CHAPTER 3. Sugarcane Ethanol

This page intentionally left blank

3.1 Sugarcane Background and Overview

3.1.1 Introduction

Sugarcane is a tall perennial grass that is a member of the genus *Saccharum* in the botanical family Poaceae, which includes most cereal crops. Cultivated cane has been known throughout southern Asia for thousands of years. It is believed to have originated in New Guinea, although there is evidence of parallel agricultural development in India (James, 2004). The sugarcane plant was brought to the Mediterranean area by Alexander the Great and to the Western Hemisphere by Christopher Columbus. Virtually all commercial varieties of sugarcane are hybrids obtained by selective breeding of three domesticated species: *S. officinarum*, *S. barberi*, and *S. sinense* and two wild species *S. spontaneum* and *S. robustum* (Clarke, 2000). Sugarcane is similar to other grasses with the exception that sucrose ($C_{12}H_{22}O_{11}$), the major carbohydrate formed as the result of photosynthesis, is stored in the stalk rather than in the grain or leaves. In addition, it converts 2% of the available solar energy into sucrose and other compounds making sugarcane the most efficient collector of solar energy in the plant kingdom (Clarke, 2000).

The sugarcane plant consists primarily of a stalk, leaves, and a root system. The stalk is made up of joints, which are separated from one another by a node (similar to bamboo). The section of stalk in between each node is referred to as an internode with leaves originating at the nodes (Figure 3.1). Mature plants can reach heights of 16 to 17 feet (5 m) and diameters of greater than 2 inches (5 cm) (Rainbolt and Gilbert, 2008) A typical sugarcane stalk weighs 3 pounds (1.4 kg) and is approximately 85% liquid (Baucum and Rice, 2006).

Figure 3.1. Sugarcane grows as a tall perennial grass with a stalk that consists of joints separated by nodes. (Photo on left by Soreng, 2009. Photo on right from Uribe, 2006).

New growth, including leaves, roots, primary stalks, and secondary shoots (tillers), all originate at a node. This feature allows sugarcane to be vegetatively propagated and thus preserve parent characteristics. Because sugarcane is a hybrid of multiple species, plants produced from sugarcane seeds are not genetically identical to the parent plants or to each other. Either whole stalks or approximately 2 foot (60 cm) -long stalk cuttings called billets, are placed horizontally in furrows in the ground. This starting material, whether a full or partial stalk, is referred to as "seed-cane" and both new stalks and roots will emerge from the buds and root primordial (respectively), which are present in the root band of the buried nodes (Figure 3.2). An inflorescence, or tassel, which appears as a white or reddish plume may form at the top a sugarcane plant. Each tassel consists of thousands of tiny flowers, each with a seed. However, in temperate and sub-tropical climates tassels are not common and because true seeds are not used in commercial propagation they are generally not utilized. Furthermore, since the stalk ceases to grow and begins to deteriorate after flowering, varieties that tend to flower in the field are avoided (Fageria *et al*., 1997).

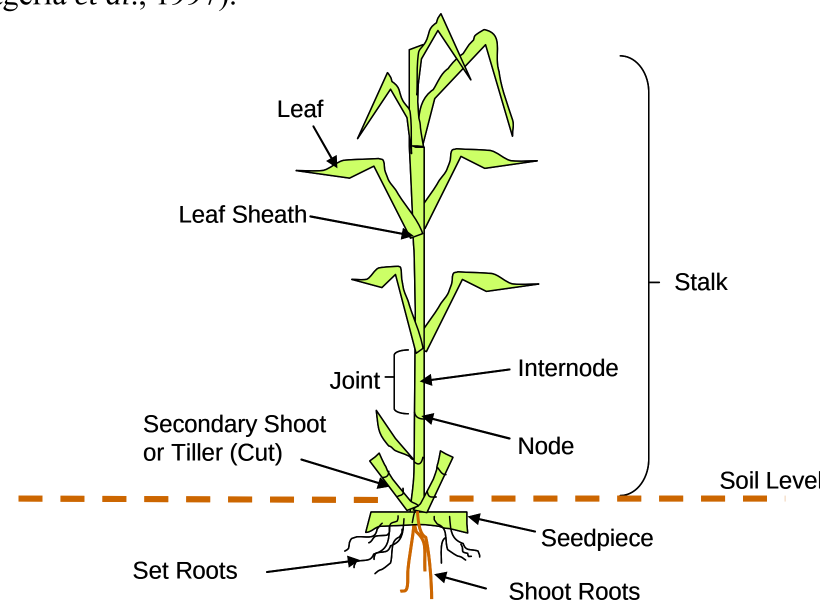

Figure 3.2. New growth on sugarcane originates at the node (after Miller and Gilbert, 2006).

In the continental US, after the seed-cane has been planted, the resulting sugarcane plant is allowed to grow for approximately one year before harvesting. In areas where there are no discernable seasons, including Hawaii, the plants may be left for as long as two years before harvesting, as this increases the sugar content. This first crop of cane that emerges from the seed-cane is referred to as the plant cane crop. Once harvested, new shoots or ratoons will emerge annually from buds located on the original buried cane (the seedpiece), producing from one to four subsequent crops referred to as ratoon crops or stubble crops. Generally, each ratoon crop is less productive than the previous crop. Fields are replanted when yields become unacceptably low, typically after no more than 3 to 4 ratoon crops and often after as few as two.

The length of each joint in the stalk tends to increase in length as the plant grows; thus the number of nodes per unit length decreases towards the top of the stalk. Because sugar tends to be concentrated in the nodes, sugar content is greatest at the base of the plant, near soil level, and minimal near the tip, especially in young plants (Miller and Gilbert, 2006). For this reason it is desirable to harvest the plants as close to the ground as possible (Duke, 1983).

Sugarcane will survive and produce sugar throughout most of the southern United States (Rainbolt and Gilbert, 2008); however, for optimal growth, 4 to 5 months of temperatures between 85 and 95 ºF (30 and 35 ºC) are needed (Fageria *et al*., 1997, Sutter, 2007a) and in areas where temperatures go below 32 ºF (0 ºC), cane must be harvested before the first freeze. Actual ripening, or sugar concentration occurs during cooler, drier times.

The ideal environment for sugarcane is one in which rainfall and/or irrigation are well distributed throughout the growing season, but where the pre-harvest ripening period is relatively dry. At least 500 mm (20 inches) of water (precipitation plus irrigation) must be supplied annually for plants to survive, but amounts of 1500 to 2000 mm (60 to 80 inches) are typically required for it to thrive (Duke, 1983; Sutter, 2007a). Irrigation is used on all sugarcane grown in Florida, most grown in Texas and Hawaii, and virtually none (1 farm) in Louisiana (USDA, 2009a). Nitrogen fertilizer is routinely applied to sugarcane, except in the Florida Everglades, where the so-called "mucky" soils are rich in organic nitrogen (Gilbert and Rice, 2006). Recent studies also have suggested that cane may form a symbiotic relationship with nitrogen fixing bacteria, although the exact species and mechanisms as well the overall influence on nitrogen budgets for sugarcane have yet to be determined (Ohyama, *et al*., 2008). The dense nature of cane fields makes it difficult to apply pesticides once the stalks have reached an appreciable height and pest management relies heavily on pre-planting treatments and selection of appropriate cultivars. The highly vegetative growth of sugarcane plants also encourages the practice of burning prior to harvest. This facilitates cutting and decreases the amount of unwanted residue that needs to be processed.

3.1.2 Historical Trends

Sugarcane is commercially grown in just four US states, Florida, Louisiana, Texas, and Hawaii, roughly 90% of it in Florida and Louisiana. The total area planted in sugarcane increased by approximately 50% between 1980 and 2000, from 732,700 acres (296,508 hectares) to a peak of just over one million acres (0.4×10^6 ha) occurring between the years 2000 and 2003. Much of the increase occurred in Louisiana. Since then, the total amount of land planted in sugarcane has dropped back steadily to 852,700 acres (345,069 ha), driven by declines in utilized acreage in all four states (Figure 3.3). While some portion of this decline was due to hurricane damage, predictions for 2010 are that total area will continue to decrease from 2009 levels by an additional 15,000 acres (6,000 hectares) (Haley and Dohlman, 2009).

The total land area required for supporting sugarcane agriculture includes that used to grow cane for sugar production as well as that used to grow seed-cane for propagation; the latter typically accounts for 5 to 6% of the total land requirement, but varies by state and by year. In Hawaii, for example, more than 10% of the land planted in sugar in the last two years was for seed (ERS, 2009a). Sugarcane farmers may grow their own seed-cane or purchase it from other growers, typically a mixture of both.

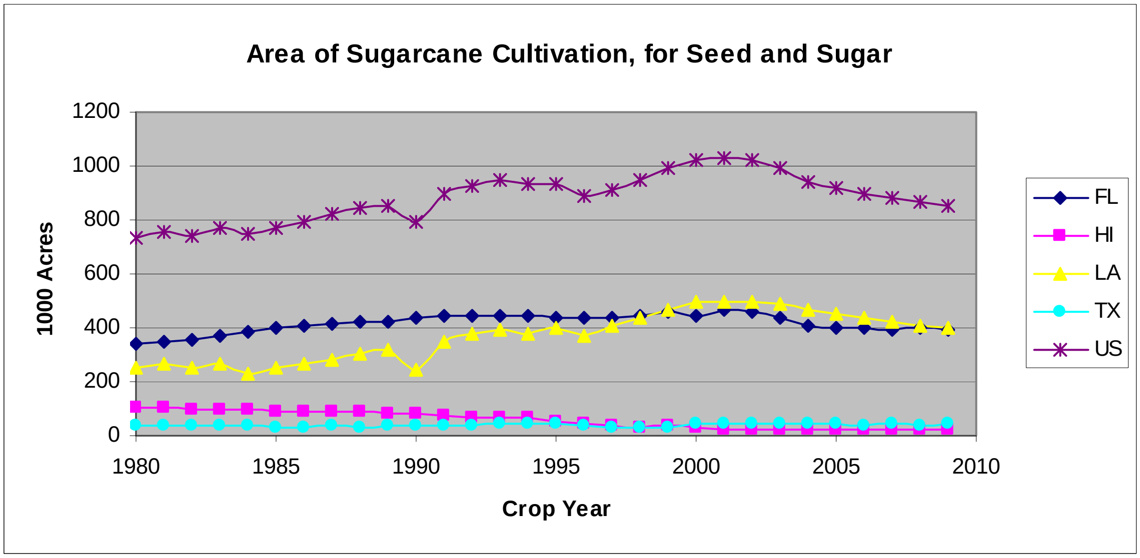

Figure 3.3. The area of US land planted in sugarcane increased by nearly 50% between 1980 and 2000 before beginning to decline; between 5 to 6% of the area is planted for seed rather than sugar production (based on data from ERS, 2009a).

Sugarcane production exhibits a trend similar to total area planted (Figure 3.4), with a steady increase in the amount produced between 1980 and 2000, followed by a decrease (ERS, 2009a). A sharp dip in production is observed in 2005 as the result of hurricane damage. Maximum production occurred in 2000, when just over 34 million short tons (31 x 10^9 kg) of sugarcane were harvested from US fields. Most of the production is from Florida and Louisiana.

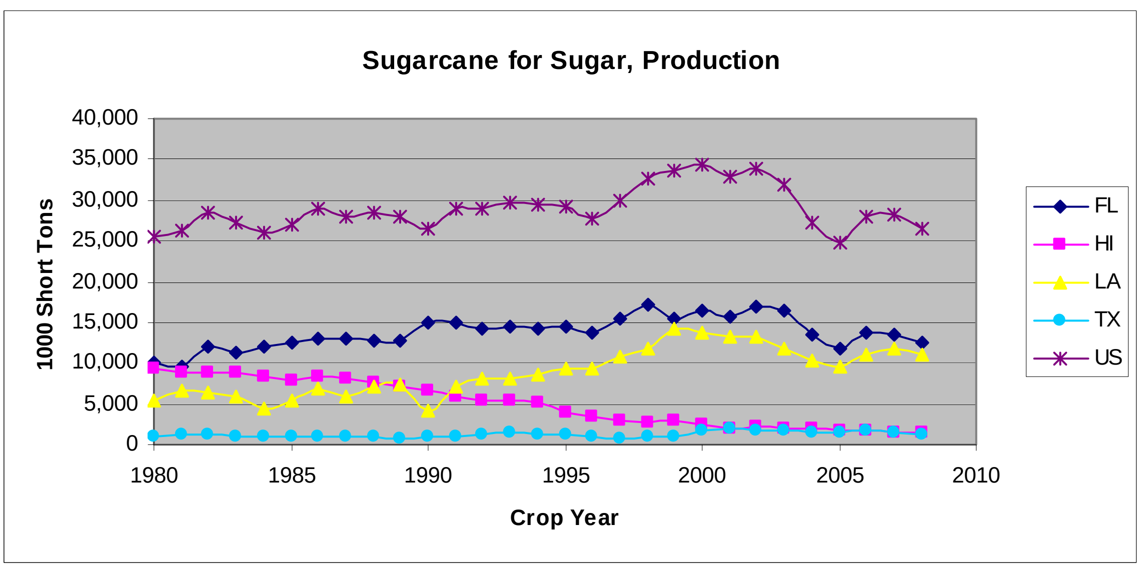

Figure 3.4. Sugarcane production has ranged from 25 to 34 million short tons per year over the past 30 years, with the maximum occurring in 2000 (based on data from ERS, 2009a).

US sugarcane yields have stayed relatively constant over the past 30 years, with the notable exception of Hawaii. Yields on the mainland have ranged between 20 and 40 tons per acre (45 to 90 Mg/ha), while in Hawaii yields have dropped from 100 to just over 60 tons per acre (230 to 140 Mg/ha) (Figure 3.5).

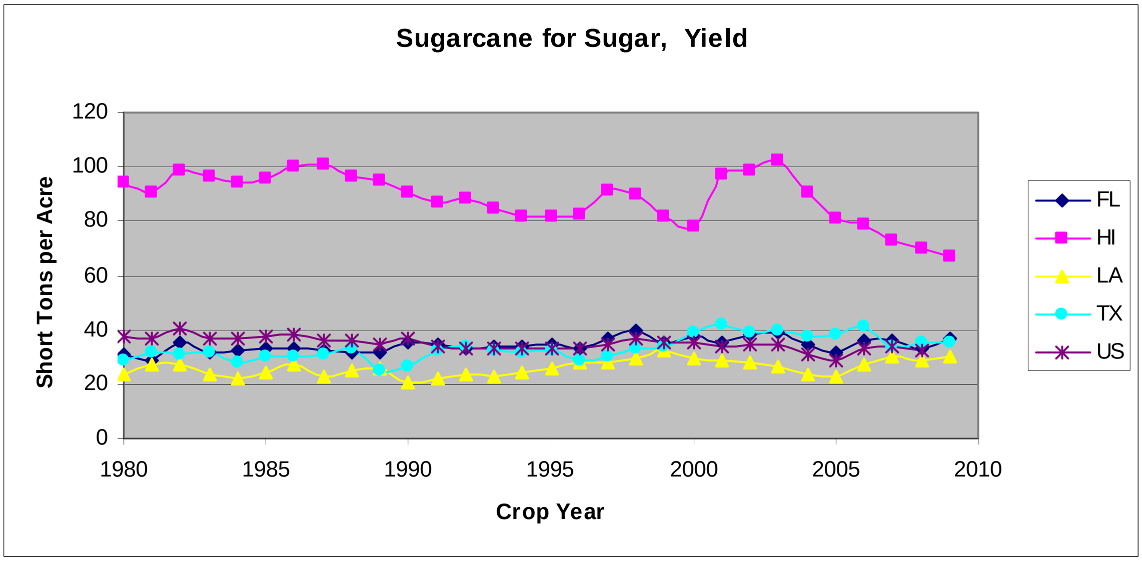

Figure 3.5. Sugarcane yield has stayed relatively constant on the mainland, but has dropped sharply in Hawaii (based on data from ERS, 2009a).

