acres)
- Harvested area = 8.2 Mm Ha (20.3 MM acres)
- Yield = 78 MT cane/Ha (34.7 tons/acre) at average sugar content of 13.7 percent.
- Sugar yield = 10.1 MT/Ha (4.5 tons/acre)
- Some 39 percent of this went to produce 31 MM MT sugar (20 percent of the world total)
- The other 61 percent was used to produce 7.3 B gallons of ethanol: 36 percent anhydrous and 64 percent hydrated
- Of the total ethanol 5.2 B gal were used as fuel within Brazil.

Potential Productivity and Ethanol (based on averages):
- Cane sugar = 4.75 t/ac/harvest = 4.38 t/ac/year. Converted to ethanol = 560-580 gal/acre/year.
- Corn yield = 154 bu/ac/year. Converted to ethanol = 420-450 gal/ac/year.
Sugarcane Cultural Practices

Sugarcane is often considered to have the characteristics of a perennial grass and be treated as such in the modeling of production systems. However, that is not entirely accurate in practice. Cultivation requires a tropical or subtropical climate, with a minimum of 24 inches (60 cm) annual rainfall. Propagation is via vegetative cuttings, or seedlings (not by seed), and the crop is grown as a short-term semi-perennial. In Brazil, the current typical regime (Fig. 6) is to plant the vegetative setts on cultivated land, often initially in a 3-8” deep furrow which is filled-in with soil as the plant establishes itself. In some situations, micropropagated plantlets are being used as a means of obtaining an established disease-free crop, since the vegetative cuttings can transmit viruses and fungal pathogens. The first harvest is 12-18 months after planting. After harvest the crop stand is left to re-establishing from new shoots (ratoons). Each successive stand produces a lower yield and, depending on the region, cultural practice, and rate of yield decline, the crop will be replanted from new stock after four to five more harvests, each at about 12-month intervals.

Fig. 6. Outline of typical Brazilian sugarcane culture cycle

The crop cycle and practices for sugarcane in Brazil have several particular features that require consideration. These include trade-off decisions on ratoon duration, disease level and control, type of replant propagules (on-farm cuttings or clean micropropagules), degree of crop protection, fallow or rotational crop, etc. The cultivation cycle also includes aspects that impact calculations of yield, energy use, and emissions: these assumptions have a large impact on the resulting outcome of the models. Here we will explore four such aspects:

1. Yield
   Yield statistics are often quoted as the weight of cane harvested per area of harvest. However, since sugarcane is not always an annual crop then that number is the yield/area but is not necessarily the yield/area/year. Calculations must be adjusted for the plant crop duration in addition to the ratoon crop (e.g. Da Silva et al., 1978). In general, we consider that the extra months in the first plant crop add about one month to each ratoon crop. Consequently, for annual yield we adjust by 0.92 times quoted harvest/area weight to reach a typical weight/area/year.
In reality, we recognize that the first plant crop will have a higher weight at harvest – but it comes from up to 18 months growth. Conversely, some analysts view the extra months as another whole year since the land was used for that time. The method described about is a conservative but reasonable approach to arrive at the overall yield.

2. Field Burning

Burning of sugarcane is a major issue (Fig. 7). Burning is an effective method to remove the excess crop biomass that arises from the leaves, small tillers, and stalk tips (called trash). This fraction makes up about 14 percent of the sugarcane crop weight in the field. Trash is a restriction at harvest (for both hand-harvesting and mechanical), results in more costly transport, and can absorb the sugar juice during crushing with a negative effect on recoverable sugar.

Burning a sugarcane field releases a considerable amount of CO₂ with estimates varying from 2,600 – 4,500 Kg CO₂/Ha. In some models, such as GREET as used by CARB, a small amount of carbon release from burning is included in the sugarcane ethanol assessment, and the Brazilian Sugarcane Association wants that to be reduced (UNICA2, 2009). The questions remain as to what is the exact amount of CO₂ emissions used by the EPA, and what is the appropriate realistic number to include.

