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Sugarcane ethanol

Contributions to climate change mitigation and the environment

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Chapter 2
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1. Historical scale and dynamics of sugarcane production

Sugarcane originates from tropical South- and Southeast Asia. Crystallized sugar, extracted from the sucrose stored in the stems of sugarcane, was known 5000 years ago in India. In the 7th century, the knowledge of growing sugarcane and producing sugar was transferred to China. Around the 8th century sugarcane was introduced by the Arabs to Mesopotamia, Egypt, North Africa and Spain, from where it was introduced to Central and South America. Christopher Columbus brought sugarcane to the Caribbean islands, today's Haiti and Dominican Republic. Driven by the interests of major European colonial powers, sugarcane production had a great influence on many tropical islands and colonies in the Caribbean, South America, and the Pacific. In the 20th century, Cuba played a special role as main supplier of sugar to the countries of the Former USSR. In the last 30 years, Brazil wrote a new chapter in the history of sugarcane production, the first time not driven by colonial powers and the consumption of sugar, but substantially driven by domestic policies fostering bioethanol production to increase energy self-reliance and to reduce the import bill for petroleum.

1.1. Regional distribution and dynamics of sugarcane production

World crop and livestock statistics collected and published by the Food and Agriculture Organization (FAO) of the United Nation are available for years since 1950. According to these data, world production of sugarcane at the mid of last century was about 260 million tons produced on around 6.3 million hectares, i.e. an average yield of just over 40 tons per hectare. Only 30 years later, in 1980, the global harvest of sugarcane had reached a level of some 770 million tons cultivated on about 13.6 million hectares of land with an average yield of 57 tons per hectare. Another nearly 30 years later, the estimates of sugarcane production for 2007 indicate more than doubling of outputs to 1525 million tons from some 21.9 million hectares harvested sugarcane. In summary, the global harvest of sugarcane had a nearly six-fold increase from 1950 to 2007 while harvested area increased 3.5 times. During the same period average global sugarcane yield increased from 41.4 tons per hectare in 1950 to 69.6 tons per hectare in 2007, i.e. a sustained average yield increase per annum of nearly 1%.

Figure 1 shows the time development and broad regional distribution of sugarcane production and area harvested.

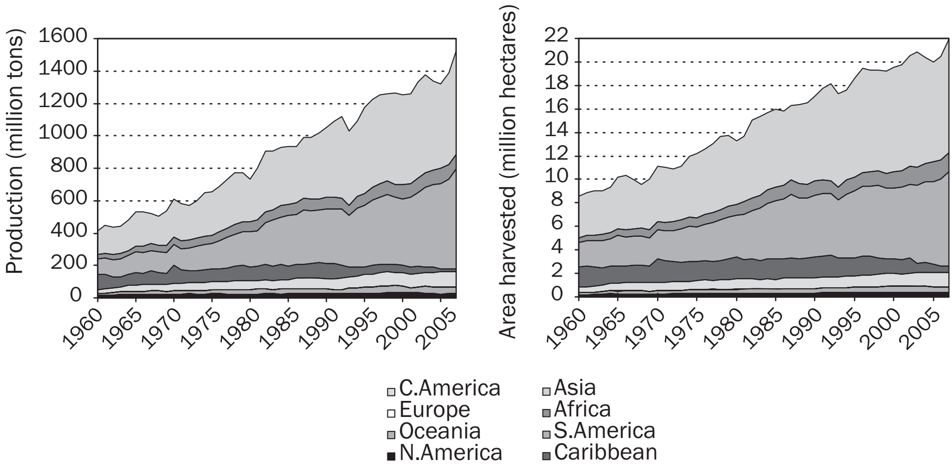

Figure 1. Global sugarcane production 1960-2007, by broad geographic region. a: production (million tons); b: area harvested (million hectares). Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008.

Table 1 indicates the main global players in sugarcane production. The countries shown are listed in decreasing order of their sugarcane production in 2007. The table includes all those countries, which ranked at least once among the 10 largest global producers in past decades since 1950, and shows their global production rank for each period.

Table 2 indicates for the same countries level of production for respectively 1950 (three-year average for 1949-1951), 1960, etc., to 2000 (three-year average for 1999-2001), and for 2007. Table 3 presents associated harvested sugarcane areas.

In 1950, and still in 1960, India and Cuba were the two largest sugarcane producers in the world. India continued to dominate sugarcane production until 1980, when Brazil took over the first rank both in terms of area harvested and sugarcane output. Cuba maintained rank three among global sugarcane producers until 1991. Then, however, with the collapse of the USSR, Cuba's guaranteed sugar export market, the sugar industry in Cuba collapsed rapidly as well. As a result, sugarcane production in 2007 was only about one-eighth of the peak reached in 1990. Another example for the decline of Caribbean sugarcane industry is Puerto Rico, the world's seventh largest producer in 1950, where sugarcane cultivation became uneconomical and was completely abandoned in recent years.

Though the FAO lists more than 100 countries where sugarcane is cultivated, Table 2 and 3 indicate that global sugarcane production is fairly concentrated in only a few countries. The 15 top countries listed in Table 1 account for about 85 percent of the harvested sugarcane area in 2007, and for a similar level in 1950 and the other periods shown. The first three

Table 1. Rank of major producers of sugarcane, 1950-2007.

	2007	1999-01	1989-91	1979-81	1969-71	1959-61	1949-51
Brazil[1]	1	1	1	1	2	3	3
India[3]	2	2	2	2	1	1	1
China[1]	3	3	4	5	8	6	8
Thailand[1]	4	4	6	12	20	27	43
Pakistan[1]	5	5	7	7	6	9	12
Mexico[3]	6	6	5	4	4	4	6
Colombia[3]	7	9	9	8	11	7	5
Australia[1]	8	7	12	10	9	12	11
United States[2]	9	10	10	9	7	5	4
Philippines[3]	10	11	11	6	5	8	10
Indonesia[1]	11	12	8	11	12	11	18
South Africa[3]	12	13	13	13	10	15	13
Argentina[2]	13	14	14	14	13	10	9
Cuba[2]	17	8	3	3	3	2	2
Puerto Rico[2]	>100	88	56	40	21	13	7

Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008; FAO, 1987.

[1] Countries that have significantly improved their rank in global production during the last five decades.

[2] Countries that have lost global importance in sugarcane production.

[3] Countries that occupied a rank in 2007 similar to their position in the 1950s.

countries – Brazil, India and China – produced more than 60 percent of the global sugarcane harvest in 2007; Brazil alone contributed about one-third. Somewhat lower, but similar ratios hold for sugarcane area harvested in 2007: the top three countries accounted for 58 percent of land harvested, Brazil for about 30%, which indicates that these countries enjoy sugarcane yields above the world average.

The dominance of Brazil in global sugarcane production and expansion – Brazil accounted for 75 percent of sugarcane area increases in the period 2000 to 2007 and two-thirds of global production increases in that period – derives from its experience and capability to respond to thriving international demand for transport fuels, which was recently triggered by measures to mitigate greenhouse gas emissions of the rapidly growing transport sector, concerns in developed countries to enhance energy security and lessen dependence on petroleum, and not the least the need of many developing countries to reduce import bills for fossil oil.

Table 2. Sugarcane production (million tons) of major producers, 1950-2007.

	2007	1999-01	1989-91	1979-81	1969-71	1959-61	1949-51
Brazil	514.1	335.8	258.6	147.8	78.5	56.6	32.2
India	322.9	297.0	223.2	144.9	128.7	87.3	52.0
China	105.7	75.1	63.9	33.8	19.6	15.0	8.0
Thailand	64.4	51.3	37.0	17.7	5.4	1.9	0.3
Pakistan	54.8	48.4	36.2	29.1	23.8	11.6	6.4
Mexico	50.7	46.1	40.8	34.4	33.3	18.8	9.8
Colombia	40.0	33.1	27.4	24.7	13.2	12.5	11.1
Australia	36.0	35.3	24.2	23.4	17.6	9.4	6.5
United States	27.8	32.1	26.6	24.5	21.4	16.0	13.5
Philippines	25.3	25.6	25.2	31.5	25.3	12.0	7.1
Indonesia	25.2	24.2	27.6	19.5	10.3	9.6	3.1
South Africa	20.5	22.1	18.9	17.3	14.6	8.2	4.7
Argentina	19.2	17.9	15.9	15.6	10.2	10.4	7.6
Cuba	11.1	34.2	80.8	69.3	60.5	58.3	44.5
Puerto Rico	0.0	0.1	0.9	2.0	5.0	9.4	9.7
Sum of above	1,317.5	1,078.2	907.1	635.5	467.1	337.0	216.5
World	1,524.4	1,259.4	1,053.5	768.1	576.3	413.0	260.8

Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008; FAO, 1987.

Tables 1 to 3 point to two main factors that underlie the dynamics of sugarcane cultivation during the last four decades: a four-fold expansion of sugarcane acreage in South America between 1960 and 2007, and a collapse of sugarcane cultivation in the Caribbean sugar islands, especially important Cuba and Puerto Rico, which still held a substantial production share until the late 1980s. Solid growth of production and about three-fold expansion of sugarcane acreage since 1960 occurred in Asia mainly fuelled by rapid domestic demand increases for sugar in China and India. Fuel ethanol production from sugarcane has played a minor role in these dynamics with the exception of Brazil where it caused a large expansion.

An additional factor promoting the global expansion of sugarcane cultivation is the plant's efficient agronomic performance and its comparative advantage relative to sugar beets. While post-war self-reliance policies and protection of agriculture in developed countries supported an expansion of sugar beet cultivation areas until the late 1970s, the last three decades witnessed a gradual decline in harvested areas of sugar beet and increasingly a substitution of temperate sugar beets as a raw material for sugar production with tropical sugarcane (Figure 2). Regional changes of sugarcane cultivation are shown in Figure 3.

