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GREENHOUSE GAS EMISSIONS AND ENERGY BALANCES IN BIO-ETHANOL PRODUCTION AND UTILIZATION IN BRAZIL (1996)

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Abstract—Production of sugar cane in Brazil in the 1996/97 season was 273 million t (harvested wet wt)/year, leading to 13.7 million m^3 ethanol and 13.5 million t of sugar. Emissions of greenhouse gases were evaluated for the agronomic/industrial production processes and product utilization including N_2O and methane. Up-dating the energy balance from 1985 to 1995 indicated the effect of the main technological trends; apparently, fossil fuel consumption due to the increasing agricultural mechanization is largely off-set by technological advances in transportation and overall conversion efficiencies (agricultural and industrial). Output/input energy ratio in ethanol grew to 9.2 (average) and 11.2 (best values). Net savings in CO_2 (equivalent) emissions, due to ethanol and bagasse substitution for fossil fuels, correspond to 46.7×10^6 t CO_2 (equivalent)/year, nearly 20% of all CO_2 emissions from fuels in Brazil. Ethanol alone is responsible for 64% of the net avoided emissions. © 1998 Published by Elsevier Science Ltd. All rights reserved

Keywords—Ethanol; greenhouse gases; biofuel; energy balance.

1. INTRODUCTION

The values published in 1992[1] for the CO_2 balance in Brazilian sugar cane agro-industry were based on a detailed energy balance for agronomic/industrial processes from 1985.[2] The fast technological development in ethanol production, including agricultural mechanization over the last 10 years or so, led to the need for re-calculation of the energy balance. The results are presented here, as well as their influence in the CO_2 balance. It was also considered important to investigate the emissions of methane and N_2O at the agricultural/industrial levels.

The same basic considerations made in 1992[1] hold for the carbon cycle in the sugar cane production and processing to sugar and ethanol; some fossil fuel is used (both in agriculture and industry) yielding ethanol and some bagasse for use as fuel in other sectors, and a fraction of bagasse is also used internally as fuel for the sugar production.

2. THE CARBON CYCLE FOR THE SUGAR CANE AGRO-INDUSTRY: OTHER GREENHOUSE GASES

Brazilian sugar cane is a rattoon crop with annual harvest, so stalks (fibre and sucrose), leaves and tops have an annual cycle. Although less than 20% of total sugar cane is harvested green, this figure is expected to grow to at least 50% in the next 8 years. Today most of the leaves and tops are burnt in the field, while fibre and pith (bagasse) from the stalks are burnt for power. Sucrose is processed to sugar and ethanol, and its carbon is also recycled into the atmosphere in a short period. Roots have a longer cycle, at least 5 years,[2] and in most cases a positive effect from incorporating carbon into soil can be observed, but it was not accounted for because of lack of sufficient data on soil conditions before the cane culture was established.

The net contribution of the sugar cane agro-industry to the evolution of atmospheric CO_2 will be:

- increased atmospheric CO_2 due to fossil fuel and energy-using inputs in the agricultural/industrial production of sugar and ethanol;
- reduction in the rate of release of CO_2 by substituting ethanol for gasoline, also, by substituting sugar cane bagasse for fuel oil in sugar production and other industrial sectors.

The magnitude of other greenhouse gases emissions from the sugar cane production/

processing/utilization was considered in the following areas:

- methane emissions from burning sugar cane before harvesting;
- methane emissions from stillage (as fertilizer) and bagasse burning in boilers;
- emissions of greenhouse gases from burning in ethanol engines (relative to gasoline engines);
- N_2O emissions from soil.

3. THE SUGAR CANE AGRO-INDUSTRY IN THE 1996/97 HARVEST YEAR

Production in Brazil was 273×10^6 t sugar cane, ethanol production was 13.7×10^6 m^3 (31% anhydrous, to blend with gasoline) and sugar production 13.4×10^6 t.