The recovery rate of raw sugar from cane depends upon the actual sugar content in the cane as well as the amount extracted during the milling and evaporative processes that follow. The US average has increased steadily from 10.7 wt% in 1980 to 12.6 wt% in 2008 (Figure 3.6).

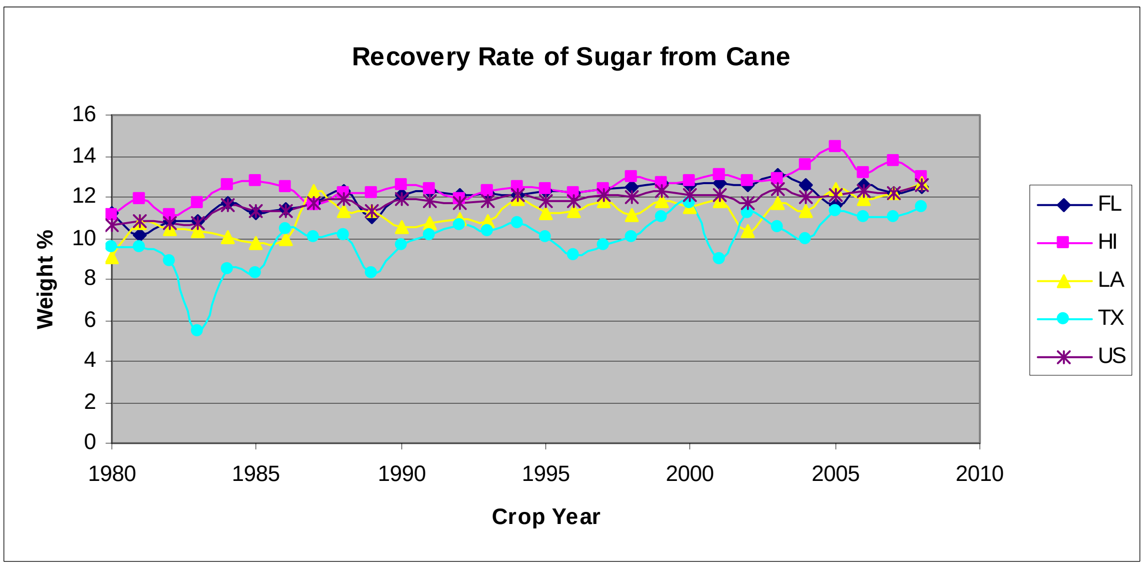

Figure 3.6. The weight percent of raw sugar recovered from cane has increased steadily over the past 30 years.

3.2 Sugarcane as a Potential Ethanol Feedstock

3.2.1 Current Supply

The US produces about 3 million metric tons of raw sugar from sugarcane per year; less than 2% of the 160 million metric tons of raw sugar (from sugarcane and sugar beets combined) produced worldwide (Haley and Dohlman, 2009). If the US were to use all of its sugarcane to produce ethanol rather than sugar, there would not be a dramatic reduction in the global supply of sugar. Various sources put ethanol yield from sugarcane at between 80 and 90 liters of anhydrous ethanol per metric ton (Mg) of sugar cane. The US produces approximately 25 x 10^6 Mg of sugarcane per year, suggesting that there is a potential annual supply of 2.1 billion liters (561 million gallons) per year, which is equal to 6% of the 9.6 billion gallons of fuel ethanol produced in the US in 2008 (EIA, 2009). The lower heating value (LHV) energy content of ethanol is 76,330 Btu per gallon, while that of conventional gasoline is 116,090 Btu/gal LHV (ANL, 2009a); thus 1.52 gallons of ethanol is equivalent to 1 gallon of gasoline. Ethanol from current supplies of sugarcane could, therefore, displace only 0.27% of the 135 billion gallons of motor gasoline consumed in the US in 2008 (EIA, 2009). Perhaps one of the biggest drawbacks to sugarcane is that it is extremely perishable and must be processed immediately upon harvesting. This means that for sugarcane production on the US mainland, milling is seasonal, leaving facilities idle a significant portion of the year. In order to maintain a uniform production schedule for ethanol, fermentation could use raw sugar rather than straight cane juice, but this is estimated to double production costs (Shapouri and Salassi, 2006).

3.2.2 Potential to Increase Supply

Two significant factors affecting sugarcane yield (mass per unit area harvested) are the maturity of the crop and the number of times the cane has ratooned (sprouted from the original seed-cane after the initial plant cane crop). Plant cane crop (the initial growth) that is allowed to mature for two years has the highest yield. Each successive ratoon crop produces smaller amounts of cane. Table 3.1 gives the average yield for various regions and sugarcane varieties from Brazil for the harvest seasons 1998-99 to 2002-03.

Table 3.1. Average yield for various regions and sugarcane varieties from Brazil for the harvest seasons 1998-99 to 2002-03 based on age and harvest type (Macedo *et al*., 2004)

		Cane Yield	
Harvest	Crop Type	tons/acre	10^3 kg/hectare
1st	12 month plant cane	34	77
	"18 month" plant cane [1]	50	113
2nd	1st ratoon	40	90
3rd	2nd ratoon	35	78
4th	3rd ratoon	32	71
5th	4th ratoon	30	67

[1] "18 month" plant cane is actually harvested after 2 years;
80% of the 1st harvest in Brazil falls into this category

In the US, with the exception of Hawaii (Clarke, 2000), allowing the plant cane crop to grow for longer than one year is not practiced. The seasonal nature of mainland sugar growing areas means that there is much less advantage (cooler temperatures during winter months decrease sugar production) and it is not possible in areas that are subjected to freezing temperatures, such as in Louisiana. Never going beyond a second ratoon crop would increase long-term average annual yield, but it would also increase demand for land to grow seed-cane as well as the frequency of plowing and planting (energy and labor intensive activities).

Cane and sugar yields have remained relatively flat since 1980, so it is unlikely that these will increase by any notable degree without some, as yet undefined, change in cropping practices, cultivar types, and/or economic incentives. It is also assumed that minimal production in Hawaii will continue due to other demands for land use. In recent years, less than 5% of US sugar has come from Hawaii.

The climate restrictions for growing sugarcane at a commercial scale mean that the total land area available in the continental US is limited. This is less so than for citrus, as sugarcane plants will survive freezing temperatures, but more so than for cotton because it needs long periods of warm weather in order to produce substantial amounts of sugar. While eight non-sugarcane species of the genus *Saccharum* L. have been noted over large geographic areas of the US (Rainbolt and Gilbert, 2008; NRCS, 2009), none of these is currently recognized as a significant source of sucrose, as are the five cross-bred species that makeup what is grown as commercial sugarcane. According to the NRCS maps (2009), within the continental US, *S. officinarum*, is found only in Texas, Louisiana, Mississippi, Alabama, and Florida. *Saccharum barberi*, *S. sinense*, *S. spontaneum*, and *S. robustum* are found nowhere in the US as a distinct species.

It would appear that the only likely means for increasing sugarcane production in the near future is to increase the amount of land used to grow it. Two scenarios for increasing sugarcane production are explored, both of which involve increasing the amount of land that is planted in sugarcane on the US mainland. In the first scenario, it is assumed that the best areas for growing sugarcane are where it is currently produced and all existing cropland in counties that currently have any acres planted in sugarcane is converted to cane fields. In the second scenario, the area where sugarcane is grown is expanded to include all areas of the US that lie within USDA Hardiness Zone 9a or higher (USNA, 2003) and within the American Horticultural Society Heat Zone 9 or higher (AHS, 1997). This restricts possible planting regimes to locations where the average annual minimum temperature is 10 ºF (-12 ºC) or greater and where there are a minimum of 120 days above 86 ºF (30 ºC). While this is not a realistic scenario, it provides a theoretical maximum for sugarcane production in the US.

CW.2.2.1 Scenario: Conversion of Existing Cropland to Sugarcane

In this scenario, all existing cropland in counties that currently grow sugarcane for either seed or sugar is converted to sugarcane. The data are taken from the 2007 Census of Agriculture, which lists sugarcane production, area harvested for both sugar and seed-cane, and total cropland for each county (USDA, 2009a). It is assumed that displaced crops would be grown on land that is not currently cropland and would thus result in land use change for non-cropland. All of the new production would be used for the production of ethanol. Sugarcane yields (mass per unit area planted) are taken to be the maximum for the last three years (ERS, 2009a) and the ratio of land used to produce seed-cane to that used to produce sugar remains constant. The 2007 supply of sugarcane, as well as sugarcane and total cropland, are given in Table 3.2.

Table 3.2. 2007 sugarcane production and land use (based on data from USDA, 2009a) plus potential production if all cropland in existing sugar-producing counties were cropped in sugar.

State	2007 Sugarcane (10^6 tons)	Yield [1] (tons per acre)	2007 Sugarcane Land Harvested (10^6 acres)		% Land Harvested for Sugar	All Cropland [2] Cropped in Sugarcane (10^6 acres)		Potential Sugarcane (10^6 tons)	Factor of 2007 Production
			Sugar plus Seed	Sugar		Sugar plus Seed	Sugar		
FL	14.1	36.7	398	379	95.2%	886	843	30.9	2.2
LA	14.1	30.4	433	405	93.6%	1,956	1,832	55.7	4.0
TX	1.3	35.5	39	38	98.0%	827	810	28.8	22.8
TOTAL	29.5		870	822	94.5%	3,669	3,468	115.4	3.9

[1] Max yield 2006 -2008, ERS, 2009a

[2] In counties with any acres planted in sugarcane in 2007

Using the mean maximum sugarcane yield for the years 2006 through 2008 based on data from the USDA (ERS, 2009a), it is predicted that the amount of sugarcane grown, and thus the amount of ethanol that could be produced is approximately 4 times that of the existing potential. Assuming 85 liters of anhydrous ethanol per metric ton of sugarcane (20.4 gallons per short ton), it would be possible to produce 2.35 billion gallons, which is the energy equivalent of 1.7% of the US consumption of motor gasoline in 2008 and 24% of the fuel ethanol produced.

3.2.2.2 Scenario: Conversion to Sugarcane of All Available Land in Suitable Temperature Regimes

Sugarcane rootstock can live through temperatures as low as 9 ºF (-13 ºC) (Duke, 1983). This is equivalent to USDA Hardiness Zone 9a or higher (USNA, 2003). While 4 to 5 months of temperatures above 86 ºF (30 ºC) are best for optimal sucrose yields (Sutter, 2007a), 3 months could produce viable amounts sugar with proper cultivar selection. This time-at-temperature requirement is met by limiting sugarcane cultivation to American Horticultural Society Heat Zone 9 or higher (AHS, 1997). Using the Zone maps as a guide to identify areas of overlap between Hardiness Zones 9a and above and Heat Zones 9 and greater, it is postulated that sugarcane could be grown over approximately 50% of California, Arizona, and Texas;10% of New Mexico, and South Carolina; 33% of Mississippi, Alabama, and Georgia; and 100% of Louisiana, and Florida. In the western states, irrigation would be an absolute necessity.

Based on data from the Natural Resources Conservation Service (NRCS, 2007) the maximum land area that in the most extreme case could be used to grow sugarcane in the US is estimated as the sum of 1) all land currently used to grow sugarcane, 2) Conservation Reserve Program (CRP) land, 3) rangeland, 4) pastureland, 5) other rural land, and 6) forestland, located in portions of states with the appropriate temperature regimes. Although much of this land actually is not and never would be available to grow sugarcane, it is, at least for this exercise, regarded as land on which sugarcane conceivably could be grown, given strong enough market forces and/or policy. Land that is considered completely unavailable includes 1) developed land, 2) cropland used for crops other than sugarcane, 3) water areas, and 4) federal land (Table 3.3). It assumed that 5% of the land is needed for producing seed-cane and that 25% of the land is either fallow or being used to grow a rotation crop.

Table 3.3. Land use (in units of 1000 acres) and calculation of maximum available land for growing sugarcane in the US, assuming a minimum annual temperatures of 10 ºF (-12 ºC) (USDA Hardiness Zone 9a or higher) and a minimum of 120 days above 86 ºF (30 ºC) (AHS Heat Zone 9 or higher); (based on land use data from USDA, 2009 and NRCS, 2007).

	"Available" Land								Unavailable Land		
	Sugarcane Land	CRP	Pasture-land	Range-land	Other Rural Land	Forest Land	Maximum New Sugarcane Land	Maximum New Sugarcane for Sugar Area per year	Non-Sugarcane Cropland	Developed, Federal, and Water Areas	Total Surface Area
State	-- 1000 Acres --										
AL [1]	0	153	1,134	24	150	7,177	8,637	6,046	836	1,668	11,141
AZ [2]	0	0	41	16,127	1,514	2,071	19,753	13,827	467	16,262	36,482
CA [2]	0	67	594	8,879	2,312	6,952	18,804	13,163	4,734	27,217	50,755
FL	398	78	3,619	2,697	2,807	12,733	21,934	15,354	2,475	12,726	37,534
GA [1]	0	98	933	0	285	7,298	8,613	6,029	1,384	2,583	12,580
LA	433	201	2,249	284	2,940	13,338	19,011	13,308	5,002	6,931	31,377
MS [1]	0	264	1,075	0	142	5,585	7,065	4,946	1,658	1,452	10,176
NM [3]	0	58	23	3,996	206	548	4,831	3,382	155	2,797	7,782
SC [3]	0	18	109	0	83	1,116	1,327	929	237	430	1,994
TX [2]	39	1,997	7,918	48,055	1,143	5,307	64,419	45,093	12,762	8,326	85,526
Total	870	2,933	17,696	80,061	11,583	62,122	174,395	122,076	29,711	80,392	285,347

[1] 33% of state total
[2] 50% of state total
[3] 10% of state total

The maximum amount of "available" new sugarcane land is thus estimated to be 174.3 million acres (70.6 x 10^6 hectares). Accounting for land used to grow seed-cane and that held in rotation, only 70% or 122.1 million acres (49.4 x 10^6 hectares) are available to produce sugarcane as feedstock for ethanol on an annual basis. The area thus defined is where sugarcane might survive, but is unlikely to thrive. As a consequence of growing in less than optimum conditions (shorter growing seasons, lower maximum temperatures, and less water), yields are likely to be lower than current values. If a yield of 20 short tons per acre is assumed (approximately 60% of current mainland yields), the new land would produce 3.3 billion tons of sugarcane. This could be used to generate 49.7 billion gallons of ethanol, enough to displace just under one-fourth of the 2008 gasoline consumption in the US and to increase fuel ethanol production by more than 400%. However, the cost of this production would require land use change for 174 million acres, 61% of the total surface area in the area considered.