Table 3. Sugarcane area harvested (million hectares) in major producing countries, 1950-2007.

	2007	1999-01	1989-91	1979-81	1969-71	1959-61	1949-51
Brazil	6,712	4,901	4,092	3,130	1,830	1,400	1,307
India	4,830	4,197	3,699	3,073	2,486	2,428	2,011
China	1,225	1,171	1,230	722	566	279	414
Thailand	1,010	903	897	549	159	62	53
Pakistan	1,029	1,042	888	894	574	407	418
Mexico	680	628	556	520	483	352	325
Colombia	450	400	344	270	260	294	280
Australia	420	412	333	314	234	159	131
United States	358	412	374	306	282	184	176
Philippines	400	365	367	409	446	240	205
Indonesia	350	381	392	234	77	75	62
South Africa	420	392	272	252	181	96	110
Argentina	290	282	258	314	242	218	264
Cuba	400	1,015	1,372	1,246	1,254	1,218	1,097
Puerto Rico	0	3	16	25	61	129	133
Sum of above	18,574	16,504	15,089	12,257	9,134	7,539	6,986
World	21,896	19,476	17,729	14,708	11,025	8,946	8,302

Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008; FAO, 1987.

1.2. Global significance of ethanol production from sugarcane

As shown in the previous analysis, for most of the 20th century sugarcane production took place in response to global demand for sugar, was largely conditioned by the heritage of colonial structures, and was greatly influenced by policy and trade agreements. With the launching of the PROALCOOL program in Brazil in the mid 1970s another important demand factor entered the scene, initially of national importance only. As a consequence of the program however Brazil became the largest sugarcane producer in the world and by now the largest exporter of transport bioethanol.

Figure 4 shows the dynamics of area expansion for sugarcane cultivation in Brazil and indicates the significant amount of land dedicated to ethanol production and the important role of the ethanol program in this process. The figure illustrates three phases that characterize the last three decades. In the first decade after launching the PROALCOOL program, i.e. during 1975 to 1986, there was a sharp increase in Brazilian sugarcane area, which is entirely due to the domestic feedstock demand of the ethanol program. Then, during 1986 to 2000, the figure suggests a growth of sugar production but a phase of stagnation in ethanol

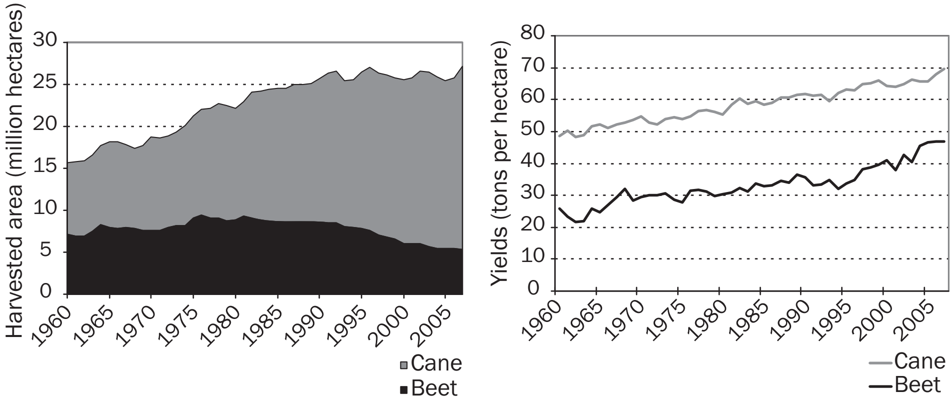

Figure 2. Harvested area and yields of sugarcane and sugar beet, 1960-2007. Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008.

production, which has been attributed to various national and international factors, not the least a low price of petroleum. Finally, the most rapid expansion of sugarcane harvested areas occurred after 2000 and in particular during 2005 to 2008. This time ethanol demand to substitute for gasoline consumption became a driving force at the global level, with many countries seeking ways to cut greenhouse gas emissions and reducing dependence of their economies on imported fossil oil.

In recent years, biofuels have re-emerged as a possible option in response to climate change, and also to concerns over energy security. At the same time, many concerns among experts worldwide have been raised about the effectiveness to achieve these goals and the possible negative impacts on the poor, in particular regarding food security (Scharlemann and Laurance, 2008) and environmental consequences.

Recent sharp increases of agricultural prices have partly been blamed on rapid growth of biofuel production, especially maize-based ethanol production in the United States, which in 2007 absorbed more than a quarter of the US maize harvest. How important is sugarcane in this respect, and what fraction of the global sugar harvest is currently used for ethanol production?

Figure 5 shows world fuel ethanol production, which is dominated by two producers, the USA and Brazil. In 2008 these two countries contribute nearly 90 percent of total fuel ethanol production. Though detailed data on used feedstocks are difficult to obtain, it can be concluded that 45-50% of the world fuel ethanol production is based on sugarcane, requiring some 280 to 300 million tons of sugarcane from an estimated 3.75 million hectares harvested area (Table 4).

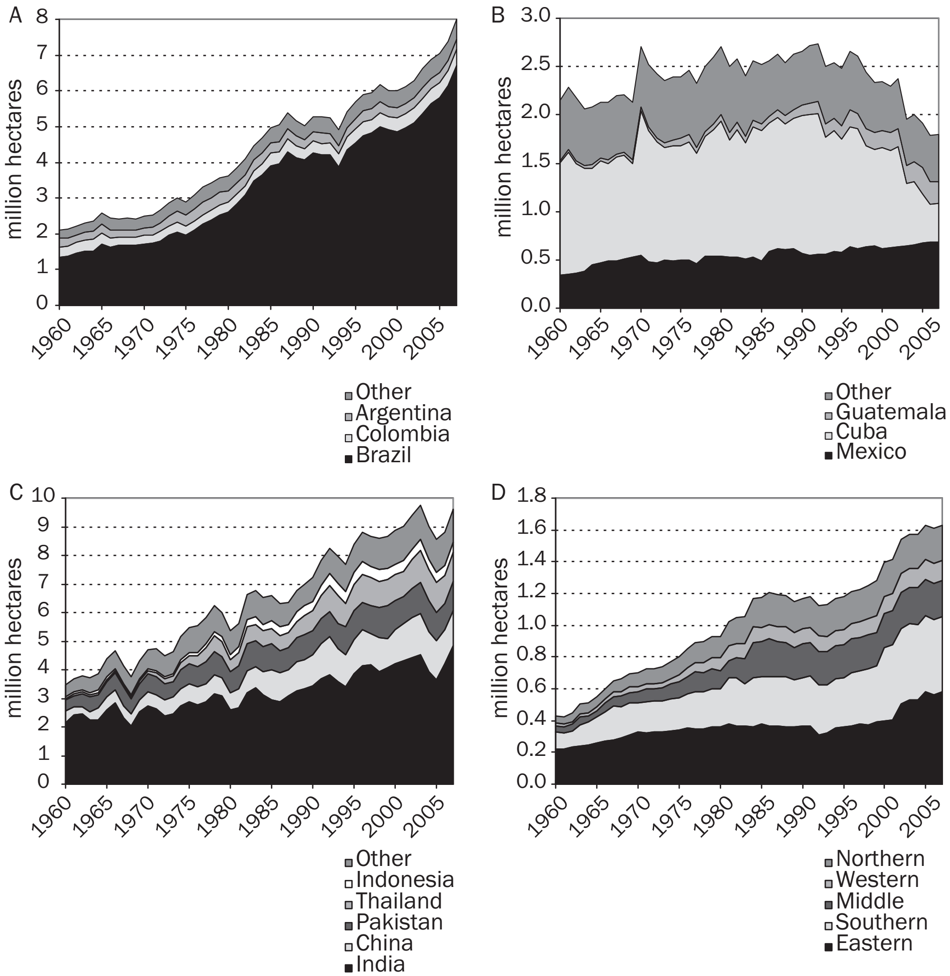

Figure 3. Change in sugarcane cultivation 1960-2007, by broad geographic region. a: South America (million hectares); b: Central America & Caribbean; c: Asia (million hectares); d: Africa (million hectares). Source: FAOSTAT, online database at http://www.fao.org, accessed July 2008.

Table 4 and 5 summarize the available data for two time points, 1969-71 and 2007. Apart from basic sugarcane statistics, the regional land-use significance of sugarcane is shown in terms of percentage of cultivated land used for sugarcane cultivation. For 1970, the region of Central America & Caribbean had the highest share where an estimated 7 percent of cultivated land was used for growing sugarcane. At that time, Brazil devoted 4.4 percent of cultivated land to sugarcane. In comparison, in year 2007 just over 10 percent of cultivated land were in use in Brazil to serve the sugar and ethanol industries. As a consequence, at the regional scale South America shows the highest share in 2007, now allocating 6.6 percent

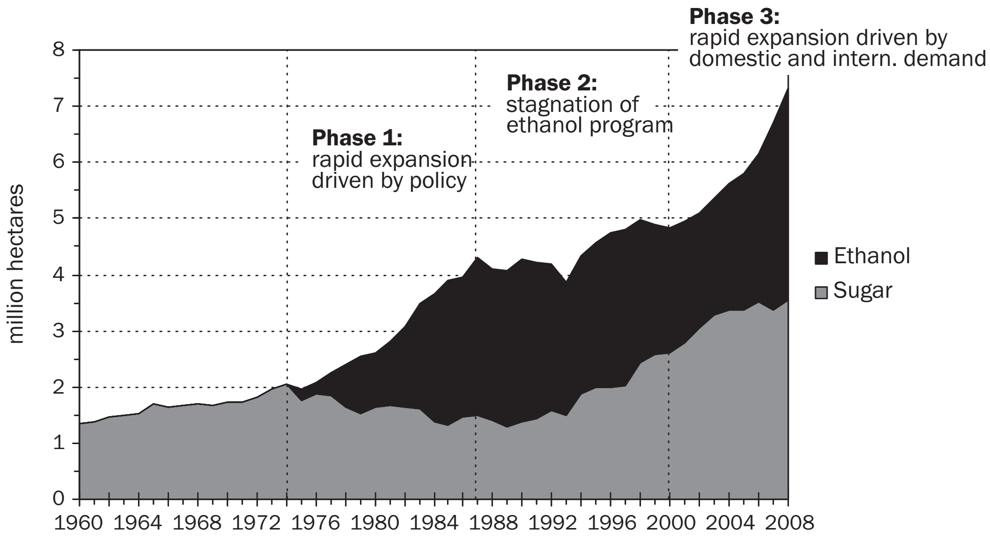

Figure 4. Use of Brazilian sugarcane land for ethanol and sugar production. Source: FAOSTAT, 2008; Conab, 2008a; Licht, 2007, 2008; calculation by authors.