Average sugar cane composition for a sample of 55 million t[3] in the centre–south of Brazil indicated a 14.1% pol (sucrose content) and 13.6% fiber.

4. NET CONTRIBUTION TO ATMOSPHERIC GREENHOUSE GASES EVOLUTION

4.1. *Fossil fuel utilization in the agro-industry*

A new energy balance has been prepared since the last detailed balance was performed 10 years ago. Energy accounting for sugar and ethanol production in Brazil (São Paulo State conditions, average and best values; sample of 60×10^6 t cane/year) can be found in Macedo and Koeller.[4] The main results are summarized in Table 1.

The main differences between the results from 1985[1] and 1995 correspond clearly to some trends:

- an increase in cane productivity (up to 80.4 t/ha harvested) and in the cane life cycle (4–5 cuts) led to lower specific energy utilization for most agricultural operations. The value for 1985 was 78 t/ha for five cuts. This trend is expected to continue;
- energy for transportation has fallen with new technologies;
- mechanical harvesting, now 20%, has increased fuel consumption, however, the use of heavier equipment and new processes is off-setting this trend. Mechanical harvesting will account for up to 50% in the next 8 years;
- an increase in overall industrial conversion efficiency (from 73 l ethanol/t cane in 1985 to 85.4 l ethanol/t cane in 1995 (averages)) led to lower energy consumption;

Table 1. Energy in sugar cane and ethanol production (MJ/t cane)*

	Averages		Best values	
Sugar cane production (total)	189.87		175.53	
Agricultural operations	30.10		30.10	
Cane transportation	34.92		31.87	
Fertilizers	66.96		56.09	
Lime, herbicides, etc.	19.06		19.06	
Seeds	5.76		5.34	
Equipment	33.07		33.07	
Ethanol production (total)†	46.08		36.39	
Electricity (bought)	0.00		0.00	
Chemicals and lubricants	7.34		7.34	
Buildings	10.78		8.07	
Equipment	27.96		20.98	
External energy flows (agriculture + industry)‡				
	Input	Output	Input	Output
Agriculture	189.87		175.53	
Industry	46.08		36.39	
Ethanol produced		1996.37		2045.27
Bagasse surplus		175.14		328.54
Totals (external flows)	235.95	2171.51	211.92	2373.81
Output/input	9.2		11.2	

*Three levels of "energy utilization" are considered: direct fuel and (external) electricity utilization; energy used for production of chemicals, lubricants, lime, etc.; and energy used for production and maintenance of equipment and buildings.

†Only "external" energy; not including energy from bagasse utilized at the sugar mill, as steam or electricity.

‡External energy inputs are mainly from fossil fuels (fuel oil, diesel), although in Brazil most of the electric power input is renewable (hydro-electric) it is considered here as a component of buildings, equipment, chemicals, etc.

Table 2. Avoided CO_2 emissions with ethanol utilization (1996) (measured as C)

	Production, 1996 (10^6 m^3/year)	Gasoline replaced (10^6 m^3/year)	Avoided release of C (10^6 t/year)*
Anhydrous ethanol	4.27	4.44	3.37
Hydrated ethanol	9.47	7.58	5.76
Total	13.74		9.13

*0.76 kg C/l of gasoline.

- the better utilization of bagasse for co-generation led to practically zero power imports at the sugar mill.

The observed trend indicates increases in bagasse availability (surplus) for the next few years, either for in-house power production or for selling as fuel. Also, the increase in green cane harvesting will produce a large amount of trash (much larger than the bagasse surplus today). This could lead to a significant improvement in the output/input energy relationship for sugar cane ethanol in the near future.

From Table 1, it is seen that the energy used from fossil sources is 236 MJ/t cane in the agriculture and industry phases (against 271 MJ/t in 1985). It corresponds to 4.7 kg C/t cane or 17.2 kg CO_2/t cane.