3.2.3 Potential Decreases in Supply

The state of Florida currently supplies nearly half of the sugarcane produced in the United States, most of it in the Everglades region. About half a million acres are located south of Lake Okeechobee, and their presence blocks the natural flow of water from the lake into the surrounding wetlands. Water, with significant amounts of phosphorus from fertilizer runoff, is instead diverted to the Atlantic Ocean and Gulf of Mexico via the Caloosahatchee and St. Lucie rivers. In June 2008, as part of the Comprehensive Everglades Restoration Plan, the state of Florida announced that it would purchase 187,000 acres, 155 thousand of which are used to grow sugarcane, from the U.S. Sugar corporation in order to help restore southward water flow from the lake through the Everglades into Florida Bay, located at the southern tip of the state (Hodges *et al*., 2008; Achenbach, 2008). The sugarcane yield in Palm Beach County was 39.5 short tons per acre in 2007 (USDA, 2009). Consequently, completion of this purchase would reduce the US sugarcane supply by approximately 6.1 million tons, or just over 20%. However, the availability of funds to make the purchase is questionable and under the agreement, U.S. Sugar would be permitted to lease the land for 20 years (Thomas, 2009).

3.3 Sugarcane Ethanol, Life Cycle Assessment

The life cycle assessment approach taken is that of an attributional rather than consequential LCA and evaluates the typical practices in the United States in the year 2007 (approximately). A description of life cycle assessment, and in particular, its application to transportation fuels is addressed in Chapter 1 of this report. A simplified process flow, illustrating the overall life cycle of anhydrous ethanol produced from a sugarcane juice feedstock, is presented in Figure 3.7.

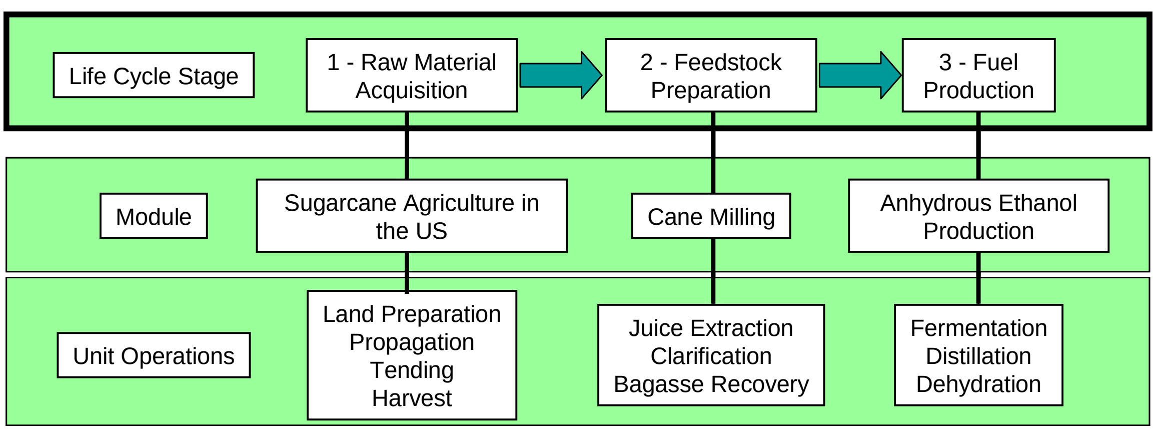

Figure 3.7. Ethanol produced from sugarcane can be characterized by three life cycle stages each possibly separated by a transportation event.

3.3.1 Sugarcane Ethanol, LC Stage 1, Raw Material Acquisition: Land Preparation, Propagation, Tending, and Harvest

3.3.1.1 General

3.3.1.1.1 System Boundaries

The first life cycle stage in the production of ethanol from sugarcane is the acquisition of cane through conventional agricultural systems in the US. This entails preparation of the land for planting, propagation through the planting of seed-cane (cane cuttings from which new cane plants grow), tending of the sugarcane plant, and harvesting of the cane. Because the greatest amount of data is available for 2007, to the extent possible, that is the reference year for this analysis. The system includes consumption of raw materials, energy, land, and water, as well as emissions to air. Emissions to land and water are addressed only as contributors to greenhouse gas emissions. Upstream energies associated with production of agricultural chemicals and fertilizers are included, but development of infrastructure and manufacture of farm equipment are not (Figure 3.8). The downstream system boundaries end at harvest; thus transport and storage activities from and off the cropland are included in life cycle stage 2. This decision is driven primarily by the change in reference flow from a unit area of land in life cycle stage one to a unit mass of cane in life cycle stage two and the recognition that activities for transportation and storage are better modeled in units of mass.

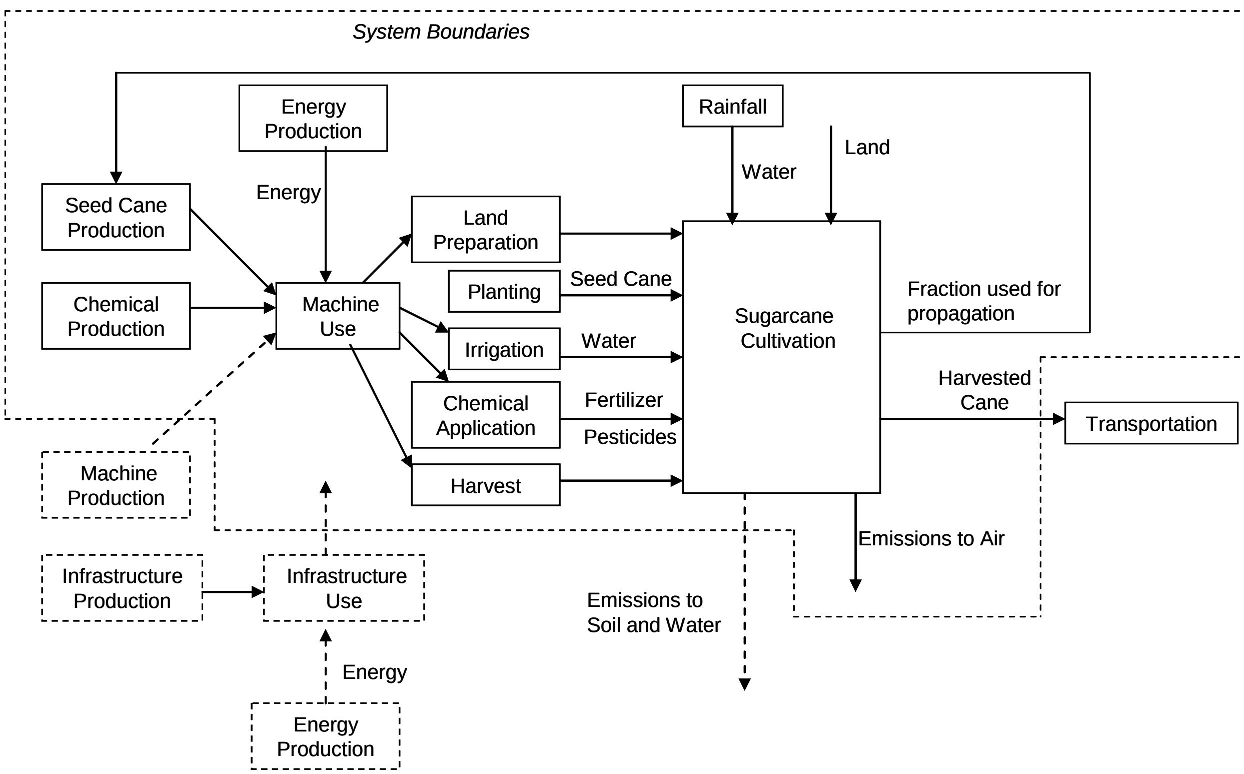

Figure 3.8. The above diagram shows a simplified process flow and the system boundaries for sugarcane ethanol life cycle stage 1 (raw material acquisition), which includes land preparation, propagation, tending, and harvest.

3.3.1.1.2 Units

The basis for this portion of the life cycle is one hectare of harvested land in one year (1 ha-yr). Most US agricultural data are reported in English units, therefore, both metric and English units will be used in the tracking of flows. Although it is more common to use the harvested product as the reference flow, this value can vary significantly because of ranges in crop yields. In addition, the material and energy flows associated with this life cycle stage are much more tightly coupled to the amount of land acted upon than they are to the mass of plant matter removed. A final transformation to mass of fresh cane produced per area of land per year (kg/hectare-yr) is performed at the end of stage one, along with the embodied inventories, for input into the second stage of the life cycle, where the basis is one kilogram (1 kg) of fresh cane with variances noted as a function of harvest yield.

3.3.1.1.3 Resources

Growing sugarcane requires, as do all agricultural products, sunlight, land (soil), water, and nutrients. Sunlight is limited by climate and location of the field (degrees latitude). The amount of land that must be committed (actively managed) in order to produce a hectare of sugarcane includes additional land needed to produce seed-cane for propagation (and average of 5 to 6% in the US). In addition, crop rotation/fallow practices may increase land requirements by as much as 33%. Finally, it is estimated that an additional 10 to 15% of land is required for access and drainage ditches. The amount of land suitable for growing sugar is limited by climate, terrain, and competing demands from both within and external to the agricultural sector. While rain is an important source of water, roughly half of the sugarcane grown in the US is irrigated. Nutrients naturally available in the soil are insufficient for commercially viable yields, thus these must also be supplied; the amounts are location dependent. Equipment, buildings, and energy in the form of electricity and liquid fuel are required to manage these resources.

3.3.1.2 Unit Operations and Activities

The unit operations involved in the growing of sugarcane plants include: land preparation and management, planting of seed-cane, tending (including application of fertilizer and pesticides, irrigation, and secondary tillage), harvesting, and transportation on the farm. Because sucrose content begins to decline from the moment sugarcane is harvested, it is not stored.

The specific list of activities that are performed within these unit operations and their descriptions, for the purpose of this analysis, are taken from cost and return documents that are supplied by state agricultural extension services, developed by agricultural economists, as planning aids for sugarcane farmers. The extension services base these budgets on information gathered through farm surveys. Therefore, these are not simply recommendations but represent actual practices within the state. In the current analysis, the final activities considered and the flows associated with them are based primarily on the detailed information provided by the state of Louisiana (Salassi and Deliberto, 2008; 2009) as they are particularly well organized and complete. In addition, Louisiana represents the largest uniform sugarcane growing environment in the US (approximately 45% of the land area). The cost and return reports include a series of tables broken out by operation. Each table gives a sequential list of equipment, labor, and products used, their rate of use, and their cost. A separate set of tables provides the fuel cost for the different pieces of equipment on a per use per acre basis. The assumed unit cost of fuel (dollars per gallon) is also given. By merging the information in these tables, an activity based model can be generated and used to calculate the material and energy balances associated with the activities. As sugarcane is not irrigated in Louisiana, information regarding irrigation practices and flows is taken primarily from Florida and Texas extension services documents (Lang, 2002; TAES, 2007).

The costs and returns documents for Florida sugarcane grown outside of the Everglades (Roka *et al*., 2009) and Texas (TAES, 2007), are less detailed and less complete than those from Louisiana, but, based on the information that is provided, the activities appear to be reasonably consistent between the three states. Any significant differences that do exist are noted and accounted for as weighted averages. Little current operational information is available for growing cane within the Everglades on the organic ("muck") soils of southern Florida, where 80% of the state's sugar is produced. Presumably this is because the growing and milling of sugarcane in this area is managed within vertically integrated corporations with their own internal budgeting operations. Two distinctions between Florida cane grown on mineral (sandy) soils and that grown on the organic soils of the Everglades are noted. First, sugarcane grown on organic soil requires no nitrogen fertilizer (Rice *et al*., 2006); and second, 50% of the area is cropped using succession planting (i.e. land is never left fallow or planted with another crop) (Roka *et al*., 2009). However, while these crops currently represent about 35% of the US sugarcane production, this area represents a unique and limited environment that has virtually no possibility of expansion or of being replicated elsewhere in the US. In addition, one-third of these eventually may be removed from production as part of the Comprehensive Everglades Restoration Plan (Hodges *et al*., 2008; Achenbach, 2008).

Sugarcane acreage at any given time is partitioned into separate areas that represent different annual stages in the biological life cycle of the sugarcane plant. Approximately one-fourth of the land will be fallow (i.e, have no cane growing within its perimeter). It is this area to which the unit operation land preparation applies. Another fourth of the land area will be planted in seed-cane to produce both additional seed-cane as well cane for sugar (the plant cane crop). This portion, which contains the first growth cycle of newly planted cane, represents the area affected by the planting unit operation and its associated activities. The remaining land (approximately half) is used to grow ratoon or stubble crops, cane that has re-grown from previous cane plantings and represents second, third, or fourth ratoons. The tending operation and the harvest operations are applicable to this area as well as to the plant cane crop area, and thus affect approximately 75% of all sugarcane land. Figure 3.9 shows a schematic illustration of how the land is used in a four year rotation as described by Salassi and Deliberto (2009). Alternatively, the ratoon area could be subdivided into three ratoon crops using successively smaller amounts of land (22% for the first ratoon crop, 19% for the second ratoon crop, and 7% for the third) as described by Roka and others (2009) as a representative farm in Florida.

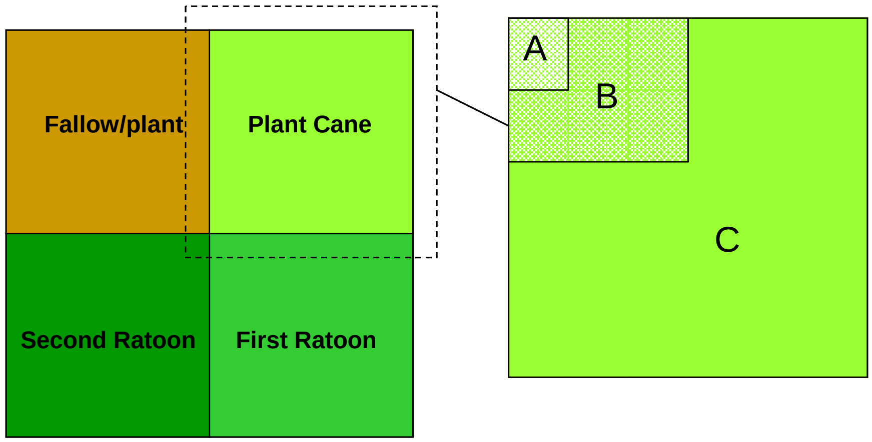

Figure 3.9. At any given time, different areas of sugarcane cropland will require different unit operations, depending upon the biological life cycle stage of the sugarcane plants being grown on that land (based on Salassi and Deliberto (2009)).