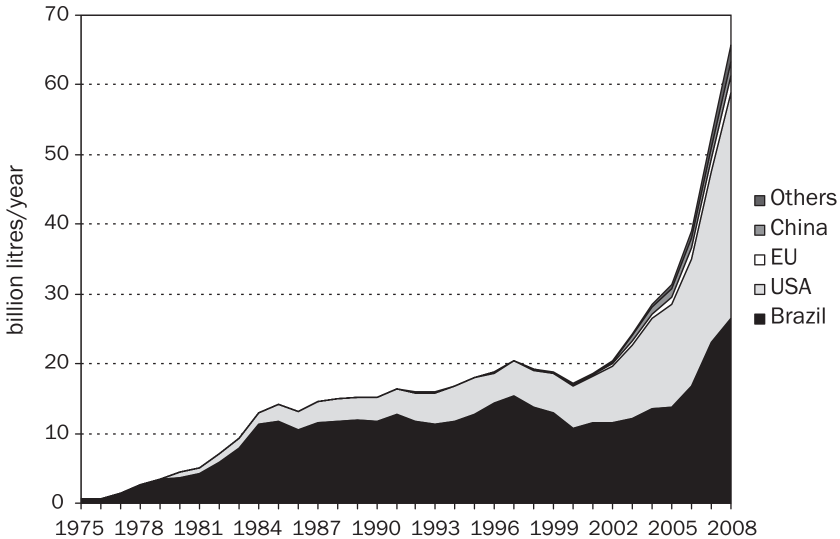

Figure 5. World fuel ethanol production (billion liters/year). Source: Licht, 2007 and 2008.

of total cultivated land to sugarcane. In comparison, the countries holding rank two and three in global production, India and China, devoted respectively 2.8 and 1.0 percent of cultivated land to sugarcane. The estimate for the global level amounts to 1.4 percent, i.e.

Table 4. Global significance of sugarcane production in 2007.

	Sugarcane			Cultivated land [1]	Sugarcane % of total cultivated	Sugarcane ethanol land	Ethanol % of sugarcane
	Harvested million ha	Production million tons	Yield tons/ha	million ha	percent	million ha	percent
North America	0.4	28	77.6	229.3	0.2	0	0
Europe & Russia	< 0.1	< 1	61.4	296.4	0.0	0	0
Oceania & Polynesia	0.5	40	79.9	54.8	0.9	0	0
Asia	9.6	639	66.4	577.1	1.7	< 0.1	< 1
Africa	1.6	92	56.8	239.3	0.7	< 0.1	< 1
Centr. Am. & Carib.	1.8	114	63.4	42.9	4.2	< 0.1	1
South America	8.0	611	76.5	121.9	6.6	3.6	45
Developed	0.9	67	78.9	580.4	0.1	0	0
Developing	21.0	1457	69.2	981.3	2.1	3.8	17.8
World	21.9	1524	69.6	1561.7	1.4	3.8	17.1
Brazil	6.7	514	76.6	66.6	10.1	3.5	50
India	4.8	323	72.6	169.7	2.8	< 0.1	n.a.
China	1.4	106	86.2	140.0	1.0	< 0.2	n.a.
Thailand	1.0	64	63.7	17.8	5.7	< 0.1	3
Pakistan	1.0	55	53.2	22.1	4.7	0	n.a.

Source: FAOSTAT, 2008; Licht, 2007, 2008; calculation by the authors.

[1] Estimates of cultivated land refer to year 2005.

Table 5. Global significance of sugarcane production in 1969-71.

	Sugarcane			Cultivated land	Sugarcane % of total cultivated
	Harvested million ha	**Production million tons**	**Yield tons/ha**	**million ha**	**percent**
North America	0.2	21	89.8	243.4	0.1
Europe & Russia	< 0.1	< 1	72.1	378.3	0.0
Oceania & Polynesia	0.3	20	75.0	46.2	0.6
Asia	4.6	227	49.5	448.7	1.0
Africa	0.7	47	66.2	180.5	0.4
Centr. Am. & Carib.	2.5	132	53.9	34.9	7.0
South America	2.5	128	51.7	90.6	2.7
Developed	0.5	42	82.8	667.9	0.1
Developing	10.2	534	52.2	754.6	1.4
World	10.7	576	53.7	1422.6	0.8
Brazil	1.8	78	45.9	41.3	4.4
India	2.5	129	48.9	164.7	1.5
China	0.6	20	41.3	102.5	0.6
Thailand	0.1	5	44.5	13.7	0.4
Pakistan	0.6	24	39.9	19.3	3.0

Source: FAOSTAT, 2008.

sugarcane harvested was 22 million hectares out of 1562 million total cultivated land. In comparison, the share of sugarcane in global cultivated land was 0.8 percent in 1970, which means that nearly a doubling of the global significance of sugarcane has occurred in the last three decades.

At first glance, the rather low percentage of global cultivated land occupied by sugarcane suggests that sugarcane area expansion and associated land competition has had little influence on food supply. Yet, this may be misleading for two reasons: (1) sugarcane is cultivated either under irrigation (e.g. India and Pakistan) or in rain-fed tropical areas with ample rainfall. Hence land productivity in areas suitable for rain-fed sugarcane production is typically much higher than for cultivated land in cooler climates or arid sub-tropical and tropical agriculture; and (2) large parts of the world cannot grow sugarcane for climatic reasons and the impact in climatically suitable areas is therefore more significant, as shown in Table 6.

Table 6. Global significance of sugarcane production in 2007 revisited.

	Sugarcane harvested area	Cultivated land		Sugarcane harvested	
		Total	With sugarcane potential	% of total cultivated land	% of cultivated land with sugarcane potential
	million ha	million ha	million ha	percent	percent
North America	0.4	229.3	17.6	0.2	2.0
Europe & Russia	< 0.1	296.4	0.8	0.0	0.1
Oceania & Polynesia	0.5	54.8	2.5	0.9	19.5
Asia	9.6	577.1	213.3	1.7	4.5
Africa	1.6	239.3	81.6	0.7	2.0
Centr. Am. & Carib.	1.8	42.9	28.0	4.2	6.4
South America	8.0	121.9	90.2	6.6	8.9
Developed	0.9	580.4	19.5	0.1	4.4
Developing	21.0	981.3	414.4	2.1	5.1
World	21.9	1561.7	434.0	1.4	5.0
Brazil	6.7	66.6	57.3	10.1	11.7
India	4.8	169.7	70.1	2.8	6.8
China	1.4	140.0	12.4	1.0	11.3
Thailand	1.0	17.8	17.0	5.7	5.9
Pakistan	1.0	22.1	15.6	4.7	6.4

Source: FAOSTAT, 2008; Fisher *et al.*, 2008.

The global analysis clearly shows that the most significant and relevant land use change dynamics related to sugarcane in the last decades have taken place in Brazil. In the following we take a short look at the Brazilian development and some issues and questions this development has raised.

1.3. Sugarcane and land use change dynamics in Brazil

Brazil has the largest area under sugarcane cultivation in the world, being responsible for approximately one third of the global harvested area and production. For the year 2007, 6.7 million hectares were harvested with a production of 514 million tons of sugarcane

(FAOSTAT, 2008). The land use change into sugarcane production is part of the history of the country, dating short after Portuguese colonization during the 16th century. Since then, the crop has maintained its characteristic of a monoculture with high elasticity of supply, expanding rapidly in response to market stimuli (Tercil *et al.*, 2007). The first establishment phase of the crop over native vegetation aimed to provide sugar to the growing European market during colonial times, during this period plantations were established in the North-East and South-East of the country where agro-ecological conditions are highly favorable for the growth of tropical grasses such as sugarcane (e.g. see Figure 2.10 in next section).

From 2000 to 2007, an impressive pace of approximately 300 thousand hectares of land was converted into sugarcane every year (FAOSTAT, 2008). This already phenomenal rate of conversion is being surpassed by recent projections for the 2007/08 harvest season, which indicate an expansion of 650 thousand hectares in Brazil (Conab, 2008a). Most of the recent expansion in sugarcane area has occurred in São Paulo state (Conab, 2008a). From 1995 to 2007, there was a 70% enlargement of the sugarcane area in São Paulo, from 2.26 million ha to 3.90 million ha, which represents 58% of the Brazilian area under sugarcane (IEA, 2007). In response to a greater demand for ethanol, São Paulo is also the region where most of the land use change into sugarcane plantation is expected to take place in the near future (Goldemberg *et al.*, 2008). The projected expansion of sugarcane for the 2007/08 harvest season is 350 thousand hectares, i.e. 54% of the Brazilian total (Conab, 2008b). Therefore, we further discuss the aspects of land use change in Brazil with special attention on São Paulo as an example of intensive conversion of other land uses into sugarcane monocultures.