4.2. *Ethanol substitution for gasoline*

Considering gasoline quality, blend properties and engines in Brazil, equivalencies are assumed to be: 1 l of hydrated ethanol substitutes for 0.8 l gasoline (neat ethanol engines) and 1 l of anhydrous ethanol substitutes for 1.04 l gasoline as a blend. Results for avoided CO_2 emissions are shown in Table 2.

4.3. *Use of bagasse as fuel*

Total bagasse production is approximately 76×10^6 t/year (1996/97) at 50% moisture. Estimates of surplus bagasse are not accurate; we assume losses of 5% of total bagasse, an average surplus of 12% for ethanol production and 5% for sugar production. Losses also account for "other uses" (cattle feed, for instance). Surplus bagasse is used as fuel in other industrial sectors (food, paper and pulp, chemical industries), and an important fraction is needed at the sugar mills as a fuel, for either sugar or ethanol production. A summary is presented in Table 3.

4.4. *Methane emissions (agronomic/industrial)*

4.4.1. *Emissions from burning sugar cane in field before harvesting*. A recent study[5] analysed emission factors by simulating burning conditions for sugar cane in a wind tunnel. Values found were 0.32 kg/t (dry fuel) in the case of a spreading fire and 0.59 kg/t (dry fuel) for fire in a pile. The first simulates the conditions for post-harvest field burning (mostly tops and green leaves) and the second pre-harvest burning of dry leaves.

The load factors in Brazil average 13.9 t (dry) residues/ha (10.1 for dry leaves, 3.0 for green leaves, 0.8 for tops) in non-irrigated areas with a total of 87.9 t cane/ha. Burning is practised today in 90% of the area (São Paulo State), thus, pre-harvest burning is mostly practised so that tops and a portion of green leaves are left in the field. For a load factor of 11 t/ha (based on the actual evaluation of the burning processes) and pre-harvest burning

Table 3. Avoided CO_2 emissions with bagasse utilization as fuel (measured as C)

	50% moisture (10^6 t/year)	Fuel oil replaced (10^6 t/year)*	Avoided C release (10^6 t/year)†
Bagasse production	76.0	—	
Bagasse utilization			
Sugar production	28.0	4.9	4.2
Energy sector (ethanol)	37.0	6.5	(5.5)‡
Fuel, other sectors	7.0	1.2	1.0
Losses, other uses	4.0	—	—
Total			5.2‡

*Wet bagasse: 7.74 MJ/kg, LHV; boiler efficiency 74% (bagasse) and 82% (fuel oil), related to LHV.

†Fuel oil: 0.86 kg C/kg fuel oil.

‡Bagasse as fuel for ethanol production is not considered as avoiding carbon release; it is treated here as an "internal transformation".

conditions, methane emissions are estimated to be 6.5 kg methane/ha.

4.4.2. *Emissions from stillage as fertilizer*. There is no evidence of methane emissions under the conditions used for irrigation; the application at levels under 200 m^3/ha is fast and no time is allowed for methane to form. The use of stillage ponds for temporary storage of the fermentation by-product is being gradually eliminated, with most of the stillage being used immediately and the cleaning of the ponds (to prevent odour) helps prevent methanogenic bacteria from developing.

4.4.3. *Emissions from bagasse boilers*. Emissions of unburnt organics, including methane, would only occur in transient or uncontrolled disturbed boiler operation. Although most boilers do not have wet scrubbers emissions of methane have not been reported. The most significant pollutant emitted by bagasse boilers is particulate matter.