3.3.1.2.1 Land preparation and management

3.3.1.2.1.1 General Description

One of the most important aspects of sugarcane farming is site or land preparation. Sugarcane is a perennial plant that is grown for 3 to 5 years before being replaced with either new sugarcane plants, left fallow, or planted with a fallow or cover crop ("green manure"). Therefore, the amount of land that is affected by this unit operation on an annual basis ranges from 20% for a 5-year rotation (if evenly distributed) to 25% for a 4-year rotation or for a 5-year rotation that successively decreases the amount of land for older ratoon crops. In the Florida Everglades where succession planting is practiced (i.e. land is never left fallow or planted in a crop other than sugarcane), 33.4% of the 2006-2007 sugar crop consisted of new plantings (Roka *et al*., 2009). For this study, 25% of US land cropped in sugarcane is taken as the representative average amount of land that is prepared for planting on an annual basis. Therefore, although all activities and flows are initially presented on a per acre or per hectare basis, in the final analysis, all flows that occur due to land preparation are taken to be one-fourth of the per unit area value.

The fallow operation, as land preparation is sometimes called, occurs after the last ratoon crop is harvested and prior to planting new seed-cane, corresponding to March through August in Louisiana and slightly earlier in Florida. It generally involves plowing (primary tillage), row formation, and construction or maintenance of irrigation and/or drainage systems. Seasonal constraints on replanting dictate a minimum amount of time that land is left fallow. However, it is common practice to leave the land free of sugarcane for an additional year. This helps control resistant weeds and discourages build-up of diseases and pests that specifically affect sugarcane plants. Planting of cover crops on fallow land helps suppress weeds and improves soil conditions, particularly the organic matter content. It also keeps soil from being left barren which can lead to erosion, loss of nutrients, and release of greenhouse gases such as CO_2 and N_2O. Cover crops, especially legumes which are nitrogen-fixing, are typically not harvested, but instead turned into the soil at the time of maximum vegetative production (i.e., when in the early flowering stage of growth and just before seed formation) in order to increase the supply of organic nitrogen and other nutrients in the soil. In Florida, a short-season crop can be planted that does not necessarily require loss of a sugarcane cropping year (Muchovej, 2008). However, while recommended, planting of rotation crops is not reflected as a typical practice in state agricultural extension cost and returns documentation and is therefore not captured in this analysis. In cases where nitrogen fixing crops are rotated in, the energy and material flows associated with growing sugarcane would need to be adjusted; equipment and related fuel inputs would increase, and chemical applications would likely decrease.

The primary objectives of land preparation are to destroy and remove remnants of the previous crop, to break up compacted soil at depth, and to improve the texture of soil within the root zone in order to maximize access to water and nutrients. In addition, while sugarcane requires significant amounts of water (through rainfall and/or irrigation), excess water must be removed; this requires well designed drainage systems that must be built, rebuilt, and/or repaired on a regular basis. Most activities involve the use of tools pulled by diesel-powered mechanical front-wheel drive (MFWD) tractors. Herbicides may be used to ensure the elimination of both weeds and residual cane. Residual pieces of cane (stools) are problematic in that they can harbor diseases and pests.

3.3.1.2.1.2 Activities

Preparation of soil before planting requires tilling at up to three different depths. At the deepest level, soil compaction must be eliminated in order to promote adequate water flow and provide adequate space for root development. Moldboard plows are a highly effective, but also highly disruptive means of providing deep tillage. The moldboard plow has a large frame that is equipped with a series of steel coulters that create a bottom cut in the compacted earth. A steel share then cuts the soil, creating a "slice" of soil that is subsequently raised and turned over by the moldboard (EPA, 2009a). When used in sugarcane cultivation, this type of plow is effective at bringing residual cane to the surface where it dries out and dies (Ellis and Merry, 2004). Although once the plow of choice, moldboards are now reserved for situations where other implements are ineffective such as heavy, wet soils and/or those with a high clay content. An acceptable substitute is the disc (also referred to as a disk or disk harrow), which is typically employed in US sugarcane fields. These implements use steel disk blades mounted in groups or gangs that rotate as they move forward and slice through crop residues and soil. Front gangs move soil toward the outside of the disk while rear gangs move soil back toward the center of the disk (EPA, 2009a). These are effective at chopping up the residual cane, but do not bring them to the surface (Ellis and Merry, 2004), therefore an herbicide must be used to ensure complete destruction of the stools (residual cane). A subsoiler is used to loosen subsoil by fracturing compacted layers known as "hard pan." In the absence of significant freeze-thaw cycles, southern soils are especially prone to compacted layers, which can result in reduced yield.

Chisel plows use curved shanks to penetrate and "stir" mid-level soil without inverting the soil layer (EPA, 2009a). These implements are used to cultivate soil within the root zone. Harrowing tines or similar implements can be used to produce a good texture (tilth) in the top level of the soil. This activity is accounted for in the planting unit operation. In new or uneven fields, the soil may need to be leveled using a grader or land plane, Land planing is particularly important in furrow-irrigated fields and in fields with very shallow slopes such as those found in US coastal plains where sugarcane is grown; lasers may be used to guide this operation (Ellis and Merry, 2004; Lang *et al*., 2002). Beds are formed using a disk bedder, known in Louisiana as a “hipper.” Final bed preparation is completed using a row plow (also known as a French plow), which is designed to till soil within a narrow band (a single row).

The land preparation operation is the most suitable time to install sub-surface drainage works to control water table levels and water quality. Drainage pipe is normally slotted PVC pipe (50 to 75 mm in diameter) installed by trenching the soil and laying the pipe narrow trench from 1.2 to 1.5 meters deep with a gravel and or sand surround to filter out soil particles. Access ports constructed from polyethylene or precast concrete are positioned at bends and junctions. The drainage pipe is flushed clean periodically using a high-pressure drain cleaner fitted with a jet nozzle (Ellis and Merry, 2004). Infrastructure is not included in this analysis, however, maintenance is.

A list of the equipment, reflecting the activities performed during land preparation in Louisiana, is presented in Table 3.4. This is taken to be representative of sugarcane grown in the US. With the exception of the drain cleaner and the boom sprayer, all of the equipment is used to condition the soil and shape beds or rows. The drain cleaning operation, which uses a jet of water, is required after all earth moving activities in order to keep the drains clear and free of obstructions that could impede the flow of water within the fields. A boom sprayer is used to apply liquid herbicide. The area passes per year reflects the number of times the activity is repeated during the season. Rarely does it reflect multiple passes within a single performance of the activity. For the interested reader, the specific order and the month in which each activity is performed is available for Louisiana (Salassi and Deliberto, 2008; 2009).

Table 3.4. Equipment used in the land preparation unit operation for sugarcane (based on Salassi and Deliberto, 2008)

Equipment	Size/	Unit Power (HP)	Fuel Use Rate		Performance Rate		Area Passes / yr	Annual Fuel Consumption	
			gal/hr	liters/hr	hr/ac	hr/ha		gal/acre	liters/ha
Disk	20 ft	190	9.76	36.94	0.10	0.25	4	3.9	36.5
Chisel Plow	13 ft	190	9.81	37.13	0.22	0.54	2	4.3	40.2
Land Plane	15 ft	150	7.72	29.24	0.30	0.74	2	4.6	43.4
3 Row Marker	18 ft	150	7.70	29.15	0.12	0.30	1	0.9	8.6
3 Row Disk Bed (Hipper)	18 ft	150	7.70	29.15	0.12	0.30	5	4.6	43.2
Subsoiler	3 shank	190	9.77	36.98	0.20	0.50	1	2.0	18.6
Chisel Plow	23 ft	190	9.81	37.13	0.12	0.30	0.5	0.6	5.5
3 Row Plow	18 ft	190	9.77	36.98	0.12	0.30	1	1.2	11.0
Drain Cleaner	6 ft	75	3.84	14.52	0.08	0.20	5	1.5	14.4
Boom Sprayer	16 ft	150	7.70	29.15	0.12	0.30	2	1.8	17.3
TOTAL								25.5	238.7

3.3.1.2.1.3 Direct Material and Energy Flows

The direct material and energy flows associated with the land preparation and management unit operation include land, diesel fuel to power the equipment, as shown in Table 3.4, nutrients, herbicides, water used in drain cleaning, and emissions to air.

Roka and others (2009) report applications of calcium silicate slag and dolomite ($CaMg(CO_3)_2$) at rates of 1.5 and 1.0 tons per acre, respectively, on Florida mineral soils. Rice and others (2006) state that use of these substances is not required on muck soils upon which the majority of Florida sugarcane fields are located. For this analysis, application of these materials is weighted at 10%, as representative of US sugarcane production, or 0.15 tons of slag per acre (336 kg/ha) and 0.1 tons of dolomite per acre (224 kg/ha).

Estimated use of herbicides during land preparation is reported from four different sources (Table 3.5). Activities and flows in Texas are weighted at 10% (the approximate percent of all US sugarcane land). Practices for Louisiana are weighted at 45%; however, for situations where there is a discrepancy between 2008 and 2009 numbers, slightly more weight (25% as opposed to 20%) is given to the 2009 report. The data for Florida sugarcane grown on mineral soil is assumed applicable to that grown on organic soils and is weighted at 45%. Based on these data, a weighted average for the US is assumed to be 0.24 kilograms per hectare (0.21 lb/acre) of atrazine, 0.23 kg/ha (0.21 lb/acre) of pendimenthalin, and 2.80 kg/ha (2.5 lb/acre) of glyphosate.

Table 3.5. Herbicide treatments applied during land preparation

Trade Name	Common Chemical Name	Active Ingredient (a.i.)	Product Use Rate		Active Ingredient Use Rate		Reference	% of US cane	Weighted Mean	
		lb/gal [5]	gal/ acre	liters/ ha	lb/ acre	kg/ ha			lb/ acre	kg/ ha
Atrazine 4L	atrazine	4	0.5	4.7	2.0	2.2	1	20%	0.70	0.78
			0.8	7.0	3.0	3.4	4	10%		
Prowl 3.3 EC	pendimethalin	3.3	0.6	5.8	2.1	2.3	4	10%	0.21	0.23
Roundup UltraMAX	glyphosate	5	0.5	4.7	2.5	2.8	1	20%	2.77	3.11
Roundup PowerMAX	glyphosate	5.5	0.3	3.2	1.9	2.1	2	25%		
unspecified	glyphosate	4	1.0	9.4	4.0	4.5	3	45%		

[1] Louisiana, 2008 projected (Salassi and Deliberto, 2008)

[2] Louisiana, 2009 projected (Salassi and Deliberto, 2009)

[3] Florida Mineral Soils 2007-2008 (Roka *et al*., 2009)

[4] Texas 2008 projected (TAES, 2007)

[5] MWSC, 2009

The quantity of water used for drain cleaning is unknown. In Florida, the standard layout for drainage ditches is on a 660 ft by 2640 ft grid (one-half a section by one-eighth of a section), which subdivides the farm into 40 acre blocks (Lang *et al*., 2002). The total ditch length can be thus estimated to be 3300 feet per 40 acres (82.5 ft/ac, 62.1 m/ha). The ditches ranges from 3 to 6 feet (1 to 2 meters) wide and are at least 3 to 4 feet deep (0.9 to 1.2) meters deep. The typical width is taken to be 1.5 meters wide and it is assumed that a nominal water depth of 2 inches (0.05 meters) is required to clear the ditches of debris. The total water required to clean drainage ditches per event is calculated as

$$62.1 \text{ meters/hectare} * 1.5 \text{ meters} * 0.05 \text{ meters} = 4.658 \text{ cubic meters / hectare} = 4658 \text{ liters/hectare-cleaning event} \quad (3.1)$$

The land preparation and management unit operation requires 5 drain cleaning events and the water used for this activity is estimated as

$$5 \text{ cleaning events} * 4658 \text{ liters/ hectare -cleaning event} = 23{,}288 \text{ liters/ hectare} \quad (3.2)$$

This water is assumed to be withdrawn and discharged to surface water with little lost to evaporation. The quality of the water would be degraded by the presence of suspended soils as well as chemical run-off (pesticides and fertilizers) from the surrounding cropland.

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Table 3.4 are calculated from the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The equipment population is based on lifetime expectancies for the equipment (Salassi and Deliberto, 2008) with most of the equipment at or near the median age. The pieces of equipment are primarily implements pulled by a tractor, which is estimated to have a lifetime of 8 years.

Therefore, in 2007, most of the equipment is assumed to be model years 2003 to 2005 and representative of Tier 2 technology. Lower power equipment (75 horsepower or less) is Tier 0 or Tier 1. Sulfur content of the diesel is assumed to be 0.05 wt%, as would be expected for agricultural equipment in 2007. Additional details are provided in section 3.3.1.3.4of this report. Emissions in grams per liter and grams per hectare for the land preparation unit operation are given in Table 3.6.

Table 3.6. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the land preparation unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from Salassi and Deliberto (2008))

Equipment	Unit Power (HP)	Fuel Use liters/ha	Emissions g/liter					Emissions g/ha				
			VOC	CO	NOX	PM	SO2	VOC	CO	NOX	PM	SO2
Disk	190	36.5	1.71	6.19	21.40	0.97	0.84	63	226	781	36	31
Chisel Plow, 13 ft	190	40.2	1.70	6.16	21.29	0.97	0.83	68	248	855	39	33
Land Plane	150	43.4	1.86	7.16	21.75	1.33	0.83	81	311	943	58	36
3 Row Marker	150	8.6	1.87	7.18	21.81	1.33	0.84	16	62	189	12	7
3 Row Disk Bed (Hipper)	150	43.2	1.87	7.18	21.81	1.33	0.84	81	311	943	58	36
Subsoiler	190	18.6	1.71	6.19	21.37	0.97	0.83	32	115	398	18	16
Chisel Plow, 23 ft	190	5.5	1.70	6.16	21.29	0.97	0.83	9	34	117	5	5
3 Row Plow	190	11.0	1.71	6.19	21.37	0.97	0.83	19	68	234	11	9
Drain Cleaner	75	14.4	2.40	19.64	24.56	2.01	0.93	34	282	352	29	13
Boom Sprayer	150	17.3	1.87	7.18	21.81	1.33	0.84	32	124	377	23	14
TOTAL		238.7						435	1780	5190	287	200

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide (CO_2) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of CO_2 per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg CO_2 per liter of diesel burned. Similarly, the IPCC default value for methane (CH_4) is 4.15 kilograms per terajoule (TJ) and the default value for N_2O is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of CH_4 and N_2O respectively per liter of diesel combusted. Applying these values to the total fuel consumed (238.7 liters per hectare), the operation of diesel powered equipment during the land preparation unit operation results in per hectare emissions of 633 kg of CO_2, 0.0355 kg of CH_4, and 0.244 kg of N_2O.