The basis for the success of the crop in the South-East of Brazil is the favorable environmental conditions in terms of temperature, radiation, precipitation, soil characteristics and relief that match the crop physiological requirements. The potential to achieve high yields, today an average near 80 t/ha (Conab 2008b), has diluted fixed production costs and has established Brazilian ethanol as one of the most competitive bio-fuel options with an estimated cost of US$ 0.21/liter (Goldemberg, 2007).

1.4. What are the drivers for these changes in Brazil?

The main drivers for the recent expansion of sugarcane in Brazil, particularly São Paulo, were market opportunities created by the international demand for sugar and ethanol in conjunction with national policies that promoted ethanol production and commercialization. During these periods, intense and initially heavily subsidized investments (e.g. PROALCOOL in mid 70's) allowed the development of a solid industrial capacity and know-how (Goldemberg, 2006). The historical background of sugarcane as a traditional land use and the investments in the ethanol production chain created ideal conditions for the development of indigenous technologies on agronomical (e.g. plant nutrition, management and high yielding genetic material) and industrial aspects of production. For example, the flexibility to shift between sugar and ethanol production (mixed production units) mitigates fluctuations on the demand side, which makes the business highly attractive as a land use option. Currently, mixed production units process 85.4% of Brazil's industrialized sugarcane (Conab, 2008b). Another aspect that favors rapid expansion of sugarcane in Brazil is the current land tenure structure in this agri-business. There is a large concentration of land in the hands of the industry, 67% of Brazilian sugarcane producing areas (Conab, 2008b). The operation of extensive sugarcane farms reduces the cost of production through economy of scale (Goldemberg, 2006) contributing to the overall competitiveness of sugarcane production in relation to other land uses options. Finally, the environmental conditions in vast areas of Brazil's arable land are adequate not only for achieving high sugarcane yields (see Figure 10) but also high sucrose concentrations, i.e. a cool and dry winter period in São Paulo favors accumulation of sugar, which increases industrial efficiency (Conab, 2008b). In combination, these favorable biophysical conditions and socio-economical historical aspects produced a setting for effective response to political and market stimuli explaining the rapid expansion of sugarcane monoculture in Brazil.

1.5. What have been the impacts on environmental parameters?

The recent boom of ethanol production has drawn international attention to the environmental impacts of land conversion into sugarcane monocultures. Site-specific biophysical and socio-economical aspects largely determine the impacts of land use change. The conversion of land use, its susceptibility to land degradation and the choice of agronomic and agro-processing technologies for sugarcane production and conversion determine the magnitude of impacts on environmental quality at the local level. Major areas of concern include deforestation and threats to biodiversity, environmental pollution and competition with food crops.

1.5.1. Deforestation and threats to biodiversity

The expansion of sugarcane could increase deforestation rates either 'directly' by intruding in areas of native non-protected forest areas or 'indirectly' by forcing other land uses (e.g. displaced livestock production and agricultural crops such as soybeans) to open up new land. Past surges of sugarcane expansion in Brazil are not regarded as a major cause of deforestation (Martinelli and Filoso, 2008). The current sugarcane area represents only 2.5% of the 264 million ha of agricultural land use in Brazil, of which nearly 200 million ha are pastoral lands. The hotspots of deforestation in the Amazon region, however have a low suitability for sugarcane production and are not directly threatened by the current sugarcane expansion (Smeets *et al.*, 2008). Amazon deforestation has been caused mainly by conversion to pastoral lands for livestock production and, more recently, also for expansion of soybean production (Fearnside, 2005).

From 1988 to 2007 the average rate of expansion of sugarcane was 0.14 million ha/year when rates of Amazon deforestation ranged from ~1.1 to 2.9 million ha per year (Fearnside, 2005) indicating that sugarcane expansion is by far insufficient to have forced 'direct' or the 'indirect' reallocation of pasture and soybeans northwards intruding into Amazon rainforests.

Currently, the savannah region ('Cerrados'), considered a world bio-diversity hotspot (Myers *et al.*, 2000), is the ecosystem most threatened by sugarcane expansion in Brazil as it is situated on the frontier of agricultural expansion and has at least partly excellent cultivation potentials (Klink and Machado 2005; Smeets *et al.* 2008). The Cerrado is characterized by high biodiversity (e.g. >6.5 thousand plants species from which 44% are endemic to the biome) and has suffered rates of conversion to either cultivated pasture land or to crop cultivation land that are higher than the deforestation rates in Amazon (Conservation International, 2008; Klink and Machado, 2005). In 2002, nearly 40% of a total of about 205 million ha of Cerrado had already been converted (Table 7), mainly into pastures and cash-crops such as soybeans (Machado *et al.*, 2004; Sano *et al.*, 2008).

From the early 1970s to 2000 around 0.36 million ha of Cerrado vegetation were lost in São Paulo (Florestar, 2005). However, from 2001 to 2005, total native vegetation areas in this state were maintained at about 3.15 million ha suggesting that more recent sugarcane expansion was not a major lever of deforestation during this period. Nevertheless, specific ecological systems such as riparian forests were highly affected in regions of intensive sugarcane production to give way to cropping areas (Martinelli and Filoso, 2008). In major watersheds in São Paulo State, where pastures and sugarcane are the main land uses, it is

Table 7. Land use shares of the Brazilian Cerrado region in 2002 (Adapted from Sano *et al.*, 2008 and Ministério do Meio Ambiente, 2007).

Land use classes	**Area (million ha)**	**Percent of total**
Native areas	124	60%
Native forest	75	37%
Native non-forest [1]	48	24%
Anthropic areas	80	39%
Cultivated pastures	54	26%
Agriculture	21	10%
Reforestation	3	2%
Urbanized plus mining	1	<1%
Water	1	1%
Total cerrado area	205	100%

[1] The 48 million ha of non-forested areas are estimated to include 28 million ha of native pastures (Ministério do Meio Ambiente, 2007).

shown that 75% of the riparian vegetation (a reservoir of biodiversity and a buffer against sedimentation of water bodies) had disappeared (Silva *et al.*, 2007).

1.5.2. Air, water and soil pollution and degradation

During the past surges of sugarcane expansion, cases of environmental pollution were identified at different stages of production and industrialization. The impacts on air, water and soil quality largely depend on the choices of technologies applied in agronomic and agro-processing practices. Beyond carbon releases and biodiversity losses caused by land conversion (discussed above), the main environmental effects concern air pollution from pre-harvest sugarcane burning, water pollution from cultivation and processing of sugarcane, and soil erosion and compaction as a consequence of sugarcane cultivation.

For example, air quality is highly compromised by the common practice of sugarcane burning, a technique used before harvest to facilitate manual cutting. The emission of pollutants during the dry months of the year, when harvest occurs in São Paulo, has direct negative impacts on health (e.g. respiratory disorders mainly in children and elderly citizens). It promotes erosion of topsoil, causes loss of nutrients and leads to soil compaction (Tominaga *et al.*, 2002; Cançado *et al.*, 2006; Ribeiro, 2008).

Soil degradation through erosion and compaction are also considered a problem in sugarcane fields, which are under intense mechanization during soil cultivation and harvesting (Martinelli and Filoso, 2008). Soil compaction is a consequence of the traffic of heavy machinery in conjunction with the lack of implementation of best management cultivation practices (Naseri *et al.*, 2007). Compaction exacerbates erosion problems because soil porosity is reduced, which decreases water infiltration and increases runoff (Oliveira *et al.*, 1995; Martinelli and Filoso 2008). The main periods when soil remains bare and subjected to erosive forces by rain and winds are (1) during the process of land conversion, (2) between crop harvesting and subsequent canopy closure, and (3) during re-planting of sugarcane fields every 5-6 years. The conversion of natural vegetation and extensive pastures (which are less intensively managed) into sugarcane increases the risk soil degradation (Politano and Pissarra, 2005). Erosion rates of 30 Mg of soil/ha.year were estimated for sugarcane fields in the São Paulo State in comparison with less than 2 Mg/ha.year for pastures and other natural vegetation (Sparovek and Schnug, 2001). Soil erosion in poorly managed sugarcane areas also causes sediment deposition into water reservoirs, wetlands, streams and rivers (Politano and Pissarra, 2005). This is aggravated by the transport of fertilizer and agro-chemical residues that directly compromise water quality (Corbi *et al.*, 2006).

Water pollution has been a severe environmental problem in sugarcane production regions until early 80's in Brazil when legislation was implemented to ban direct discharge of vinasse (Martinelli and Filoso, 2008; Smeets *et al.*, 2008). The main industrial sources of pollutants of sugarcane industry are wastewater from washing of stems before processing and vinasse produced during distillation. These by-products have a large potential of water contamination due to a high concentration of organic matter, which increases the biochemical oxygen demand (BOD_5) of water bodies receiving such effluents (Gunkel *et al.*, 2007). While the Brazilian standards for wastewater emission are BOD_5 of 60 mg/l, values for wastewater from cane washing are up to 500 mg/l and > 1.000 mg/l for vinasse (Gunkel *et al.*, 2007; Smeets *et al.*, 2008). In addition, agro-chemicals residues have been found as a important component of water pollution in areas of intense sugarcane production (Corbi *et al.*, 2006; Silva *et al.*, 2008).