Burning sugarcane also results in NOₓ emissions and, again, the exact amount is somewhat unclear although some reports indicate measured NOₓ emissions in the order of 25 Kg (N)/Ha (22 lb (N)/acre): this is reported to be about 30 percent of the N fertilizer applied to sugarcane (Oppenheimer et al, 2004).

In addition to the CO₂ and NOₓ emissions per unit area, there is a large area of cane that is burnt. The Sao Paulo area, in the Central South region, produces about 60 percent of the sugarcane, has higher yields and more modern technologies, yet cane burning covers 8,000 sq. miles or equivalent to ~5 MM acres in this area alone. UNICA makes the point that a considerable number of mills have moved to mechanical harvesting, instead of manual sugarcane cutting, and that this will remove the emissions from burning (UNICA2). However, while the more advanced Sao Paulo area now has ~49 percent mechanical harvesting, there is still 69 percent of the harvested cane area being burnt each year: while mechanical harvesting overcomes the necessity for burning, it is still more efficient

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*Fig. 7. Orindiúva, Brazil, 21st July 2007. Sugarcane field burning to facilitate harvest. Source: UN Photo/Eskinder Debebe*
to harvest mechanically after burning-off the trash. With no burning in the field, the trash will have to be harvested -- at a higher cost, using more energy, with additional transport, just to be combusted into CO₂ at the mill in any case.

In addition to environmental issues, health problems have also been associated with the practice of sugarcane burning due to particulates and volatile compounds filling the air. For example, in Piracicaba, Sao Paulo, samples were collected to analyze inhalable particles, and hospital admissions for respiratory problems were examined by Cancado et al (2006). Factors arising from sugarcane burning were statistically significant and highly associated with both child and elderly respiratory admissions. The authors indicate that there is a clear and adverse impact of sugarcane burning emissions on the health of the population.

In submissions to the Californian Air Regulations Board (CARB), UNICA has positioned that Brazilian sugarcane ethanol should be given preferential treatment as an advanced biofuel under the RFS rules (UNICA2, 2009). In these submissions, it has been claimed that sugarcane burning is declining and that there are mandates for future restrictions. UNICA claim that their member companies will phase-out burning over the next 5-10 years. The Brazilian regulations for the Sao Paulo region seem to call for sugarcane field burning to be phased-out by 2021 from areas where mechanical harvesting is possible with existing technology, and by 2031 in areas where this may not be possible. Brazilian sugarcane ethanol should be assessed for what it is today, not for what it might be in 12-20 years time.

3. **Post-Ratoon Cultivation**

The indirect land-use change (ILUC) concept focuses on the theory that long-term forest, or prairie grass, results in carbon build-up in the soil. Changing that vegetation type by ploughing or cultivation is reported to result in release of oxidized carbon from the soil (Vellinga et al, 2004). Sugarcane culture is often thought to be perennial in nature, and treated as such in assessment models. However, as shown in Fig. 6, Brazilian sugarcane culture is not a perennial crop, but rather a crop treated like grassland that is ploughed-up every 4-6 years. During the ratoon crop phase, there will be an increase in soil organic matter from the cane roots and crop residues. However, as with most vegetative crops, pests and diseases build-up and the yield declines each year. Consequently, the crop is ploughed-up and the soil cultivated to replant either with cane or with another rotational crop. The carbon sequestration that was ongoing during the cane ratoon crops will mostly be lost to emission during the transition year. Thus, while there is a short-term buffer with increased carbon matter in the soil, over a 6-year period the sugarcane crop is essentially the same as an annual crop. We don’t believe that this factor has been included in any model assessments of the overall emissions.