The application of dolomite on Florida mineral soils contributes to CO_2 emissions. IPCC guidelines (IPCC, 2006b) give an emission factor of 0.13 for dolomite. This is multiplied by the mass of dolomite used and by 44/12 to convert carbon to CO_2 for a total emission rate of

$$0.13 \ * \ 224 \text{ kg/ha} \ * \ 44/12 \ =$$

$$106.8 \text{ kilograms } CO_2 \text{ / hectare} \qquad (3.3)$$

Stools and roots remaining in the ground from the last ratoon crop contain nitrogen. Upon decay, the nitrogen in the residual plant matter is converted through microbial action to dinitrogen (N_2), the form of nitrogen present in the atmosphere. An intermediate product in the reaction is nitrous oxide (N_2O). The amount of nitrogen present in the roots is estimated to be that typical of other plants in the grain family, or 0.9% (IPCC, 2006b, Table 11.2). The roots themselves are estimated to be 10% of the total biomass (Fageria *et al*., 1997) or 14.8% of the harvested cane. The total mass per hectare is thus dependent on the plant density, which is best represented through yield. The mean yield in the US during the past 10 years, weighted by area, is 73,000 kg per hectare, as discussed in greater detail in section 3.1.3.1 of this report. The average total available nitrogen from residual below-ground biomass is, therefore, estimated to be 73,000 * 0.148 * 0.009 or 97.2 kg/ha. The rate of direct N_2O emissions due to root decomposition can be expressed as

$$N_2O_{CR} = N_{b\text{-}g\,BM,\,N} * EF_{N,\,CR} * N_2O_{mw} /(2 * N_{aw}) \tag{3.4}$$

where

N_2O_{CR} is the mass of annual direct nitrous oxide emission per unit area due to crop residues

$N_{b\text{-}g\,BM,\,N}$ the mass of nitrogen in biomass remaining below ground per unit area

$EF_{N,\,CR}$ is the emission factor for crop residue nitrogen, taken to be 0.01 per IPCC guidelines

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Thus direct N_2O emissions from residual root stock are calculated as

$$97.2 \text{ kilograms /hectare-year} * 0.01 * 44/28 = 1.53 \text{ kilograms /hectare-year} \tag{3.5}$$

The land preparation and management unit operation is assumed to apply only to that portion of land designated as fallow. For this study, it is assumed that this is equal to 25% of US land cropped in sugarcane. The total direct material and energy flows for the land preparation unit operation are summarized in Table 3.7.

Table 3.7. Direct material and energy flows for land preparation of US sugarcane cropland

Resource	Calculation	Value	Units
Land [1]	0.25 hectares / 1 hectare-year	0.25	1/yr
Diesel			
Volume	0.25 / year * 238.7 liters / hectare	60	l/ha-yr
Mass [2]	59.7 liters / hectare-year * 0.837 kilograms / liter	50	kg/ha-yr
Energy [2]	59.7 liters / hectare-year * 35.8 megajoules / liter	2136	MJ/ha-yr
Pesticides			
Atrazine	0.25 / year * 0.24 kilograms / hectare	0.060	kg/ha-yr
Pendimethalin	0.25 / year * 0.23 kilograms / hectare	0.058	kg/ha-yr
Glyphosate	0.25 / year * 2.80 kilograms / hectare	0.700	kg/ha-yr
Nutrients			
Dolomite	0.25 / year * 224 kilograms / hectare	56	kg/ha-yr
Slag	0.25 / year * 336 kilograms / hectare	84	kg/ha-yr
Water			
Withdrawn	0.25 / year * 23,288 liters/ hectare	5822	l/ha-yr
Consumed		0	l/ha-yr
Criteria Air Pollutants and Precursors			
VOC	0.25 / year * 0.435 kilograms / hectare	0.11	kg/ha-yr
CO	0.25 / year * 1.780 kilograms / hectare	0.45	kg/ha-yr
NO_X	0.25 / year * 5.190 kilograms / hectare	1.30	kg/ha-yr
PM	0.25 / year * 0.287 kilograms / hectare	0.07	kg/ha-yr
SO_2	0.25 / year * 0.200 kilograms / hectare	0.05	kg/ha-yr
Greenhouse Gases			
CO_2	0.25 / year * (107 + 632) kilograms / hectare	184.75	kg/ha-yr
CH_4	0.25 / year * 0.0356 kilograms / hectare	0.0089	kg/ha-yr
N_2O	0.25 / year * (0.243 + 1.53) kilograms / hectare	0.4433	kg/ha-yr

[1] 35% is organic wetland and 65% is mineral sandy soil, both are located in a warm temperate, moist climate.

[2] US conventional diesel (default inputs to GREET (ANL, 2009)

Density is 3167 grams per gallon, equivalent to 0.837 kg/liter.

Lower heating value (LHV) energy content is 128,450 Btu per gallon, equivalent to 35.8 MJ/liter

3.3.1.2.2 Seeding and planting:

3.3.1.2.2.1 General Description

Sugarcane is planted by laying seed-cane into furrows dug into rows, which in Louisiana are 6 feet (1.8 meters) apart. Seed-cane can consist either of whole stalks or pieces of stalks (billets) cut into approximately 0.4 to 0.6 meter (18-24 inch) lengths, each containing 3 to 4 nodes. While there is interest in mechanical planting systems, hand planting of whole stalks is still the dominant practice in both Florida (Baucum and Rice, 2006) and Louisiana. At any point in time 25% of all US sugarcane cropland is taken to be representative of the amount of land dedicated to planting and to which the seeding and planting unit operation applies.

Planting of whole stalks can result in irregular spacing of emerging plants due to a phenomenon referred to as apical dominance, which is the tendency for the cane to bud near the tip rather than lower on the stalk. One approach to counteract this is to plant stalks in staggered pairs or in pairs that are lain top to bottom to compensate for non-uniform growth along the stalk. Another approach is to apply a heat treatment that entails exposing the seed cane to 50 ºC for 30 minutes (Irvine, 2004), which has the effect of suppressing apical dominance (Ellis and Merry, 2004). Whole stalks are placed lengthwise into shallow furrows 3-8 inches (8-20 cm) deep and covered with soil (Baucum and Rice, 2006). In Louisiana, planting occurs from August through September. During the winter, the cane shoots may be frozen back to the ground, but new sprouts re-emerge in the spring (AMSCL, 2009).

Seed-cane production occurs in a two step process. The general practice is to purchase desired cultivars of cultivated seed-cane. These are planted in with the plant cane crop and harvested specifically as seed-cane for the following year. Approximately 3.2% of the land area of a farm that contains 25% plant-cane (or 0.8% of the total cropland) is planted in cultivated cane (Salassi and Deliberto, 2009). An additional 16.7% of plant cane crop is harvested and re-planted as plant cane crop. Thus a total of 20% of the land that is planted with seed-cane (or 5% of the total cropland) (Figure 3.9) is not used to produce sugar. This is accounted for by burdening the seeding and planting operation by a factor of 1.2. In the absence of data specific to seed-cane cultivation, stage one of the life cycle inventory for sugarcane ethanol could be burdened by a factor of 1.008 to account for this activity. However, given that the amount of error introduced in estimating land allocation is likely larger than 0.8%, this particular contribution is ignored in this analysis.

3.3.1.2.2.2 Activities

The first activity in the planting operation is to acquire seed-cane to plant. Cultivated seed-cane activities and its associated flows are estimated to be a small fraction (0.8%) of the entire first stage in the sugarcane from ethanol life cycle and are not specifically accounted for. Farm-grown seed cane activities are assumed to affect 20% of the area to be planted or 5% of sugarcane cropland. This includes separate harvesting of the cane (as it is not burned) and commercial heat treating. The total charge for the heat treatment itself is $15 per acre for a 2 hour process. As this includes labor, it is assumed that the energy cost is negligible. However, the cane does need to be harvested, loaded, and unloaded using diesel powered equipment.

Immediately before planting, fertilizer is applied and worked into the upper surface of the soil; beds are reformed as necessary. Planting furrows are made in the raised rows using an opener. After stalks are placed in the furrows they are covered and rolled to ensure good contact between the soil and the seed-cane. Weed removal is accomplished both mechanically and through application of herbicide(s) using a boom sprayer. The drain cleaning operation, which uses a jet of water, clears the drains of debris that may have been dislodged during the planting activities.

A list of the equipment, which reflects the activities performed during seeding and planting in Louisiana, is presented in Table 3.8. This is taken to be representative of sugarcane grown in the US. The area passes per year (times over) reflects the number of times the activity is repeated during the planting operation. There are no multiple passes within a single performance of the activity. The activities associated with harvesting and treating seed-cane are assumed to affect only 20% of the plant cane area. For the interested reader, the specific order and the month in which each activity is performed is available for Louisiana (Salassi and Deliberto, 2008; 2009).

Table 3.8. Equipment used in the seeding and planting unit operation for sugarcane (based on Salassi and Deliberto, 2008)

Equipment	Size/ Unit	Unit Power (HP)	Fuel Use Rate		Performance Rate		Times Over	Fuel Consumption	
			gal/hr	liters/hr	hr/ac	hr/ha		gal/acre	liters/ha
2 Row Harvester	12 ft		8.00	30.3	0.39	0.96	0.2	0.6	5.8
2 Row Loader	12 ft		7.00	26.5	0.30	0.74	0.4	0.8	7.9
Rototiller	18 ft	190	9.81	37.1	0.22	0.54	1	2.1	20.1
3 Row Disk Bed (Hipper)	18 ft	150	7.70	29.2	0.12	0.30	2	1.8	17.3
3 Row Opener	18 ft	150	7.70	29.2	0.12	0.30	1	0.9	8.6
Cane Planters Aid	6 ft	150	7.72	29.2	1.00	2.47	1	7.7	72.2
3 Row Cover, 2WD	18 ft	170	7.73	29.3	0.12	0.30	1	0.9	8.7
Flat Roller	18 ft	150	7.71	29.2	0.19	0.47	1	1.5	13.7
Drain Cleaner	6 ft	75	3.84	14.5	0.08	0.20	3.2	1.0	9.2
Boom Sprayer	16 ft	150	7.70	29.2	0.12	0.30	1	0.9	8.6
TOTAL								18.4	172.1

3.3.1.2.2.3 Direct Material and Energy Flows

The direct material and energy flows associated with the seeding and planting unit operation include diesel fuel to power the equipment, listed in Table 3.8, nutrients, herbicides, water used in drain cleaning, and emissions to air. The planting operation is not called out separately for either Florida or Texas and fertilizer and pesticide applications are lumped in with tending of the plant cane crop. As the area planted is assumed to be identical to the area of plant cane crop tended, and because the amounts applied in at planting are relatively small, all of these flows are combined within the tending operation.

The quantity of water used for drain cleaning is unknown. An estimate of 4658 liters/hectare-cleaning event is made in Equation 3.1. The seeding and planting unit operation requires 3.2 drain cleaning events and the water withdrawn for this activity is estimated as:

$$3.2 \text{ cleaning events } * \text{ 4658 liters/ hectare -cleaning event } = 14{,}904 \text{ liters/ hectare} \quad (3.6)$$

This water is assumed to be withdrawn and discharged to surface water with little lost to evaporation. The quality of the water would be degraded by the presence of suspended soils as well as chemical run-off (pesticides and fertilizers) from the surrounding cropland.

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Table 3.8 are calculated from the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The equipment population is based on lifetime expectancies for the equipment (Salassi and Deliberto,

2008) with most of the equipment at or near the median age. As most of the equipment is an implement pulled by a tractor, which is estimated to have a lifetime of 8 years, most of the equipment is assumed to be model years 2003 to 2005 in 2007 and representative of Tier 2 technology; lower power equipment (75 horsepower or less) is dominated by Tier 0 or Tier 1 technology (EPA, 2004). The sulfur content of the diesel is assumed to be 0.05 wt%. Additional details are provided in section 3.3.1.3.4 of this report. Emissions in grams per liter and grams per hectare for the land preparation unit operation are given in Table 3.9.

Table 3.9. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the planting unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from Salassi and Deliberto (2008))

Equipment	Unit Power (HP)	Fuel Use liters/ha	Emissions g/liter					Emissions g/ha				
			VOC	CO	NOX	PM	SO2	VOC	CO	NOX	PM	SO2
2 Row Harvester *	175	5.8	2.32	8.87	28.52	1.79	0.94	13	52	166	10	5
2 Row Loader *	100	7.9	1.69	14.35	17.60	1.34	0.68	13	113	138	11	5
Rototiller	190	20.1	1.70	6.16	21.29	0.97	0.83	34	124	428	19	17
3 Row Disk Bed (Hipper)	150	17.3	1.87	7.18	21.81	1.33	0.84	32	124	377	23	14
3 Row Opener	150	8.6	1.87	7.18	21.81	1.33	0.84	16	62	189	12	7
Cane Planters Aid	150	72.2	1.86	7.17	21.76	1.33	0.83	135	518	1571	96	60
3 Row Cover, 2WD	170	8.7	2.11	8.11	24.63	1.50	0.94	18	70	214	13	8
Flat Roller	150	13.7	1.87	7.17	21.78	1.33	0.83	26	98	299	18	11
Drain Cleaner	75	9.2	2.40	19.64	24.56	2.01	0.93	22	180	226	18	9
Boom Sprayer	150	8.6	1.87	7.18	21.81	1.33	0.84	16	62	189	12	7
TOTAL		172.1						326	1403	3795	232	145

* Unit power estimated from fuel use rate

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide (CO_2) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of CO_2 per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg CO_2 per liter of diesel burned. Similarly, the IPCC default value for methane (CH_4) is 4.15 kilograms per terajoule (TJ) and the default value for N_2O is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of CH_4 and N_2O respectively per liter of diesel combusted. Applying these values to the total fuel consumed (172.1 liters per hectare), the operation of diesel powered equipment during the planting unit operation results in per hectare emissions of 457 kg of CO_2, 0.0256 kg of CH_4, and 0.176 kg of N_2O.

The seeding and planting unit operation is applied only to that portion of land designated as plant cane crop. For this study, it is assumed that this is equal to 25% of US land cropped in sugarcane. In addition, because 20% of the crop is used for propagation, a factor of 1.2 is used such that the land allocation is 30% rather than 25%. The total direct material and energy flows for this unit operation are summarized in Table 3.10:

Table 3.10. Direct material and energy flows for planting of US sugarcane cropland. Fertilizer and pesticide material flows are included with tending of the plant cane crop.

Resource	Calculation	Value	Units
Land [1]	0.30 hectares / 1 hectare-year	0.3	1/yr
Diesel			
Volume	0.30 / year * 172.1 liters / hectare	52	l/ha-yr
Mass [2]	51.6 liters / hectare-year * 0.837 kilograms / liter	43	kg/ha-yr
Energy [2]	51.6 liters / hectare-year * 35.8 megajoules / liter	1848	MJ/ha-yr
Water			
Withdrawn	0.30 / year * 14904 liters/ hectare	4,471	l/ha-yr
Consumed		0	l/ha-yr
Criteria Air Pollutants and Precursors			
VOC	0.30 / year * 0.326 kilograms / hectare	0.10	kg/ha-yr
CO	0.30 / year * 1.403 kilograms / hectare	0.42	kg/ha-yr
NO_X	0.30 / year * 3.795 kilograms / hectare	1.14	kg/ha-yr
PM	0.30 / year * 0.232 kilograms / hectare	0.07	kg/ha-yr
SO_2	0.30 / year * 0.145 kilograms / hectare	0.04	kg/ha-yr
Greenhouse Gases			
CO_2	0.30 / year * 456 kilograms / hectare	136.84	kg/ha-yr
CH_4	0.30 / year * 0.0256 kilograms / hectare	0.0077	kg/ha-yr
N_2O	0.30 / year * 0.176 kilograms / hectare	0.0527	kg/ha-yr

[1] 35% is organic wetland and 65% is mineral sandy soil, both are located in a warm temperate, moist climate.