1.5.3. Land use and competition with food crops

A major area of concern is the threat to food security (Goldemberg *et al.*, 2008). Rapid expansion of sugarcane areas could potentially reduce the availability of arable land for the cultivation of food and feed crops causing a reduction in their supply and increase of food prices. Fast rates of expansion of sugarcane in São Paulo state in the mid 70s at the expense of maize and rice cropping areas seem to have had a short-term impact on regional food supply and prices (Saint, 1982). However, the recent sugarcane expansion in São Paulo from mid 90's has not compromised food crop production as most of the expansion intruded in pastoral lands (Figure 6).

For Brazil as a whole, in the 2006/07 season, nearly two thirds of sugarcane expansion occurred at the expense of pastures (0.42 million ha) in comparison with one quarter coming from land under crop cultivation (Conab, 2008b). This conversion of pastures into sugarcane

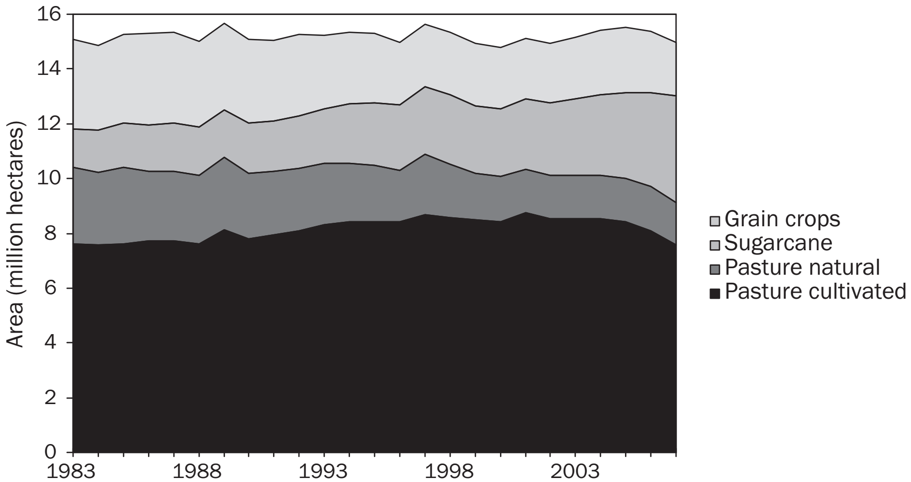

Figure 6. Evolution of areas of sugarcane, pasture and grain crops in São Paulo State. Source: IEA, 2007; Conab, 2008c. Note: The total area of São Paulo State is 24.8 million ha.

areas is explained by their relative abundance (200 million ha) as well as occurrence adjacent to existing sugarcane estates (Goldemberg *et al.*, 2008).

The area of main grain crops has decreased by 0.9 million ha in the State of São Paulo from early 80's to 2005 (Conab, 2008c), while sugarcane area expanded nearly 1.7 million ha (IEA 2007), Figure 7. At the national level the magnitude of these regional land use changes is diluted (Figure 8) as the total area of major crops, including sugarcane, is about 50 million ha (Conab, 2008c). By far more important than sugarcane has been the rapid expansion of soybeans in Brazil, from less than 10 million hectares in the early 1980s to around 23 million hectares, more than a third of all cropping land.

1.6. Lessons from Brazilian sugarcane land development dynamics

The learning experience with deploying sugarcane based ethanol production in Brazil during the last 30 years has put the country in a unique position to respond to the current wave of energy systems developments, particularly renewable transport fuels. As to land use, the following conclusions can be summarized:

- There was a very rapid and large land use change into sugarcane production in Brazil in the last 30 years, particularly in São Paulo State.
- Main drivers for the expansion of sugarcane areas were a combination of favorable biophysical conditions, a historical foundation of logistical and technological conditions to respond to market opportunities, national policies giving incentives to the sugarcane

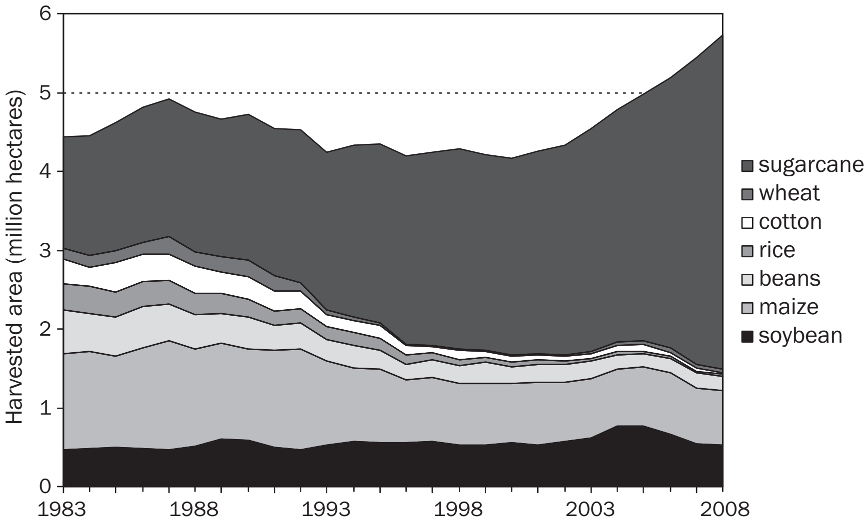

Figure 7. Area of selected crops in São Paulo. Source: Conab, 2008c.

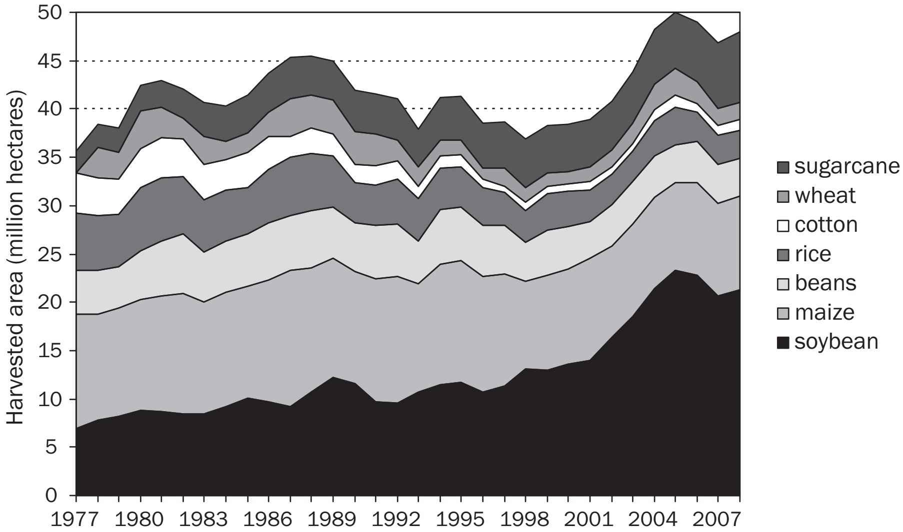

Figure 8. Area of selected crops in Brazil. Source: Conab, 2008c.

agri-business, and a growing demand for sugar and bioethanol, setting favorable conditions to benefit from economies of scale.

- The trend in sugarcane area expansion continues at record rates, now fostered by both the domestic and international demand for ethanol.
- The savannah ecosystem (Brazilian 'Cerrados') is the current frontier of sugarcane expansion.
- There are risks of environmental degradation in different stages of sugarcane production and processing. Negative impacts have been caused by the lack of implementation of best management practices and ineffective legislation and control. Examples from São Paulo state indicate that environmental sustainability of sugarcane production and processing has been substantially improved during the last three decades. Nevertheless, further improvements are necessary.
- While more effective and environmentally less harmful technologies are now available, there is nevertheless a risk of affecting biodiverse ecosystems of the savannah region. Strict regulation and enforcement are needed to safeguard against environmental losses, for example by guaranteeing the protection and recuperation of specific biomes such as the Cerrado and riparian forests.

2. Global potential for expansion of sugarcane production

2.1. Future land requirements for food and feed

Several inter-linked processes determine the dynamics of world food demand and supply. Agro-climatic conditions, availability of land resources and their management are clearly key aspects, but they are critically influenced by regional and global socio-economic pressures including current and projected trends in population growth, availability and access to technology, market demands and overall economic development.

While climate and farm management are key determinants of local food production, agro-economics and world trade combine to significantly shape regional and global agricultural land use. Catering to consumers and industries in OECD countries is an important driver for agricultural activities in well-resourced developing countries. Computations of current and future cultivated land were carried out by assessing land potential with the global Agro-ecological Zones model (GAEZ) and economic utilization with IIASA's world food system model (Fischer *et al.*, 2002; Fischer *et al.*, 2005). In 2000 about 1.5 billion hectares of arable land were in use for food, fiber and fodder crop production, or roughly 10% of all available land on earth. Of these, about 900 million hectares were in developing countries. By 2050, under a IIASA designed plausible global socio-economic development scenario (Grübler *et al.*, 2006; Tubiello and Fischer, 2006; Fischer *et al.*, 2006), for developed countries a slightly lower level of cultivated land use was projected compared to 2000, i.e. a modest net decrease in land under cultivation for food and feed crops was projected, while additional production resulted from increased productivity and input use. In developing countries, by contrast, cultivated land in 2050 was projected to increase by roughly 190 million ha (+21%) relative to year 2000. In the scenario, most of this additional cropland is brought into use in Africa (+85 million ha, or +42%) and Latin America (70 million ha, or +41%).