4. **Irrigation and Fertilizers**

Sugarcane is sensitive to drought and requires >24 inches of water/year. Currently, about 75 percent of Brazilian sugarcane can be irrigated (Brehmer and Sanders, 2009). The majority of irrigation systems have the capability for fertigations since this method is typically used to apply fertilizers, and the stillage liquid from mills (called vinasse), back onto the fields. The energy required to run this system can be considerable, and varies with local evapotranspiration and rainfall.
Many reports indicate that sugarcane does not require much fertilizer. This is not entirely accurate since the crop does require adequate fertilization to achieve the sugar yield. Typical uptake reported by Brehmer and Sanders, 2009) includes:

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Kg/Ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>112</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>42</td>
</tr>
<tr>
<td>K₂O</td>
<td>185</td>
</tr>
<tr>
<td>CaO</td>
<td>309</td>
</tr>
<tr>
<td>MgO</td>
<td>70</td>
</tr>
<tr>
<td>SO₃</td>
<td>35</td>
</tr>
</tbody>
</table>

Nitrogen levels at 112 Kg N/Ha are relatively lower than corn (~170 Kg N/Ha), but we need to consider that corn provides 850 Kg protein/Ha that is harvested and used mainly for feed, while sugarcane has no protein component.

Overall, the cultural practices for sugarcane are more complex and have more implications than is typically considered in LCA modeling. However, if sugarcane ethanol is to be considered for beneficial treatment then it would be meaningful to tighten-up the assumptions regarding cultural practices and production areas.

To determine the issue with particular crop systems, it is often instructive to explore the research targets to see what problems currently exist, that need to be addressed. The Brazilian Agricultural Research Corporation, EMBRAPA, lists the following key targets for sugarcane: yield, sugar level, consistency, fertilizer, disease control, biotic and abiotic stresses, environmental and sustainability factors.

Sao Paulo is often quoted as the basis for sugarcane production practice and output, however, this area utilizes highly productive soils, produces higher yields, and utilizes more advanced technologies than other parts. Some 40 percent of the sugarcane in Brazil is not produced in the Sao Paulo area, and the less efficient methods used should be accounted for in the overall assessment. The area distribution of cane, sugar, and ethanol production is:

<table>
<thead>
<tr>
<th>REGION/STATE **</th>
<th>SUGAR CANE PRODUCTION (million tonnes)</th>
<th>% OF TOTAL</th>
<th>SUGAR PRODUCTION (million tonnes)</th>
<th>ETHANOL PRODUCTION (billion liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast</td>
<td>235.8</td>
<td>60.0%</td>
<td>21.5</td>
<td>15.2</td>
</tr>
<tr>
<td>São Paulo (SP)</td>
<td>235.8</td>
<td>60.6%</td>
<td>19.1</td>
<td>13.5</td>
</tr>
<tr>
<td>Minas Gerais (MG)</td>
<td>35.6</td>
<td>7.3%</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Centerwest</td>
<td>30.6</td>
<td>7.5%</td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Goiás (GO)</td>
<td>20.6</td>
<td>5.0%</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Mato Grosso (MT)</td>
<td>14.9</td>
<td>3.7%</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Mato Grosso do Sul (MS)</td>
<td>14.6</td>
<td>3.4%</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Northeast</td>
<td>58.7</td>
<td>12.0%</td>
<td>4.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Acre (AC)</td>
<td>24.7</td>
<td>6.1%</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Alagoas (AL)</td>
<td>17.1</td>
<td>4.4%</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Pernambuco (PE)</td>
<td>40.5</td>
<td>10.3%</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Paraíba (PB)</td>
<td>40.4</td>
<td>10.3%</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>North</td>
<td>1.3</td>
<td>0.3%</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>467.0</td>
<td>100%</td>
<td>30.6</td>
<td>22.0</td>
</tr>
</tbody>
</table>

Notes: *estimated data as of January/2008; **only states with more than 10 million tonnes are considered; Southeast = SP, MG, RJ and RS; Centerwest = GO, MT, MS and DF; Northeast = PA, AL, SE, BA, PI, CE, RN, PB and MA; South = PR, SC and RS; North = AC, AM, RR, PA, AP, AM and TO. Sources: Unica (2008) and Mapa (2008). Data compiled by Unica.
Sugarcane Processing

Overview

Sugarcane processing only occurs for part of the year, depending on harvest timing for cane lines and regions. Unlike corn, which can be stored for three years, sugarcane must be processed immediately after harvest, especially with mechanical harvesting that damages the cane stalks. Consequently, the mills (Fig. 8) are closed down for about half of the year.