[2] US conventional diesel (default inputs to GREET (ANL, 2009)

Density is 3167 grams per gallon, equivalent to 0.837 kg/liter.

Lower heating value (LHV) energy content is 128,450 Btu per gallon, equivalent to 35.8 MJ/liter

3.3.1.2.3 Tending

3.3.1.2.3.1 General Description

The primary functions of the tending unit operation are to control pests (insects and weeds), to add nutrients to the soil, and to control the water supply. This is done through secondary tillage (cultivation, or mechanical manipulation of soil and plants), dry substance applications, and/or wet substance applications (including irrigation).

The tending activities for plant cane crops differ only slightly from those used for subsequent ratoon (stubble) crops, therefore they are discussed collectively with differences noted as appropriate. In addition, because 20% of the plant cane crop is used for propagation rather than harvested for sugar, the land allocation will differ. Plant cane crops are assumed to require 25% of sugarcane cropland with 20% used for propagation; thus, the effective land occupation is 30%. The total amount of cropland occupied by ratoon crops is assumed to be 50% regardless of the number of ratoon crops (total number of times the original plant is allowed to re-grow). In the case where there are 3 or more ratoon crops, it is expected that the 50% land area would be subdivided into progressively smaller land allocations, but with no change in the total allotment for ratoon crops. Consequently, this distinction has no effect on determining the material and energy balances for the tending operation in this analysis, since it is based on a per unit area and tending practices are averaged for all ratoon crops. The annual US representative portion of land affected by the tending unit operation is taken to be 80% (1.20*25% (30%) for plant cane crops plus 50% for all ratoon crops).

3.3.1.2.3.2 Activities

The first activity performed on both plant cane and ratoon crop is off-barring, which occurs as new plants begin to emerge. Off-barring draws the soil away from the plants in order to remove weeds. After fertilizer is applied, beds are reformed. Multiple applications of herbicide are made during the first few months of growth as competition with weeds can reduce sugarcane yields. Bedders (also referred to as hippers) are used concurrently to maintain and rebuild soil depth around the young plants. After three to four months of growth, the sugarcane plants are large enough that they prevent sunlight from reaching the soil, thus making it difficult for weeds to grow. It also becomes impractical to perform ground-level cultivation or pesticide application. Insecticide is sprayed from the air during the last few months before harvest. The independent farmer pays a service to perform this activity in what is known as a custom operation. The Louisiana costs and returns document estimates this at $3.00 per acre (excluding the cost of the chemicals). As this includes labor and use of the plane, it is assumed that the fuel use is very small relative to other operations and can be ignored in this analysis.

A list of the equipment, which reflects the activities performed during tending of both plant cane and ratoon (stubble) crops in Louisiana, is presented in Table 3.11. This is taken to be representative of sugarcane grown in the US. The area passes per year reflects the number of times the activity is repeated during the planting operation. Almost none of the operations require multiple passes within a single performance of the activity. The primary difference in the use of equipment in tending the plant cane crop and the subsequent ratoon crops is the number of times the activity is repeated within the season. For the interested reader, the specific order and the month in which each activity is performed is available for Louisiana (Salassi and Deliberto, 2008; 2009).

Table 3.11. Equipment used in the tending unit operation for sugarcane (based on Salassi and Deliberto, 2008)

		Power	Fuel Use Rate		Performance Rate		Times Over		Fuel Consumption			
									Plant Cane Crop		Ratoon Crop	
Equipment	Size	HP	gal/ hr	liters/ hr	hr/ acre	hr/ ha	Plant Cane	Ratoon Crop	gal/ acre	liters/ ha	gal/ acre	liters/ ha
4 Row Disk Bed (Hipper)	38"	150	7.72	29.22	0.15	0.36	1	0	1.1	10.6	0.0	0.0
3 Row Disk Bed (Hipper)	18 ft	150	7.70	29.15	0.12	0.30	5	4	4.6	43.2	3.7	34.6
3 Row Off-bar	18 ft	150	7.70	29.15	0.12	0.30	1	4	0.9	8.6	3.7	34.6
Drain Cleaner	6 ft	75	3.84	14.52	0.08	0.20	5	5	1.5	14.4	1.5	14.4
Boom Sprayer	16 ft	150	7.70	29.15	0.12	0.30	4	5	3.7	34.6	4.6	43.2
Fertilizer Lq App, 3 Row	18 ft	150	7.72	29.22	0.13	0.32	1	1	1.0	9.4	1.0	9.4
Fertilizer Dry Sling App	42 ft	150	7.83	29.65	0.06	0.15	1	1	0.5	4.3	0.5	4.3
TOTAL									13.4	125.1	15.0	140.4

According to the 2007 census (USDA, 2009a) only one sugarcane farm (of undisclosed area) in Louisiana practiced irrigation. In contrast, all sugarcane cropland in Florida and most of that in Texas (86% of land used to grow cane for sugar and 90% of that used for seed-cane production) is irrigated. The representative value for the proportion of US sugarcane cropland irrigated is taken to be 55%; however, it is likely that any expansion of sugarcane cropland outside existing areas would be irrigated (Shaffer *et al*., 2009). Furthermore, if Louisiana farmers were incentivized to increase yields, the likely first step would be to begin irrigation. Thus, 55% of sugarcane cropland irrigated is probably a lower bound.

Texas uses furrow irrigation, where water is supplied to the plants through a system of open ditches. Florida sugarcane growers irrigate their fields using subirrigation, also known as seepage irrigation. In this process, water is supplied to the root zone of the cane by controlling an artificial or "perched" water table above an impermeable soil layer. Water is pumped into the fields when needed and removed from the fields through open drainage ditches when the water table is too high. While there is some evidence that a suppressed water table can actually increase yield, the minimum distance to the top of the water table is generally held to be 30 inches (75 cm) below the surface of the soil. This system of subirrigation and drainage requires large pump capacities, adequate area-wide distribution canals and reservoirs, and extremely flat land surfaces that are generated using laser guided land grading systems (Lang *et al*., 2002).

Although sugarcane requires significant amounts of water in order to thrive, too much water for extended periods of time can severely damage the plants. During a heavy rainfall, the root zone can fill rapidly and massive crop losses may result if water is not removed quickly (Lang *et al*., 2002). Consequently, in all three states, sugarcane fields are drained using a system of open ditches. In Florida, the use of perched water tables and extremely low relief requires that the water be removed by pumping. Louisiana sugarcane is planted on raised rows, which allows water to drain by gravitational forces.

Field flooding of fallow fields is practiced in Florida for a variety of reasons including disease, weed, and insect control, improvement of the soil properties, and the reduction of soil subsidence (Lang *et al*., 2002). No mention of this practice was noted for Texas or Louisiana. Temporary earth dikes are built around the area to be flooded and water is supplied using temporary diesel powered pumps mounted on trailers. As this occurs primarily during the summer when rainfall is ample, the main resource requirement is the fuel used to run the pumps. Seepage and loss through solution holes in underlying limestone requires pumping from ditches back into the fields to maintain the desired water levels. Flooding occurs over two 3 week periods. Depths of flooding are generally 4 to 16 inches above the ground surface (Lang *et al*., 2002).

3.3.1.2.3.3 Direct Material and Energy Flows

The direct material and energy flows associated with the tending unit operation include diesel fuel to power the equipment, listed in Table 3.11, as well as additional energy to power irrigation and drainage pumps. Nutrients and pesticides are applied in both dry and liquid form. Water is added through irrigation and removed through drainage and through the plants. Emissions to air are associated primarily with operation of diesel equipment and application of fertilizer.

3.3.1.2.3.3.1 Water

Most irrigation in Texas occurs from the beginning of April through the end of September, when temperatures are high and sugarcane plants are rapidly increasing in size. After September, water stress is desirable, as it promotes sugar accumulation in the stalks (Wiedenfled, 2004). The reported amount of water used to irrigate Texas sugarcane is 5 acre-feet per acre for plant cane crops and 4.5 acre-feet per acre for ratoon crops (TAES, 2007). An acre-foot is the volume of water that would cover an acre to the depth of one foot and is equal to 325,851 gallons (1,233,480 liters) of water. Thus plant cane crops in Texas require irrigation at the rate of 1.63 million gallons per acre-year (15.2 x 10^6 liters/ha-yr) and ratoon crops require 1.47 million gallons per acre-year (13.7 x 10^6 liters/ha-yr).

The volume of water withdrawn for irrigation per unit area per year in Texas is calculated as

$$V_{\text{withdrawn}} = fraction_{\text{pc}} * V_{\text{irr, pc}} + fraction_{\text{rat}} * V_{\text{irr, rat}} \qquad (3.7)$$

where

$V_{\text{withdrawn}}$ is the volume of water withdrawn

$fraction_{\text{pc}}$ is the fraction of land that contains plant cane crop, burdened for seed-cane

$V_{\text{irr, pc}}$ is the volume of water used to irrigate the plant cane crop

$fraction_{\text{rat}}$ is the fraction of land that contains ratoon crop

$V_{\text{irr, rat}}$ is the volume of water used to irrigate the ratoon crop

Total water withdrawals for irrigation of Texas sugarcane are estimated to be

$$0.30 * 15.2 \times 10^6 \text{ liters/ha-yr} * 1.0 + 0.5 \text{ ac/ yr} * 13.7 \times 10^6 \text{ liters/ha-yr} * 1.0 =$$
$$11.41 \times 10^6 \text{ liters / hectare-year } (1.22 \times 10^6 \text{ gal/acre-yr}) \qquad (3.8)$$

In furrow irrigation, water is not preferentially applied to the plants; instead the entire field is irrigated and water is (at least ideally) applied uniformly. An application of 5 acre-feet is equivalent to an irrigation depth of 5 ft (1524 mm); similarly 4.5 acre-feet is equivalent to 1372 mm. However, furrow irrigation is generally held to be at best about 70% efficient, thus the actual irrigation depth supplied is equivalent to approximately 960 to 1070 mm. An additional 600 mm of water is provided annually by rainfall for an estimated annual crop evapotranspiration value (ET_C, equal to rainfall plus effective irrigation), of 1560 to 1670 mm. Weighting these respectively by the area irrigated for ratoon crops (50%) and plant cane (30%, including the area burdened for seed-cane production), and assuming the fallow plots are not irrigated, gives an annual water depth requirement of:

$$0.5 * 1560 + 0.3 * 1670 + 0.25 * 0 =$$

$$1280 \text{ millimeters/year} \qquad (3.9)$$

This is slightly higher than the empirical ET_C values of 805 to 1188 determined by Wiedenfled (2004), but may reflect differences between a commercial field and an experimental plot. Using 1280 mm per year as the amount lost to the atmosphere, the total volume of water consumed for Texas sugarcane is equal to 1.28 meter * 10,000 m2 or 10,000 m3 per hectare-year, which is equal to 12.8 x 10^6 liters per hectare-year (1.37 x 10^6 gallons per acre-year).

Recommended irrigation rates for Florida sugarcane were not found. The US Geological Survey reports that in 2005, a total of 875 x 10^6 gallons per day (1.21 x 10^{12} liters per year) were withdrawn for sugarcane agriculture (Marella, 2008). During 2005, Florida had 406,000 acres (164,000 ha) planted in sugarcane (ERS, 2009a). From this data, water withdrawals for irrigation of Florida sugarcane are determined to be 7.36 x 10^6 liters per hectare-year (0.787 x 10^6 gallons per acre-year).

Lang and others (2002) estimate that the crop evapotranspiration value (ET_C) for Florida sugarcane is equal to 42 to 45 inches per year (1067 to 1143 mm); taking the average gives 1.11 m per year. In succession crop planting, this would affect all land area and the total volume of water lost due to crop evapotranspiration is estimated to be 11.1 x 10^6 liters per hectare-year (1.03 x 10^6 gallons per acre-year). In rotation crop planting, sugarcane evapotranspiration would affect only 75% of the acreage, however, there also would be evaporation from the fallow areas during periods of flooding. Evaporation pan data were taken from the South Florida Water Management District database (SFWMD, 2009) for the months June through September for the years 2007, 2008, and 2009. The average amount of evaporation for the Lake Okeechobee Basin during these time periods is 0.163 inches (4.14 mm) per day. If fields are flooded for two 3-week periods, or 42 days during the summer, this is equal to 174 mm year or 1.74 x 10^6 liters per hectare-year, affecting 25% of the total area.

Total water consumption for Florida sugarcane grown using rotational cropping is calculated as:

$$0.75 * 11.1 \times 10^6 \text{ liters / hectare-year} + 0.25 * 1.74 \times 10^6 \text{ liters / hectare-year} =$$

$$8.76 \times 10^6 \text{ liters / hectare-year } (0.96 \times 10^6 \text{ gallons / acre-year}) \qquad (3.10)$$

All of the Florida sugarcane produced on mineral soils (20% of Florida sugarcane cropland) and half of that produced on organic soils are grown in rotation, for a total of 60% of sugarcane cropland. The remaining 40% is grown in succession. Thus total volume of water consumed for Florida sugarcane is equal to:

$$0.60 \ * \ 8.76 \times 10^6 \text{ liters / hectare-year} + 0.40 \ * \ 11.1 \times 10^6 \text{ liters per hectare-year} =$$

$$9.68 \times 10^6 \text{ liters per hectare-year } (1.03 \times 10^6 \text{ gallons / acre-year}) \qquad (3.11)$$

Louisiana sugarcane cropland is essentially all rainfed, and total withdrawals for irrigation are assumed to be zero. The crop evapotranspiration value (ET_C) for Louisiana sugarcane was not specifically found. Three-quarters of Louisiana sugarcane is grown in nine parishes. Average rainfall, weighted by area planted in sugarcane, in these counties is 63 inches (1600 mm) per year (WorldClimate, 2008), equivalent to 5.25 acre-feet. The total effective area of plant growth is taken to be 1.2*25% (30%) for plant cane and 50% for ratoon or 80% total land area. Thus the maximum input to the plants from rainfall is 5.25 divided by 80% which is equal to 6.56 acre-feet. However, given that some of the precipitation will be lost through drainage, the number will be less than this amount. At 90% utilization, consumption (ET_C) is estimated to be 5.91 x 10^6 liters per hectare-year. Given that Louisiana has higher humidity, lower temperatures, a shorter growing season, and lower sugarcane yields than Texas or Florida, this number, while low, seems reasonable.