From a range of alternative scenario runs predicting world food system development (Fischer *et al.*, 2002; 2005) it can be concluded that global food and feed demand will require some additional land to be used for cultivation, depending on socioeconomic scenario in the range of 120-180 million hectares, notably in developing countries. Therefore, when adopting a 'food first' paradigm, to realize a substantial contribution of agricultural biomass to energy sources would necessitate (1) focused efforts of national and international R&D institutions and extension services to enable sustainable agricultural production increases on current agricultural land, which go beyond 'business as usual' trends and expectations, in particular to mobilize undeveloped agricultural potentials on the African continent, and (2) tapping into resources currently not or only extensively used for cultivation or livestock production, e.g. certain grass, scrub and woodland areas where environmental and social impacts might be regarded as acceptable. For this reason, we next look into the question as to how much land, where and under what current uses, could be potentially available for expanding global sugarcane production.

2.2. AEZ assessment of land suitable for sugarcane production

2.2.1. AEZ background

The range of uses that can be made of land for human needs is limited by environmental factors including climate, topography and soil characteristics, and is to a large extent determined by demographic and socioeconomic drivers, cultural practices, and political factors, e.g. such as land tenure, markets, institutions, and agricultural policies.

The Food and Agriculture Organization of the United Nations (FAO) with the collaboration of IIASA, has developed a system that enables rational land-use planning on the basis of an inventory of land resources and evaluation of biophysical limitations and production potentials of land. This is referred to as the Agro-ecological Zones (AEZ) methodology.

The AEZ methodology follows an environmental approach; it provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production. Crop modeling and environmental matching procedures are used to identify crop-specific limitations of prevailing climate, soil and terrain resources, under assumed levels of inputs and management conditions. This part of the AEZ methodology provides maximum potential and agronomically attainable crop and biomass yields globally at 5-minute latitude/longitude resolution grid-cells.

2.2.2. Land suitability for sugarcane

Sugarcane belongs to the crops with C4 photosynthetic pathway; it is adapted to operate best under conditions of relatively high temperatures and, in comparison to C3 pathway crops, has high rates of CO_2 exchange and photosynthesis, in particular at higher light intensities.

Sugarcane is a perennial with determinate growth habit; its yield is located in the stem as sucrose and the yield formation period is about two-thirds to three quarters of its cultivated life span. Climatic adaptability attributes of sugarcane qualify it as being most effective in tropical lowland and warm subtropical climates; it does particularly well in somewhat drier zones under irrigation, but is sensitive to frost. A short dry and moderately cool period at the end of its cultivation cycle significantly increases sugar content at harvest.

Ecological requirements of sugarcane include warm, sunny conditions and adequate soil moisture supply during most of its cultivation cycle. Sugarcane prefers deep, well drained, well structured and aerated loamy to clayey fertile soils. Ideal pH ranges are between 5.5 and 7.5.

2.2.3. AEZ procedures applied for sugarcane

Box 1 summarizes the AEZ methodology and information flow as applied for the assessment of global sugarcane potentials.

Box 1. AEZ procedures (see Figure 9).

Land Utilization Type (LUT): The AEZ procedures have been used to derive by grid-cell potential biomass and yield estimates for rain-fed sugarcane production under high level inputs/ advanced management, which includes main socio-economic and agronomic/farm-management components:

The farming system is (1) market oriented; (2) commercial production of sugar and bioethanol are management objectives, and (3) production is based on currently available yielding cultivars, is fully mechanized with low labor intensity, and assumes adequate applications of nutrients and chemical pest, disease and weed control.

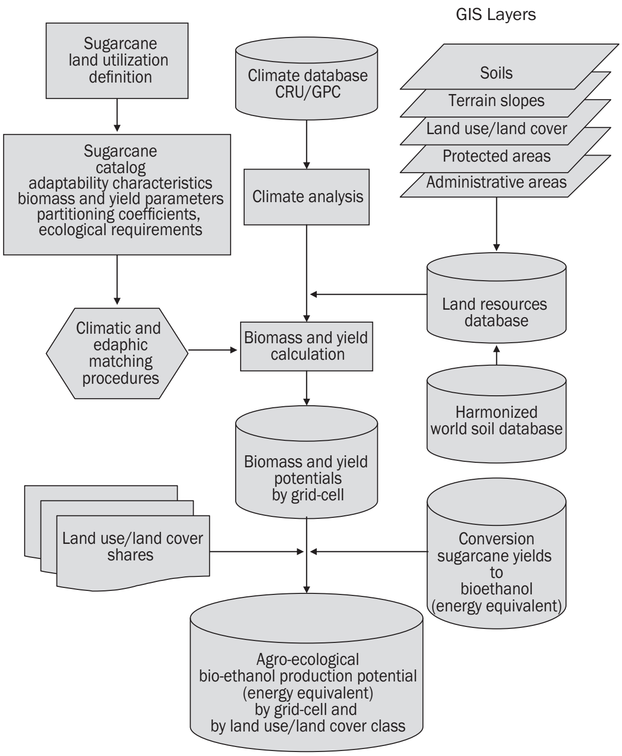

Figure 9. AEZ methodology: information flow and integration.

The quantified description of sugarcane LUTs include characteristics such as vegetation period, ratoon practices, photosynthetic pathway, photosynthesis in relation to temperature, maximum leaf area index, partitioning coefficients, and parameters describing ecological requirements of sugarcane produced under rain-fed conditions.

Climatic data: Climate data are from the Climate Research Unit (CRU CL 2.0 (New *et al.*, 2002, CRU TS 2.1; Mitchell and Jones, 2005), and precipitation data from VASClimO (Global Precipitation Climatology Centre - GPCC). Average climate and historical databases were used to quantify: (1) the length of growing period parameters, including year-to-year variability, and (2) to estimate for each grid-cell by crop/LUT, average and individual years agro-climatically attainable sugarcane yields.

Soils data: Spatial soil information and attributes data is used from the recently published Harmonized World Soil Database (FAO, IIASA, ISRIC, ISSCAS & JRC, 2008)

Terrain data: Global terrain slopes are estimated on the bases of elevation data available from the Shuttle Radar Topography Mission (SRTM) at 3 arc-second resolution

Land use/land cover: Potential yields, suitable areas and production were quantified for different major current land cover categories (Fischer *et al.*, 2008). The estimation procedures for estimating seven major land-use and land cover categories are as follows: Cultivated land shares in individual 5’ grid cells were estimated with data from several land cover datasets: (1) the GLC2000 land cover regional and global classifications (http://www-gvm.jrc.it/glc2000), (2) the global land cover categorization, compiled by IFPRI (IFPRI, 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCC) ver. 2.0, EROS Data Centre (EDC, 2000) (3) the Forest Resources Assessment of FAO (FAO, 2001), and global 5’ inventories of irrigated land (GMIA version 4.0; FAO/University of Frankfurt, 2006). Interpretations of these land cover data sets at 30-arc-sec. were used to quantify shares of seven main land use/land cover, consistent with land use estimates of published statistics. These shares are: cultivated land, subdivided into (1) rain-fed and (2) irrigated land, (3) forest, (4) pasture and other vegetation, (5) barren and very sparsely vegetated land, (6) water, and (7) urban land and land required for housing and infrastructure.

Protected areas: The principal data source of protected areas is the World Database of Protected Areas (WDPA) (http://www.unep-wcmc.org/wdpa/index.htm.) Two main categories of protected areas are distinguished: (1) protected areas where restricted agricultural use is permitted, and (2) strictly protected areas where agricultural use is not permitted.

Land resources database: Spatial data linked with attribute information from soils, terrain, land use and land cover, and protected areas are combined with an administrative boundary GIS layer in the land resources database

Climate analysis: Monthly reference evapotranspiration (ETo) has been calculated according to Penman-Monteith. A water-balance model provides estimations of actual evapotranspiration (ETa) and length of growing period (LGP). Temperature and elevation are used for the characterization of thermal conditions, e.g. thermal climates, temperature growing periods (LGP_t), and accumulated temperatures. Temperature requirements of sugarcane were matched with temperature profiles prevailing in individual grid-cells. For grid-cells with an optimum or sub-optimum match, calculations of biomass and yields were performed.

Edaphic modifiers: The edaphic suitability assessment is based on matching of soil and terrain requirements of the assumed sugarcane production systems with prevailing soil and terrain conditions.
Land productivity for rain-fed sugarcane: The combination of climatic and edaphic suitability classification provides by grid-cell potential biomass and yield estimates for assumed production conditions

2.3. Agro-ecological suitability of sugarcane – risks and opportunities of expansion

Figure 10 presents a map of climatically attainable relative yields for rain-fed conditions, normalized to a range of 0 (i.e. no yield possible) to 1 (i.e. geographical locations where highest rain-fed yields would be obtained). According to the AEZ assessment, the most suitable climates are found in the southeastern parts of South America, e.g. including São Paulo State in Brazil, but also large areas in Central Africa as well as some regions in Southeast Asia. Very wet areas with low temperature seasonality such as parts of the Amazon basin[1] produce substantially lower yields due to lower sugar content, high pest and disease incidence combined with lower efficacy of control, and in extreme wet areas difficulties with field operations and harvest. Note that in India and Pakistan, the world's second and fifth largest producers of sugarcane, irrigation is needed to exploit the thermal and radiation resources in these countries for sugarcane cultivation.

[1] Conditions in the equatorial parts of Africa differ substantially in wetness as compared to parts of the Amazon basin and provide from climate viewpoint better sugar yields.