![Costa Pinto Production Plant located in Piracicaba, São Paulo state](http://en.wikipedia.org/wiki/Ethanol_fuel_in_brazil)

In the processing sugar mill, the sugarcane is washed, chopped and shredded by revolving knives, repeatedly mixed with water and crushed between triple rollers (Fig. 9). The extracted juices contain 10–15 percent sucrose. The remaining fibrous solids, called bagasse, are typically burnt for heat or to generate electrical power, but may also be used for animal feed or in paper manufacture.

The extracted juice (Fig. 9) has the pH adjusted to 7 (added lime) to inhibit sucrose degradation. After settling, the clarified juice is concentrated in a multiple-effect evaporator to make syrup of ~60 percent w/w sucrose. This syrup is further concentrated under vacuum until it becomes supersaturated, and then seeded with crystalline sugar. Upon cooling, sugar crystallizes out of the syrup. Typically, a centrifuge is used to separate the sugar from the remaining liquid, called molasses. The raw mill sugar is sent to a refinery where further clarification and recrystallization processes result in edible sugar for use in various foods and for table use.

Alternatively, the extracted juice (Fig. 9) may be sent to a yeast fermentation process to generate crude ethanol. The process beer is then distilled to produce ethanol. In the U.S. fuel ethanol must be anhydrous and that requires the additional removal of virtually all the water, from the azeotrop mixture. In Brazil, fuel ethanol may contain up to five percent water (called hydrated) and this is the basic product from distillation in the sugarcane ethanol mill. Some mills will add the extra step (and cost) of making anhydrous ethanol. The 2008 reported ethanol output was made up of 64 percent hydrated and 36 percent anhydrous ethanol.
The cane harvest period runs only for five to six months/year in one particular region and harvested cane is generally crushed within 24 hours or degradation will impact the recoverable sucrose. Some mills will process for ethanol only but it is expensive to build an ethanol plant that sits idle for half the year. Sugarcane cannot be stored and it is expensive to transport low-density biomass and water (cane is ~75 percent moisture content and 14 percent sugars). The average cane transport distance is about 12 miles. Some 60 percent of the 350 mills can process sugar and/or ethanol.

The main decision factor in switching between fuel ethanol and edible sugar was historically related to the world price of sugar (Fig. 10). Today, with 35 percent on the mills being ethanol only, the volume of ethanol produced in Brazil has been increasing (Fig. 11) despite the fact that edible sugar price has also been increasing. At the same time ethanol price has been relatively low and some mills are selling at below production cost: those mills had government help with their investment, and already sit idle half the year.

While sugar percent in the stalks has recently been ~13-14.5 percent (MAPA, 2009), the recoverable sugars (called ATR) typically range from 12.2 – 14.2 percent: the number for 2008 was 14.2 percent and recent process reports indicate a current level of 12.4 percent ATR due to the heavy rains in June. Conversion of sucrose by fermentation generates ethanol plus CO₂ and, in theory, 1 ton sugar would provide for 162 gal ethanol (50:50 anhydrous:hydrated). With conversion efficiencies and practical operations at ~80 percent efficiency (extraction, fermentation and distillation combined), 1 ton sugarcane (13.75 sugar) is likely to generate ~17.8 gallons ethanol. One ton molasses could be used to generate another three gal. of ethanol if desired. These calculated conversions are similar to those reported by Shapouri and Salassi (2006) for U.S. sugarcane.

Fig. 9. A diagrammatic representation of sugarcane processing to sugar and ethanol.
Fig. 10. Global sugar prices. Source: Contracts, Caribbean No 11 (raw) and London No 5 (refined)

![Graph of US cents/lb for sugar prices from 1999 to 2009]

Fig. 11. Brazilian ethanol production. Data source: MAPA

![Graph of Brazilian ethanol production from 1999 to 2008]

Given the practical conversion rates the amount of CO$_2$ released by the fermentation part of the process (excluding the boilers, etc.) process is equal to 7.9 lb CO$_2$/gal ethanol. Given the ethanol volume produced (Fig. 11), then the CO$_2$ emissions from the 2008 sugar fermentation was 56 billion lbs.