The quantity of water used for drain cleaning is unknown. An estimate of 4658 liters/hectare-cleaning event is made in Equation 3.1. The tending unit operation requires 5 drain cleaning events for both plant cane and ratoon crops and the water withdrawn for this activity is estimated as:

$$5 \text{ cleaning events } \ * \ 4658 \text{ liters/ hectare -cleaning event} =$$

$$23{,}288 \text{ liters/ hectare} \qquad (3.12)$$

This water is assumed to be withdrawn and discharged to surface water with little lost to evaporation. The quality of the water would be degraded by the presence of suspended soils as well as chemical run-off (pesticides and fertilizers) from the surrounding cropland. A summary of water used in the tending unit operation is given in Table 3.12.

Table 3.12. Water used in the tending unit operation for sugarcane

State / Activity	Withdrawals		Consumption		% US sugarcane
	10^6 liters/ha-yr	10^6 gal/ac-yr	10^6 liters/ha-yr	10^6 gal/ac-yr	
Florida / Irrigation	7.36	0.79	9.68	1.03	45%
Louisiana / Irrigation	0	0	5.91	0.63	45%
Texas / Irrigation	11.41	1.22	12.80	1.37	10%
All / Drain Cleaning	0.02	0.02	0.02	0.02	100%
US weighted average	4.47	0.50	8.32	0.91	

3.3.1.2.3.3.2 Energy for Irrigation and Pumping

The Texas costs and returns budget estimates a cost of $20 per acre-foot of water for irrigation (TAES, 2007). It is assumed that the bulk of the cost is due to the energy required to deliver the water using an electric pump. At $0.10 per kilowatt-hr, 200 kWh (720 MJ) is required to pump one acre-foot. Given that one-acre foot is equal to 1.23 x 10^6 liters, this equates to 162 kWh per 10^6 liters. Consequently, the 11.41 x 10^6 liters of water per hectare-year withdrawn in Texas for sugarcane irrigation is estimated to require 1848 kWh (6654 MJ) of electricity per hectare-year. Weighting this value for 10% of US crops gives 185 kWh (665 MJ) of electricity per hectare-year.

The Florida costs and returns budget (Roka *et al*., (2009) allocates $20 per acre for pumping and water control. It is assumed that diesel pumps are used, as is common in citrus irrigation. If the cost of diesel is $2.50 per gallon, then this activity uses 8 gallons of diesel per acre (74.8 liters/ha). At 7.36 x 10^6 liters of water per hectare-year, the unit amount of diesel required for irrigation is 10.16 liters of diesel per 10^6 liters of water. The lower heating value of diesel is 35.8 MJ/liter, yielding 2679 MJ/hectare-year as the energy costs for irrigation and pumping of Florida cane fields. Weighting this value for 45% of US crops gives 3.6 gallons of diesel per acre (33.7 liters/ha).

In summary, Louisiana does not irrigate or use assisted drainage, therefore its energy costs for water management are zero; Texas sugarcane is estimated to require 1727 kWh (6216 MJ) of electricity per hectare- year for irrigation; and Florida is assumed to use 2679 MJ/hectare-year in the form of diesel for both irrigation and drainage. The US representative number for direct energy used for water management in sugarcane tending, taken as 45% of that used in Florida, 45% of Louisiana, and 10% of Texas, is calculated as

$$0.45 * 2679 \text{ MJ/ha-yr} + 0.45 * 0.0 \text{ MJ/ha-yr} + .10 * 6654 \text{ MJ/ ha-yr} =$$

$$1871 \text{ MJ/hectare-yr (757 MJ/acre-year)}, \qquad (3.13)$$

with roughly one third (665 MJ) supplied by electricity.

3.3.1.2.3.3.3 Nutrients

The amount of nutrients applied to sugarcane fields varies significantly by location and somewhat by whether the plants are plant cane or ratoon crops. Louisiana cost and return documents differentiate between first ratoon crops and second (or older) ratoon crops. As the other two states do not account for difference in applications at this level, the Louisiana numbers are averaged to give single values for ratoon crops. There are also some differences between the projected values for 2008 and 2009 in Louisiana. A slight preference is given to the more recent numbers using a weighted value basis of 45% for 2008 and 55% for 2009.

Based on cost and return documents, Louisiana sugarcane requires the most nitrogen (N), followed by Florida ratoon crops grown on mineral soil. However, Rice and others (2006) recommend much higher amounts of nitrogen (180 lb/ac-yr) than that reported from survey data by Roka and others (2009). Nitrogen is not recommended for Florida sugarcane grown in the "muck" soils of the Everglades, as there is an adequate supply of organic nitrogen available (Gilbert and Rice, 2006). While the type of nitrogen used on Florida mineral soils is not noted; it is specified as being in dry form with a cost of $.60/lb, suggesting that it is anhydrous ammonia. Louisiana cost and return documents specify the application of nitrogen fertilizer in liquid form; however, it is priced as $0.53 /lb (Salassi and Deliberto, 2008; 2009) suggesting that it is purchased dry in the form of anhydrous ammonia and subsequently liquefied. It is assumed that the amount of nitrogen reported in the cost and returns documents is as units of nitrogen unless otherwise specified.

Texas plant cane crops receive both nitrogen (N) and phosphate (P_2O_5) in the form of ammonium phosphate. Potassium oxide (K_2O, also referred to as "potash" fertilizer) is not used on either plant cane or ratoon crops. The only fertilizer added to ratoon crops in Texas is nitrogen in the form of UAN (32% N), which consists of 45% ammonium nitrate and 35% urea. There are no applications of either phosphate (P_2O_5) or potassium oxide (K_2O) made on Texas ratoon crops (TAES, 2007).

The use of micronutrients for Florida sugarcane grown on mineral soils is noted, but the specific makeup is not mentioned in the costs and returns document (Roka *et al*., 2009). Muck soils are known to be deficient in boron (B), copper (Cu), iron (Fe), manganese (Mn), silicon (Si), and zinc (Zn) (Gilbert and Rice, 2006), but the authors do not recommend a specific treatment. Texas ratoon crops are treated with one application of foliar iron sulfate, but the amount applied is not given.

Nutrients applied to plant cane crops are listed in Table 3.13; those applied to ratoon crops are presented in Table 3.14.

Table 3.13. Nutrients applied to plant cane crops during the tending and planting unit operations.

Nutrient	Product Use Rate		Reference	% of US sugarcane cropland	Weighted Mean	
	lb/ acre	kg/ ha			lbs/ acre	kg/ ha
Nitrogen (N)	104	116.6	1	45%	53.80	60.30
	50	56.0	2	10%		
	20	22.4	3	10%		
Phosphate (P_2O_5)	45	50.4	1	45%	54.05	60.58
	60	67.3	2	45%		
	68	76.2	3	10%		
Potash (K_2O)	125	140.1	1	45%	92.25	103.40
	80	89.7	2	45%		
	0	0.0	3	10%		
Micronutrients	20	22.4	2	10%	2.00	2.24

1 Louisiana, 2008 and 2009 projected (Salassi and Deliberto, 2008; 2009), with 55% wt given to 2009 values

2 Florida Mineral Soils 2007-2008 (Roka *et al*., 2009)

3 Texas 2008 projected, in form of 10-34-0 ammonium phosphate (TAES, 2007)

Table 3.14. Nutrients applied to ratoon crops during the tending unit operation

Nutrient	Product Use Rate		Reference	% of US sugarcane cropland	Weighted Mean	
	lb/ acre	kg/ ha			lbs/ acre	kg/ ha
Nitrogen (N)	121	135.3	1	45%	68.94	77.27
	50	56.0	2	10%		
	96	107.6	3	10%		
Phosphate (P_2O_5)	42	47.4	1	45%	46.01	51.57
	60	67.3	2	45%		
	0	0.0	3	10%		
Potash (K_2O)	109	122.2	1	45%	85.05	95.33
	80	89.7	2	45%		
	0	0.0	3	10%		
Sulfur	24	26.9	1	45%	10.80	12.11

1 Louisiana, 2008 and 2009 projected (Salassi and Deliberto, 2008; 2009), with 55% wt given to 2009 values

2 Florida Mineral Soils 2007-2008 (Roka *et al*., 2009)

3 Texas 2008 projected (TAES, 2007); in the form of UAN (32% N)

3.3.1.2.3.3.4 Herbicides

There are seven different herbicides reported as being used on both plant cane and ratoon crops in the three different states. These include 2,4-D amine, dicamba, asulam, atrazine, metribuzin, pendimethalin, and trifluralin. In addition, glyphosate is used on ratoon crops both to control weeds and as a "ripener" on the last ratoon crop. This latter practice is noted in Florida and Louisiana but not in Texas. A surfactant may be added to certain herbicides as a dispersion aid.

Activities and flows in Texas are weighted at 10% (the approximate percent of all US sugarcane land). Practices for Louisiana are weighted at 45% of the US; however, for situations where there is a discrepancy between 2008 and 2009 numbers, slightly more weight is given to the more recent values (0.45 and 0.55 for 2008 and 2009, respectively). Because ripeners are used only on the last ratoon crop, the land area affected is assumed slightly less than half that for all ratoon crops in each state (20% rather than 45% for both Florida and Louisiana). The data for Florida sugarcane grown on mineral soil is assumed applicable to that grown on organic soils and is weighted at 45% for the US. Estimated use of herbicides during the tending unit operation is reported from four different sources (Tables 3.15 and 3.16).

Table 3.15. Herbicides applied to plant cane crops during the tending and planting unit operations.

Trade Name	Common Chemical Name	Active Ingredient (a.i.)	Product Use Rate		Active Ingredient Use Rate		Reference	% of US cane	Weighted Mean	
		lb/gal [4]	gal/ acre	liters/ ha	lbs/ acre	kg/ ha			lbs/ acre	kg/ ha
2,4-D Amine 4	2,4-D amine	3.8	0.5	4.7	1.9	2.1	2	45%	1.39	1.56
Weedmaster		2.87	0.4	3.9	1.2	1.3	1	45%		
	dicamba	1.5	0.4	3.9	0.6	0.7	1	45%	0.28	0.31
Asulox/Asulam	asulam	3.34	0.5	4.7	1.7	1.9	1	45%	2.25	2.53
			1.0	9.4	3.3	3.7	2	45%		
Atrazine 4L	atrazine	4	0.5	4.7	2.0	2.2	1	45%	3.30	3.70
					4.0	4.5	2	45%		
			1.5	14.0	6.0	6.7	3	10%		
Sencor DF	metribuzin				2.4	2.6	1	45%	1.06	1.19
Prowl 3.3 EC	pendimethalin	3.3	1.1	10.7	3.8	4.2	1	45%	3.60	4.04
			1.0	9.4	3.3	3.7	2	45%		
			1.3	11.7	4.1	4.6	3	10%		
Treflan HFP	trifluralin	4	0.5	4.7	2.0	2.2	1	45%	0.90	1.01
unspecified *	surfactant		0.4	3.7	2.7	3.0	1	45%	1.20	1.35

1 Louisiana, 2008 and 2009 projected (Salassi and Deliberto, 2008; 2009), with 55% wt given to 2009

2 Florida Mineral Soils 2007-2008 (Roka *et al*., 2009); assume similar for organic soils

3 Texas 2008 projected (TAES, 2007)

[4] MWSC, 2009

* Assume a density of 0.8 kg/liter

Table 3.16. Herbicides applied to ratoon crops during the tending unit operation

Trade Name	Common Chemical Name	Active Ingredient (a.i.)	Product Use Rate		Active Ingredient Use Rate		Reference	% of US cane	Weighted Mean	
		lb/gal [4]	gal/ acre	liters/ ha	lbs/ acre	kg/ ha			lbs/ acre	kg/ ha
Weedmaster	2,4-D amine	2.87	0.5	4.9	1.5	1.7	1	45%	0.68	0.76
	dicamba	1.5	0.5	4.9	0.8	0.9	1	45%	0.35	0.40
Asulox/Asulam	asulam	3.34	0.7	6.8	2.4	2.7	1	45%	2.59	2.91
			1.0	9.4	3.3	3.7	2	45%		
Atrazine 4L	atrazine	4	0.5	4.7	2.0	2.2	1	45%	3.30	3.70
					4.0	4.5	2	45%		
			1.5	14.0	6.0	6.7	3	10%		
Roundup	glyphosate	5	0.1	0.9	0.5	0.6	3	10%	0.23	0.25
Polado or unnamed "ripener" **					0.5	0.6	1	20%		
					0.4	0.4	2	20%		
Prowl 3.3 EC	pendimethalin	3.3	0.2	2.3	0.8	0.9	1	45%	2.27	2.54
			1.0	9.4	3.3	3.7	2	45%		
			1.3	11.7	4.1	4.6	3	10%		
Sencor DF	metribuzin				0.9	1.0	1	45%	0.39	0.44
Treflan HFP	trifluralin	4	0.5	4.7	2.0	2.2	1	45%	0.90	1.01
unspecified *	surfactant		0.5	4.7	3.3	3.7	1	45%	3.12	3.50
			0.5	5.1	3.6	4.0	2	45%		

1 Louisiana, 2008 and 2009 projected (Salassi and Deliberto, 2008; 2009), with 55% wt given to 2009

2 Florida Mineral Soils 2007-2008 (Roka *et al*., 2009); assume similar for organic soils

3 Texas 2008 projected (TAES, 2007)

[4] MWSC, 2009

* Assume a density of 0.8 kg/liter

** Only used on last ratoon crop so area affected is assumed at less than half the total ratoon area

3.3.1.2.3.3.5 Insecticides

Sugarcane is relatively resistant to pests. The key problem insects are the sugarcane borer, white grubs, wireworms, yellow sugarcane aphid, and the lesser cornstalk borer for crops grown on sandy soil (IPM, 2008). No insecticides or additional chemicals are reported for sugarcane grown in Texas. In Louisiana, the insecticide Confirm 2F, is applied by air to both plant cane and ratoon crops at the rate of 16 fluid ounces or one pint per acre-year. The active ingredient is tebufenozide present in amounts of 2 lb per gallon or 0.5 lb per pint. It is used to combat the sugarcane borer (*Diatrea saccharalis*) and the Mexican rice borer (*Eoreuma loftini*). Florida plant cane grown on mineral soils is treated with 15 pounds per acre-year of Thimet. The active ingredient is phorate, which is present as 20 wt% of the product. This systemic organophosphate is particularly effective against aphids and wireworms. It is assumed that the same insecticide is used on all Florida sugarcane. Multiplying each of these by 45%, as the portion of US sugarcane affected gives representative US values of 0.45 lbs/acre (0.50 kg/hectare) of tebufenozide and 6.75 lbs/acre (7.6 kg/hectare) of phorate on plant cane only.

3.3.1.2.3.3.6 Emissions to Air

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Table 3.11 are calculated from the formulas and emission factors used in the US Environmental Protection Agency (EPA) NONROAD model (EPA, 2004; EPA, EPA, 2005). The equipment population is based on lifetime expectancies for the equipment (Salassi and Deliberto, 2008) with most of the equipment at or near the median age. The pieces of equipment are primarily implements pulled by a tractor, which is estimated to have a lifetime of 8 years. Therefore, in 2007, most of the equipment is assumed to be model years 2003 to 2005 and representative of Tier 2 technology. Lower power equipment (75 horsepower or less) is Tier 0 or Tier 1. Sulfur content of the diesel is assumed to be 0.05 wt%. Additional details are provided in section 3.3.1.3.4of this report.