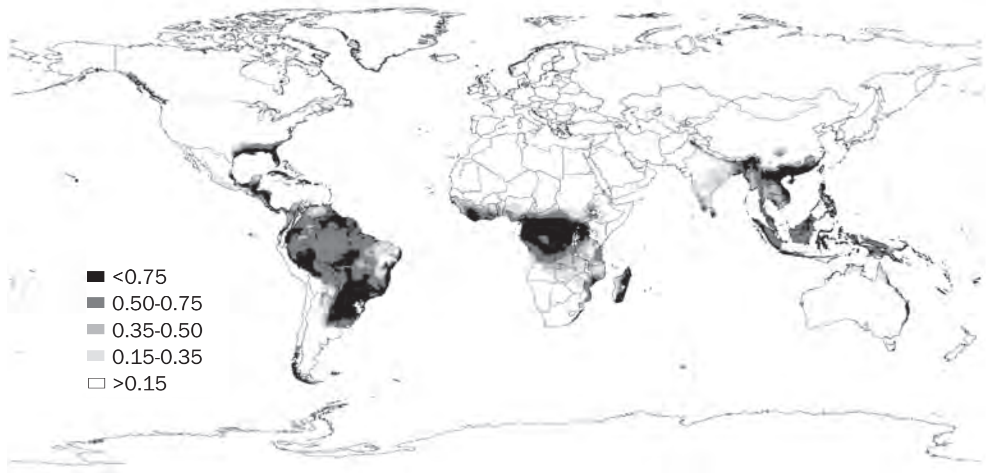

Figure 10. Normalized agro-climatically attainable yield of rain-fed sugarcane. Source: Fisher *et al.*, 2008, IIASA. Note: Maximum attainable yields in this global map are about 15 tons sugar per hectare.

Table 8 summarizes by region the current distribution of cultivated land, the land harvested for sugarcane in 2007, and the area of current cultivated land assessed as very suitable (VS), suitable (S) and moderately suitable (MS). Globally, the currently harvested 22 million hectares of land for sugarcane compare to the potential of 28 million hectares VS-land and 92 million hectares rain-fed S-land. In other words, of currently 1550 million hectares cultivated land about 120 million hectares is very suitable or suitable for rain-fed sugarcane cultivation, with the majority of this land located in developing countries of Africa (28 million hectares), Asia (34 million hectares) and South America (40 million hectares).

The Brazilian experience has shown that a major land source of sugarcane expansion was from pastures. The assessment of sugarcane suitability in current grass, scrub, wood land concluded that some 130 million hectares of this land would be very suitable or suitable for rain-fed sugarcane production, of which 48 million hectares were found in Sub-Saharan Africa and 69 million hectares in South America; Brazil accounts for nearly half this potential (Table 9). There is only very little potential of this kind, about 7 million hectares, in Asia as all the vast grasslands of Central Asia are too cold and too dry for rain-fed sugarcane production.

The maps for South America and Africa shown in Figure 11 indicate the suitability of climate, soil and terrain conditions for rain-fed sugarcane production. The respective suitability class is shown for areas where 50 percent or more of a grid-cell of 5’ by 5’ latitude/longitude is currently used as cultivated land and/or is covered by grass, scrub or woodland ecosystems. Hence, it shows the suitability of land where a substantial fraction is non-forest ecosystems. This geographical filter was used to indicate the distribution of land for potential sugarcane expansion, i.e. areas where further expansion of sugarcane would not cause direct deforestation and, provided the biodiverse native Cerrado ecosystem can be protected, would not create associated major risks for biodiversity and substantial carbon debts as is the case with forest conversion.

The maps shown in Figure 12 indicate the suitability of climate, soil and terrain conditions for rain-fed sugarcane production in areas where 50 percent or more of each grid-cell of 5’ by 5’ latitude/longitude is classified as forest or protected land, highlighting land at risk of undesirable conversion ‘hot spots’ due to its suitability for sugarcane expansion. Unlike the areas shown in Figure 11, conversion of these forest and protected areas would likely be associated with high environmental impacts.

While legally protected areas, both forests and non-forest ecosystems, are less exposed to conversion, unprotected forest areas with good suitability for rain-fed sugarcane cultivation are of particular concern due to possible severe environmental impacts. The AEZ methodology was therefore used to assess the magnitude and geographical distribution of unprotected forest areas. A summary of results by region is provided in Table 10.

Table 8. Suitability of current cultivated land for rain-fed sugarcane production.

	Cultivated land	Land potentially suitable, of which			Share of VS+S in cultivated land	Sugarcane harvested (2007)
		Very suitable (VS)	Suitable (S)	Moderately suitable		
	million ha	million ha	million ha	million ha	percent	million ha
North America	230	2.7	4.6	7.7	3.1	0.4
Europe & Russia	305	0	0	0	0.0	0.0
Oceania & Polynesia	53	0.4	0.6	0.6	1.9	0.5
Asia	559	5.7	28.6	70.6	6.1	9.6
Africa	244	6.8	20.6	27.0	11.2	1.6
Centr. Am. & Carib.	43	3.1	7.3	5.7	24.1	1.8
South America	129	9.7	30.3	30.6	31.0	8.0
Developed	591	2.7	4.8	7.9	1.3	0.9
Developing	972	25.6	87.1	134.3	11.6	21.0
World	1563	28.3	91.9	142.2	7.7	21.9
Brazil	66	5.0	19.6	18.0	37.4	6.7
India	167	0.7	2.9	8.1	2.1	4.8
China	139	1.6	4.1	11.1	4.1	1.2
Thailand	19	0.1	0.6	6.3	3.0	1.0
Pakistan	21	0.1	0.5	1.1	2.5	1.0

Source: Fisher *et al.*, 2008, IIASA; FAOSTAT, 2008; calculation by the authors. Suitability classes are mutually exclusive, i.e. do not overlap.

Table 9. Suitability of unprotected grass/scrub/wood land for rain-fed sugarcane production.

	Unprotected grass/scrub/ wood land	**Land potentially suitable, of which**			**VS+S in grass & wood land**
		Very suitable	**Suitable**	**Moderately suitable**	
	million ha	**million ha**	**million ha**	**million ha**	**percent**
North America	566	1.1	2.1	3.7	0.6
Europe & Russia	666	0	0	0.0	0.0
Oceania & Polynesia	519	0.4	1.6	3.2	0.4
Asia	699	1.3	5.7	22.5	1.0
Africa	973	11.9	36.0	65.0	4.9
Centr. Am. & Carib.	98	1.1	2.4	3.5	3.6
South America	613	22.0	47.2	90.8	11.3
Developed	1741	1.2	2.5	4.5	0.2
Developing	2394	36.6	92.5	184.2	5.4
World	4135	37.8	95.0	188.7	3.2
Brazil	260	7.7	26.5	49.9	13.2
India	26	0.0	0.1	0.2	0.3
China	268	0.7	1.4	2.9	0.8
Thailand	12	0.0	0.1	1.2	0.6
Pakistan	14	0.0	0.0	0.0	0.0

Source: Fisher *et al.*, 2008; calculation by authors. Suitability classes are mutually exclusive, i.e. do not overlap.

In total, globally some 3.2 billion hectares of land are classified as unprotected forests, of which 7.3 percent were regarded as very suitable (49 million hectares) or as suitable (some 185 million hectares; see Table 10) for rain-fed sugarcane cultivation. Of the suitable extents in both of these prospective suitability classes, Africa and South America contribute about 85 percent of the total.

2.4. Sustainability of land use changes

Sugarcane is widely accepted as one of the most promising – economically and with regard to greenhouse gas saving potential – bioenergy feedstock options currently available. For instance, the fossil energy ratio (output biofuel energy per unit of fossil fuel input energy) of sugarcane ethanol was 9.3 in 2006 and is projected to reach 11.6 by 2020 with

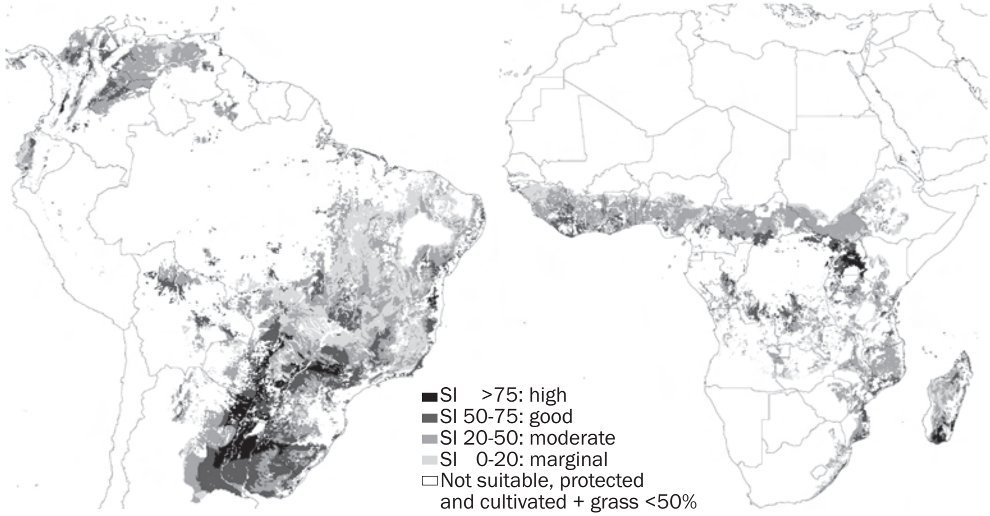

Figure 11. Suitability of current cultivated land and grass, scrub, woodland areas for rain-fed sugarcane production. Source: Fisher *et al.*, 2008.