4.4.4. *Emissions from burning ethanol in ethanol engines (different to gasoline engines)*. Between 1980 and 1996 the legal emission limits for automotive engines have changed significantly in two steps (1990 and 1992).[6] The analysis of averages from 1986 to 1992 shows that CO emissions were always lower for the ethanol engines than for the gasoline–gasohol blend engines; NO_x emissions were equivalent and HC emissions were also lower or equivalent. From the emissions of CH_4, CO, non-methane hydrocarbons and NO_x, in this case only NO_x must be considered as an important greenhouse effect gas, because the others will be oxidized and ultimately the resulting CO_2 will be mostly re-absorbed in the sugar cane cycle. NO_x emissions have been shown to be equivalent to emissions from gasoline engines (from 1990 to 1995 ethanol engines ranged from 1.00 to 0.70 g/km and gasoline engines from 1.20 to 0.70 g/km), so that we can neglect them in the "net" effect with respect to gasoline. However, it might be interesting to quantify the nature of the HC formed; there are no specific measurements for methane, for instance, for the ethanol engine. It is known for internal combustion engines that the mass ratio of CO_2/CH_4 is typically 4700 (gasoline, diesel) and 3900 (methanol); the significance of methane is expected to be small.

CETESB data[7] shows that, with the different technologies co-existing in 1993 the ratio of ethanol/THC (total hydrocarbon) in ethanol engines was in the range of 0.70–0.85, and non-ethanol HC was typically 0.6 g/km. Even if 30% of the HC was methane, the result would be 15 kg CO_2 equivalent/m^3 ethanol and the difference with respect to gasoline emissions would be even smaller. This would be less than 1% of the avoided emissions and, thus, will be neglected.

In conclusion, we consider the pre-harvest burning of sugar cane trash (tops, green and dry leaves) as the only significant source of methane formation in sugar cane and ethanol production/utilization in the comparison with the gasoline cycle.

The value estimated for Brazilian conditions is 6.5 kg methane/ha (for 87 t cane/ha) or approximately 0.9 kg methane/m^3 ethanol.

4.5. *N_2O emissions from soil*

Although few studies on N_2O emissions from soil are available, we can estimate its value for sugar cane plantations based on some assumptions:[8] (1) N_2O emissions depend on the amount of N fertilizer used, its form of application (NO_3 or NH_4) and soil conditions; and (2) emissions (by weight) correspond to 0.5–1.5% of the applied fertilizer, the higher value for NH_4 type fertilizers.

For the conditions in the centre–south region of Brazil we assume that 28 kg N are used for the planting of sugar cane and 87 kg N for each ratoon,[9] leading to 75 kg N/ha/year for the cycle. Most of the fertilizer is NH_4-type.

The result is 1.7 kg N_2O/ha/year, since N_2O has a greenhouse effect potential 150 times higher than that of CO_2, and this corresponds to 250 kg CO_2 equivalent/ha/year or 3.17 kg CO_2/t cane.

5. SUMMARY AND CONCLUSIONS

Table 4 summarizes the main results. In 1996 (96/97 season) the sugar cane industry in Brazil processed 273×10^6 t sugar cane: 59% was used to produce ethanol (13.7×10^6 m^3) and 41% for sugar (13.5×10^6 t). The recycling of carbon in the sugar cane growing process results in the avoidance of large CO_2 emissions in both cases:

- in the sugar cane to ethanol cycle by the substitution of ethanol for gasoline, and in

Table 4. Net CO_2 (equivalent) emissions due to sugar cane production and utilization in Brazil (1996) (measured as C)

	10^6 t C (equiv.)/year
Fossil fuel utilization in the agro-industry	+1.28
Methane emissions (sugar cane burning)	+0.06
N_2O emissions	+0.24
Ethanol substitution for gasoline	−9.13
Bagasse substitution for fuel oil (food and chemical industry)	−5.20
Net contribution (carbon uptake)	−12.74

a small amount the substitution of surplus bagasse for fuel oil in other industries;

- in the sugar cane-to-sugar cycle by the substitution of bagasse for coal (or oil) at the sugar factory, and by the use of surplus bagasse in other industries.

The net savings in CO_2 (equivalent) emissions was 12.74×10^6 t C/year or 46.7×10^6 t CO_2 (equivalent). This corresponds to nearly 20% of all CO_2 emissions from fossil fuels in Brazil.

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