The sugarcane ethanol process also generates another by-product, which is basically the stillage left after distillation of ethanol, called vinasse. Typically, 12 gal. vinasse are generated per gal ethanol, which means that with the 2008 ethanol volume (Fig. 11) the volume of vinasse was 85 billion gallons. Such a large volume of vinasse is a problem to deal with. Moreover, the vinasse contains a high level of potassium resulting in toxic levels if concentrated in one place.
In recent years, the dumping of vinasse via large lagoon has declined and more mills are using vinasse as a liquid fertilizer. Application can be in a fertigation system (modified irrigation) and the growing crop can utilize the nutrients. However, the cost of pumping and/or transport is high, especially to disperse the vinasse over long distances. The energy and emissions related to vinasse dispersal should also be included in the sugarcane ethanol LCA assessments.

Another by-product of sugarcane processing is the biomass left after crushing, called bagasse (biomass at ~50 percent moisture). Obviously, there is a large volume of bagasse generated since the sugar content of cane is only 14 percent yet the whole stalk (plus water) must be transported to the mill. In order to deal with the problem of excess bagasse, many mills are exploring the production of surplus electricity via combustion of the bagasse. Beyond supplying the internal needs of the mill, generation of electricity for the grid requires the use of high efficiency boilers operating with high pressures and temperatures. These are costly to install, especially when the investment may sit idle for half the year. Nevertheless, in Brazil some 3,081 MW of capacity has been installed (ISO, 2009) to be driven by combustion of bagasse. This enterprise is dependent on the price captured for the electricity, continuation of supply to the grid (month-to-month), consistency of supply (day-to-day), bagasse storage/supply during the off-season, availability of wood or coal to run the boiler in the off-season, and having the appropriate grid infrastructure.

Beyond the opportunities for economic return (ISO, 2009), there are other aspects to consider. For example, if co-generation with wood (or coal) is required to allow the economics to work over the course of the year, then should the emissions generated from the transport, handling, and emission of that feedstock be included in an overall LCA for sugarcane?

It should be noted that, irrespective of method and economics, the combustion of bagasse does result in considerable CO₂ emissions (and some NOₓ, SOₓ, etc). One school of thought claims that this is irrelevant since the CO₂ is cycled back to be re-fixed by the photosynthetic process in the next crop. This type of buffer cycle does occur and is basically CO₂ neutral – i.e. there is no large benefit effect such as occurs in carbon sequestration and any small benefit is limited by the size of the buffer. A superior carbon benefit would occur if the bagasse were used for other purposes such as feed or paperboard. In the case of corn, the equivalent by-product, is either left in the field as carbon residue or, if from the grain, is used as a feed product: in neither case is it combusted back to CO₂ for immediate release.

One by-product that is not present in sugarcane but is present in the processing of corn to ethanol is protein. This is the advantage of having a slightly lower biomass yield, and having sufficient nitrogen applied. In other words, corn is used to produce ethanol plus feed while sugarcane can be used only to generate edible sugar or ethanol. With the global population expanding and the trend being towards eating more nutritious diets with higher protein, it could be questioned whether using good arable land for any crop that does not contribute protein should be allowed.

Sugarcane is an old crop that does not have clean germplasm for improvement, does not easily fit mechanical culture practices, does not provide a storable harvest material, does not have a consistent supply, does not yield well in poor soil nor without significant water, does not contribute protein, does not really grow as a perennial, and….with these factors applied to the assumptions, how can it be considered as a sustainable feedstock for advanced biofuels?
References


UNICA. Brazilian Sugarcane Industry Association for the promotion of sugar and sugarcane-based ethanol created in 1997, following government deregulation of the sugar and ethanol sectors. [http://english.unica.com.br/](http://english.unica.com.br/)


APPENDIX

Where does consistency of supply and reliance become a factor?