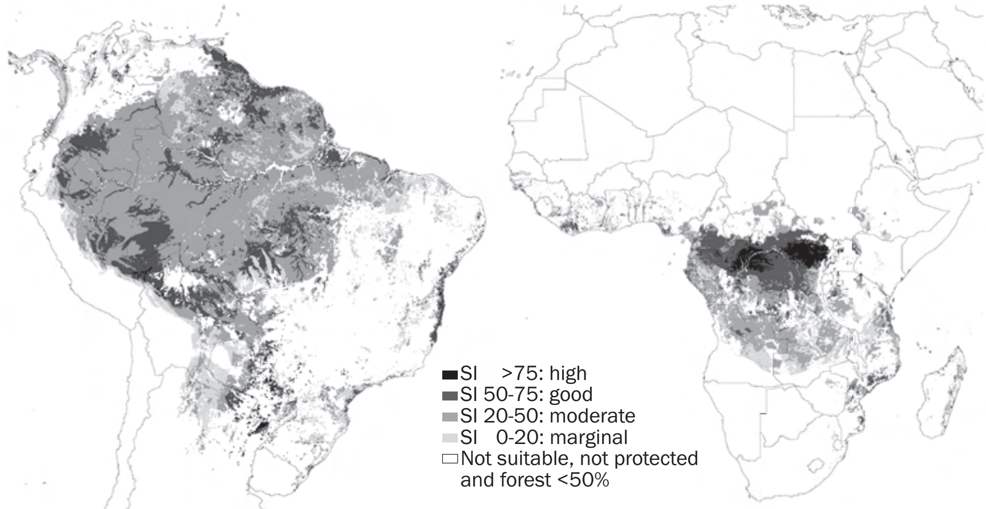

Figure 12. Hot spots of suitability of forest land for rain-fed sugarcane production. Source: Fisher *et al.*, 2008; calculation by authors.

the implementation of commercial technologies already available (Macedo *et al.*, 2008). In comparison, as reviewed by Goldemberg (2007), fossil energy ratio is 10.0 for cellulose ethanol in the United States, 2.1 for sugar beet in Europe and 1.4 for maize ethanol in the United States. The energy and greenhouse gas balance of sugarcane compares very favorably

Table 10. Suitability of unprotected forest land for rain-fed sugarcane production.

	Unprotected forest	Land potentially suitable, of which			VS+S in unprotected forest
		Very suitable	Suitable	Moderately suitable	
	million ha	million ha	million ha	million ha	percent
North America	496	3.1	8699	16.1	2.4
Europe & Russia	910	0	0	0.0	0.0
Oceania & Polynesia	121	0.8	4.6	8.2	4.5
Asia	476	1.7	10.5	41.4	2.6
Africa	444	28.0	79.5	81.4	24.2
Centr. Am. & Carib.	81	1.9	3.7	5.2	6.9
South America	694	13.1	78.2	266.9	13.2
Developed	1516	3.5	10.2	18.0	0.9
Developing	1706	45.2	175.0	401.2	12.9
World	3222	48.7	185.2	419.2	7.3
Brazil	414	4.4	45.0	174.8	11.9
India	61	0.3	0.6	2.0	1.4
China	158	0.5	1.2	2.7	1.1
Thailand	9	0.0	0.1	1.3	0.6
Pakistan	2	0.0	0.0	0.1	0.8

Source: Fisher *et al.*, 2008; calculation by authors. Suitability classes are mutually exclusive, i.e. do not overlap.

with other first generation biofuels; as reviewed in several studies, bioethanol based on sugarcane can achieve greenhouse gas reductions of more than 80% compared to fossil fuel use (e.g. Macedo (2002); Macedo *et al.* (2004); De Oliveira *et al.* (2005)).

The rapid further expansion of sugarcane areas forecasted for Brazil is expected to continue at the expense of current crop land and extensively managed pastoral land in the Cerrado region. This expansion may directly or indirectly affect parts of the Cerrado area with native vegetation and unprotected forest where biophysical, infrastructural and socio-economic conditions are favorable for sugarcane cultivation. Most threatened are those lands adjacent to current production areas. Environmental consequences of sugarcane expansion might range from quite acceptable (conversion of crop land and managed pastures) to very negative where sugarcane expands directly or indirectly in unprotected areas, which still have native vegetation with high bio-diversity or into unprotected native forest areas. Apart from the question, which land will be converted, environmental impacts will be molded by agricultural and industrial technologies applied in newly converted areas.

Current concerns regarding sustainable expansion of the sugarcane industry in Brazil (see Box 2) have been recently investigated (Goldemberg *et al.*, 2008; Martinelli and Filoso, 2008; Smeets *et al.* 2008).

Pressure on native ecosystems and threats to biodiversity can be avoided by effective environmental regulation and control and by implementation of agricultural policies supporting intensification of production. Increasing demand for food and livestock products will require replacement of the land converted to sugarcane, leading to substantial shifts of crop land and pastures to other regions, causing pressure on the ecosystems there. Such indirect land use changes would negatively affect the greenhouse gas efficiency of sugarcane production.

So far sugarcane in Brazil has mostly intruded in the cultivated and pasture areas of São Paulo State. For this state, the estimated remaining area of pastures, of which many are bordering on the sugarcane production expansion front, is 7.6 million ha (IEA, 2007). In the entire Cerrado region (205 million ha) there are currently about 54 million ha of these pastures (Ministério do Meio Ambiente, 2007).

Assuming that cultivated pastures will continue to be converted into sugarcane and that on top of this, demand for livestock products further increases, substantially higher stocking rates will be required. This implies adoption of new technologies (Corsi, 2004) for intensification of pastoral management (e.g. use of fertilizers, rotational grazing) with consequent increases of agro-chemical inputs, production costs and greenhouse gas emissions. The remaining 124 million ha of Cerrado with native vegetation (see Table 7), which are susceptible to loss

Box 2. What are key concerns and environmental issues with sugarcane expansion?

- Deforestation and habitat loss.
- Land competition with food and feed production.
- Indirect effects of land conversion because of strong expansion of sugarcane production out-competing other crop and livestock activities, which in turn encroach on natural habitats.
- Water pollution and eutrophication.
- Soil erosion and soil compaction (mainly during land preparation and early growth phases when soil is barren combined with sub-optimal tillage methods and relative high rainfall and the use of steep slopes).
- Air pollution (mainly through burning of sugarcane before harvest)
- Possible extensive use of transgenic sugarcane types

of bio-diversity and land degradation are an imminent target for sugarcane expansion and needs therefore serious attention. Expansion of protected areas, zero deforestation policies for native forest land as well as reforestation of already deforested areas are important elements of a sustainable agricultural development (Machado *et al.*, 2004; Durigan *et al.*, 2007). Currently, less than 6% of the Cerrado region is legally protected. A share of 20% of natural vegetation is required as a 'legal reserve' by the Brazilian Forest Code in this region, in comparison to 80% in the Amazon rainforest (Conservation International, 2008; Klink and Machado, 2005).

The use of genetically modified sugarcane, with associated risks of impacting biodiversity or becoming invasive in natural habitats, has been identified as an additional area of concern for future expansion of sustainable sugarcane production (Smeets *et al.*, 2008). The sequencing of sugarcane genes and development of transgenic varieties has been pursued in Brazil as a means of conferring disease resistance, stress tolerance and efficiency of nutrient use in the plant, which could contribute to sustainable expansion in the future (Cardoso Costa *et al.* 2006). The country has a well-established research in the biotechnology field with reported successes in developing disease and herbicide resistant agricultural and horticultural crops. Although potential benefits are high, there is still a lack of understanding of the potential impacts of genetically modified organisms on environmental parameters (Smeets *et al.*, 2008), which prompted the removal of permits for commercial trials with transgenic sugarcane after public concerns.

Pollution problems require strict enforcement of legislation and inspection of agricultural and industrial activities. Strict regulation and control of the disposal of nutrient-rich waste from industrial processes (e.g. vinasse) is required to avoid deterioration of water quality near production areas (Gunkel *et al.*, 2007). Recycling of byproducts of sugarcane in the fields reduces chemical fertilizers application rates; however, there is a risk of excess application in particular at close distance to the processing plants (Smeets *et al.*, 2008).

Various technologies have been identified for immediate increases in the efficiency and sustainability of current and future sugarcane mills, e.g. reducing water consumption with closure of water-processing circuits and the use of bagasse (fibrous residue left after cane milling) to generate electricity, improving the energy balance of ethanol production; as well as in production and harvesting processes. Air pollution caused by sugarcane burning can be effectively avoided by the adoption of mechanized harvesting. In São Paulo, where more than one third of the area of sugarcane is already harvested mechanically (Conab, 2008b), a schedule of phasing out burning is in place. Targets are that by 2020 all land with slopes <12% and by 2030 all the sugarcane land should harvested mechanically (Smeets *et al.*, 2008). These authors also indicate that high investment requirements and difficulties with mechanization on, for example steep land, increase the risks of the full implementation of mechanized harvest. An additional challenge are the social consequences of mechanical harvesting because of the significant losses of jobs, i.e. currently 80 workers would be replaced by one mechanical harvester (Conab, 2008a). In 2007, about three quarters of the Brazilian sugarcane area was still manually harvested and some 300,000 workers depend for their livelihood on manual cutting of cane. The pace of introduction of mechanized harvesting will therefore be affected by the cost/benefit of substituting manual labor and on suitable socio-economic conditions to reallocate the current contingent of sugarcane-cutting workers.

Adequate know-how and well developed technology is available to achieve sustainable sugarcane production and expansion (Goldemberg *et al.*, 2008). However, the adoption of new technologies requires a favorable economic and political environment that facilitates investments in clean technologies. While Brazil has accumulated considerable experience on sustainable sugarcane production through its PROALCOOL program, it will be critical to share and transfer this knowledge and ensure application of new technologies and of 'best practices' in other regions of the Americas, Asia and especially Africa, where large expansion potentials may materialize quickly due to the current urgency to develop bioenergy resources.

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