Bad weather hurts Brazil’s cane harvest in June

(BIOFuelsBusiness.com, July 16, 2009)
by Biofuels Business Staff

SAO PAULO, BRAZIL – Rains during much of June in the sugarcane growing areas of South-Central Brazil reduced the number of days available for cane crushing at several mills, which lowered the sucrose content as well as the volume of harvested cane as well. The state most affected was Parana, where only 61.3 percent of available harvest days were utilized, resulting in about 11.5 days stopped. The utilization rates were also low in Mato Grosso do Sul, which came in at 68.9 percent during the month. In the top cane producing state, Sao Paulo, utilization reached 79.5 percent, similar to the average for the South-Central region, which accounts for 88 percent of Brazil’s total sugarcane harvest.

In the second half of June, the harvest totaled 33.23 million tons of sugarcane, 0.74 percent less than in the same period a year before. The reduction would have been even greater during that two-week period if not for the entry of 10 mills that began production in the current harvest. Of these, three are new mills making their very first harvest. In all, four new mills started production in June and another two in the first half of July. Among previously operating mills, twenty have yet to begin their harvest in the 2009/10 crop year.

Total recoverable sugars obtained per ton of sugarcane (known as ATR in Portuguese) reached 133.03 kg per ton of cane crushed in the second half of June, 1.61 percent lower than in the same period last year. The total accumulated since the beginning of the crop year is 123.98 kg per ton of cane crushed, 0.01 percent above accumulated amounts for the same period a year ago. Since the beginning of the harvest, the total sugarcane crush stood at 176.22 million metric tons on June 30, a 24.77 percent increase compared to the same period in the previous harvest.

Of the total sugarcane harvested in the second half of June, 44.91 percent was utilized to make sugar, with production reaching 1.89 metric tons in the period, a 6.6 percent increase compared to the same period in the last crop year. Since the beginning of the current harvest, the South-Central region has produced 8.67 million metric tons of sugar, 33.67 percent above last year’s total at this time. Up to now, 41.63 percent of the sugarcane harvest in South-Central Brazil this year went to sugar production.

Ethanol production in that period reached 1.424 billion liters, 8.2 percent below the same period in the last crop year. Of this total, ethanol production was split into 359 million liters of anhydrous ethanol and 1.065 billion liters of hydrous ethanol. From the beginning of this harvest to the end of June, anhydrous ethanol production in South-Central Brazil totaled 1.532 billion liters, down 23.84 percent from the same period a year before. Hydrous ethanol, used to fuel Brazil’s rapidly expanding fleet of flex-fuel vehicles reached 5.950 billion liters, up 40.29 percent from the same period in last year’s harvest.

By StrathKirn Inc.
Sugar exports in the entire country during the first three months of the harvest (April through June) reached 5.69 million tons, compared to 4.23 million tons during the same period last year. VHP type sugar accounted for 74 percent of all sugar exports since the start of the harvest, compared to 68 percent during the same period last year.

Total ethanol exports since the beginning of the harvest totaled 985 million liters, compared to 1.1 billion liters in the same period last year. There has been a significant reduction in exports of anhydrous ethanol to the United States, which totaled only 22.3 million liters during the first three months of the harvest, compared with 376.2 million liters of anhydrous ethanol shipped to the U.S. during the same period last year. Exports to Caribbean countries and to Europe remain at about the same levels as last year. The reduction in direct exports to the United States has been offset by a large increase in exports to India, Japan and South Korea.

In the Brazilian market, demand for anhydrous ethanol has been stable, even with increased sales of flex-fuel cars. As for hydrous ethanol, in the first three months of the harvest (April, May and June) sales have increased 25 percent compared to the same period a year before, with shipments by producing mills totaling 1.92 billion liters, up 1.5 percent from the previous month (May).

Despite the slight improvement observed in prices paid to producers, ethanol prices remain below production costs. Three factors explain the increase in ethanol demand in the domestic market:

- The expanding flex-fuel vehicle fleet in Brazil, which now accounts for over one-third of the country’s entire light vehicle fleet;
- Competitive ethanol prices at the pump, as compared to the price of gasoline; and,
- On the supply side, a harvest that is surpassing expectations, particularly in June, both from the standpoint of quantity of sugarcane processed as well as the volume of recoverable sugars per ton of cane crushed.

It is important to note that despite better prices paid to ethanol producers, as observed in the wholesale market in the last few weeks, prices for consumers at the pump remain competitive with gasoline.