Diesel powered pumps used for water management systems (irrigation and pumping) also release emissions. Criteria air pollutants and their precursors are determined using EPA AP-42 guidelines for stationary gasoline and diesel engines (EPA, 1996, Table 3.3-1).

Emissions of criteria pollutants and their precursors in grams per liter and grams per hectare for the tending unit operation are given in Table 3.17.

Table 3.17. Emissions of criteria pollutants and their precursors in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the tending unit operation (based on EPA (1996; 2004; 2005), Salassi and Deliberto (2008), and Roka *et al*., (2009))

Equipment	Unit Power (HP)	Fuel Use liters/ha	Emissions g/liter					Emissions g/ha				
			VOC	CO	NO_X	PM	SO_2	VOC	CO	NO_X	PM	SO_2
4 Row Disk Bed (Hipper)	150	10.6	1.86	7.17	21.76	1.33	0.83	20	76	231	14	9
3 Row Disk Bed (Hipper)	150	77.8	1.87	7.18	21.81	1.33	0.84	145	559	1697	104	65
3 Row Off-bar	150	43.2	1.87	7.18	21.81	1.33	0.84	81	311	943	58	36
Drain Cleaner	75	28.7	2.40	19.64	24.56	2.01	0.93	69	564	705	58	27
Boom Sprayer	150	77.8	1.87	7.18	21.81	1.33	0.84	145	559	1697	104	65
Fertilizer Lq App, 3 Row	150	18.8	1.86	7.17	21.76	1.33	0.83	35	135	409	25	16
Fertilizer Dry Sling App	150	8.6	1.84	7.07	21.45	1.31	0.82	16	61	185	11	7
Irrigation/Drainage Pumps		33.7	5.45	14.61	67.83	4.77	4.46	184	492	2,286	161	150
TOTAL		299.3						695	2,756	8,152	533	375

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide (CO_2) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of CO_2 per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg CO_2 per liter of diesel burned. Similarly, the IPCC default value for methane (CH_4) is 4.15 kilograms per terajoule (TJ) and the default value for N_2O is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of CH_4 and N_2O respectively per liter of diesel combusted. Applying these values to the total fuel consumed (299.3 liters per hectare), the operation of diesel powered equipment during the tending unit operation results in per hectare emissions of 794 kg of CO_2, 0.0445 kg of CH_4, and 0.306 kg of N_2O.

The application of nitrogen fertilizer contributes to direct emissions of nitrous oxide (N_2O). The rate at which this occurs is based on IPCC guidelines (IPCC, 2006b, Equation as 11.1). A more general discussion and additional sources of nitrous oxide emissions that occur as the result of sugarcane farming are presented in section 3.3.1.2.7 of this report. In considering only the tending unit operation and nitrogen fertilizer application, the rate of direct N_2O emissions can be expressed as

$$N_2O_{fert} = N_{fert,N} * EF_{N\,fert} * N_2O_{mw} /(2 * N_{aw}) \quad (3.14)$$

where

N_2O_{fert} is the mass of annual nitrous oxide emissions per unit area due to fertilization

$N_{fert,N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$EF_{N\,fert}$ is the emission factor for added nitrogen, taken to be 0.01 per IPCC guidelines, (IPCC, 2006b, Table 11.1).

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Representative nitrogen fertilization rates for US sugarcane are taken to be 60.30 kg/ha-yr for plant cane crops (Table 3.13). Thus direct N_2O emissions for nitrogen fertilization of plant cane crop are calculated as

$$60.30 \text{ kg/ha-yr} * 0.01 * 44/28 = 0.9476 \text{ kg/ha-yr} \quad (3.15)$$

Similarly, representative nitrogen fertilization rates for ratoon crops are 77.27 kg/ha-yr (Table 3.14), which results in direct N_2O emissions of:

$$77.27 \text{ kg/ha-yr} * 0.01 * 44/28 = 1.214 \text{ kg/ha-yr} \quad (3.16)$$

3.3.1.2.3.3.6 Summary of Material and Energy Flows for Tending

The tending unit operation is assumed to apply that portion of land designated as plant cane crop which, burdened for seed-cane production is set equal to 30%, as well as for ratoon crops, for which 50% is assumed to be typical for the US. The final overall material and energy flows for this unit operation are summarized in Table 3.18.

Table 3.18. Direct material and energy flows for tending of US sugarcane cropland

Resource	Calculation	Value	Units
Land [1]	0.80 hectares / 1 hectare-year	0.25	1/yr
Electricity (irrigation)	0.80 / year * 185 kWh	148	kWh/ha-yr
	equivalent to	532	MJ/ha-yr
Diesel, Field Equipment and Water Management			
Volume	(0.30 / year * 125.1 + 0.5 / year * 140.4 + 0.8/ year * 33.7) liters / hectare	135	l/ha-yr
Mass [2]	134.7 liters / hectare-year * 0.837 kilograms / liter	113	kg/ha-yr
Energy [2]	134.7 liters / hectare-year * 35.8 megajoules / liter	4,822	MJ/ha-yr
Pesticides			
2,4-D amine	(0.30 / year * 1.56 + 0.50 / year * 0.76) kilograms / hectare	0.85	kg/ha-yr
Asulam	(0.30 / year * 2.53 + 0.50 / year * 2.91) kilograms / hectare	2.21	kg/ha-yr
Atrazine	(0.30 / year * 3.70 + 0.50 / year * 3.70) kilograms / hectare	2.96	kg/ha-yr
Dicamba	(0.30 / year * 0.31 + 0.50 / year * 0.40) kilograms / hectare	0.29	kg/ha-yr
Glyphosate	(0.30 / year * 0.0 + 0.50 / year * 0.25) kilograms / hectare	0.13	kg/ha-yr
Metribuzin	(0.30 / year * 1.19 + 0.50 / year * 0.44) kilograms / hectare	0.58	kg/ha-yr
Pendimethalin	(0.30 / year * 4.04 + 0.50 / year * 2.54) kilograms / hectare	2.48	kg/ha-yr
Trifluralin	(0.30 / year * 1.01 + 0.50 / year * 1.01) kilograms / hectare	0.81	kg/ha-yr
Unspecified surfactant	(0.30 / year * 1.35 + 0.50 / year * 3.50) kilograms / hectare	2.16	kg/ha-yr
Nutrients			
Nitrogen (N)	(0.30 / year * 60.30 + 0.50 / year * 77.27) kilograms / hectare	56.73	kg/ha-yr
Phosphate (P_2O_5)	(0.30 / year * 60.58 + 0.50 / year * 51.57) kilograms / hectare	43.96	kg/ha-yr
Potash (K_2O)	(0.30 / year * 103.40 + 0.50 / year * 95.33) kilograms / hectare	78.69	kg/ha-yr
Sulfur (S)	(0.30 / year * 0.0 + 0.50 / year * 12.11) kilograms / hectare	6.06	kg/ha-yr
Micronutrients	(0.30 / year * 2.24 + 0.50 / year * 0.0) kilograms / hectare	0.67	kg/ha-yr
Insecticide			
Tebufenozide	0.80 / year * 0.50 kilograms / hectare	0.40	kg/ha-yr
Phorate	0.30 / year * 7.6 kg / hectare	2.28	kg/ha-yr
Water			
Withdrawn	0.80 / year * 4.47 x 10^6 liters / hectare	3.58	10^6 l/ha-yr
Consumed	0.80 / year * 8.32 x 10^6 liters / hectare	6.66	10^6 l/ha-yr
Criteria Air Pollutants and Precursors			
VOC	0.80 / year * 0.695 kilograms / hectare	0.56	kg/ha-yr
CO	0.80 / year * 2.756 kilograms / hectare	2.21	kg/ha-yr
NO_X	0.80 / year * 8.152 kilograms / hectare	6.52	kg/ha-yr
PM	0.80 / year * 0.533 kilograms / hectare	0.43	kg/ha-yr
SO_2	0.80 / year * 0.375 kilograms / hectare	0.30	kg/ha-yr
Greenhouse Gases			
CO_2	0.80 / year * 793 kilograms / hectare	634	kg/ha-yr
CH_4	0.80 / year * 0.0446 kilograms / hectare	0.036	kg/ha-yr
N_2O	(0.30 / yr * 0.948 + 0.5 / yr * 1.214 + 0.8 / yr * 0.305) kilograms / hectare	1.135	kg/ha-yr

[1] 35% is organic wetland and 65% is mineral sandy soil, both are located in a warm temperate, moist climate.

[2] US conventional diesel (default inputs to GREET (ANL, 2009)

Density is 3167 grams per gallon, equivalent to 0.837 kg/liter.

Lower heating value (LHV) energy content is 128,450 Btu per gallon, equivalent to 35.8 MJ/liter

3.3.1.2.4 Harvesting (separation of target material from growing medium):

3.3.1.2.4.1 General Description

The harvesting unit operation includes cutting stalks of sugarcane in order to remove them from the field for subsequent transport to the mill. In the US, almost all harvesting is done by machine using either a whole stalk (soldier) harvester or a billet (combine) harvester. The soldier harvester is more commonly used in Louisiana where typical cultivars produce stalks that tend to be lighter and benefit from being left intact. Florida and Texas use combine harvesters. Manual harvesting produces the highest quality sugarcane and highest yields, but is labor intensive. Soldier harvesters inflict less damage to the stalks and consequently may produce higher yields on a per stalk basis, but a significant amount of cane stalks may be left behind, reducing overall tonnage. Combine harvesters require the least amount of labor, but are most likely to inflict damage to the cane pieces with the potential to decrease sugar yields (Salassi and Champagne, 1998). Regardless of the method, the important factors in harvesting are production of clean, undamaged cane, minimization of trash sent to the mill (vegetation that contains little to no sucrose), and maintenance of viable root stock in the field (Clarke, 2000).

The tops and leaves of sugarcane contain little sucrose but are high in starch and reducing sugars, which can result in depressed sugar yields. Cane leaves also have a high silica content which contributes machine wear during the milling process (EPA, 1997). Despite environmental and safety concerns, burning sugarcane, either immediately before or after it is harvested, is still a widely practiced method of eliminating unwanted plant material. Studies have shown little benefit (and perhaps a disbenefit) to leaving crop residues in the field (e.g., Wiedenfeld, 2009); there are also concerns that crop residues can harbor insect pests and result in slower regeneration of ratoon crops (Ellis and Merry, 2004). Harvesting of green (unburned) sugarcane by combine requires more time and fuel than harvesting burned cane (Irvine, 2004) and more "trash" (non-targeted plant matter) is sent to the mill when the cane is unburned. In addition to transporting and processing unwanted material, this extraneous biomass decreases total recovery of sugarcane juice by absorbing the targeted high sucrose liquid (where it cannot be easily recovered) and by diluting the recovered juice with its own sucrose deficient fluids (Irvine, 2004; Baucum and Rice, 2006). Cane stalks are extremely high in moisture so that controlled and rapid burns incinerate only the leaves, tops, and trash (Clarke, 2000); a 40 acre field burns in 15-20 minutes (Baucum and Rice, 2006).

Fields harvested by combine, such as is typical in Florida and Texas, are burned immediately before the cane is harvested. When whole stalk harvesting methods are used, the burning process typically takes place after the cane is cut, because the canopy is too light to support a burn on standing cane (Clarke, 2000). The cane is burned by setting fire to piles of stalks that have been made on the ground next to the rows from which they were cut, usually one day after harvest. One of the advantages of burning sugarcane after harvesting rather than before is that whole stalks of green cane may be held several days with only minor degradation of the cane (loss of sucrose). Once burned, whether before or after harvest, it must be milled within 24 hours in order to maintain sugar yields.

Harvesting does not include the fallow area (25% of the land area) and the specific harvesting of the area planted in seed-cane (5%) is addressed under the seeding and planting unit operation. The harvest unit operation, therefore, affects only 70% of the land area in any given year.

3.3.1.2.4.2 Activities

3.3.1.2.4.2.1 Combine (Billet) Harvesting

The first step in combine harvesting is to burn the fields. No equipment is listed in the Louisiana costs and returns documents and the total cost of this activity is given in the summary as $0.45 per acre (Salassi and Deliberto, 2008). The inputs are therefore presumed to be very small and are not accounted for. The combine harvester and 3 wagons are used to cut and gather the billets of cane. The drains are cleaned after the harvest operation. This method of harvesting is assumed for all of Florida and Texas (55%) plus a small portion of Louisiana, for a US total of 60%.

A list of the equipment, which reflects the activities performed during harvesting of sugarcane in Louisiana, is presented in Tables 3.19 and 3.20. These are taken to be representative of sugarcane grown in the US.

Table 3.19. Equipment used in the harvesting unit operation for combine (billet) harvesting of sugarcane (based on Salassi and Deliberto, 2008).

Equipment	Size	Power	Fuel Use Rate		Performance Rate		Times Over	Fuel Consumption	
		HP	gal/ hr	liters/ hr	hr/ acre	hr/ ha		gal/ acre	liters/ ha
Billet Harvester	6 ft		12.00	45.42	0.70	1.73	1	8.40	78.6
Billet Cane Wagon	10 ton	150	8.49	32.14	0.60	1.48	1 x 3 wagons	15.28	142.9
Drain Cleaner	6 ft	75	3.84	14.52	0.08	0.20	1	0.31	2.9
TOTAL								24.0	224.4

3.3.1.2.4.2.2 Soldier (Wholestalk) Harvesting

In soldier (wholestalk) harvesting, a 2 row harvester is used in conjunction with a 2 row loader. One-row harvesting systems are available but are not common. A burning unit moves through the fields burning piles of cane, after which the cane is loaded onto wagons and moved to a transloader used to load the cane onto highway trucks and trailers. Because the land disturbance is less with a soldier harvester, no drain cleaning is required upon completion. This method of harvesting is assumed for most of Louisiana, for a US total of 40%.

Table 3.20. Equipment used in the harvesting unit operation for wholestalk (soldier) harvesting of sugarcane (based on Salassi and Deliberto, 2008)..

Equipment	Size	Power	Fuel Use Rate		Performance Rate		Times Over	Fuel Consumption	
		HP	gal/ hr	liters/ hr	hr/ acre	hr/ ha		gal/ acre	liters/ ha
2 Row Harvester	12 ft		8.00	30.28	0.39	0.96	1	3.10	29.0
Burning Unit	18 ft	75	5.42	20.50	0.15	0.37	1	0.81	7.5
2 Row Loader	12 ft		7.00	26.50	0.30	0.74	1	2.10	19.6
Cane Wagon	10 ton	150	7.72	29.22	0.50	1.24	1 X 2 wagons	7.72	72.2
Transloader			4.70	17.79	0.25	0.62	1	1.18	11.0
TOTAL								14.9	139.4

More detailed information about both types of harvesting is available in the Louisiana cost and returns documents (Salassi and Deliberto, 2008; 2009) as well as Salassi and Champagne (1998).

3.3.1.2.4.3 Direct Material and Energy Flows

The direct material and energy flows associated with the harvest unit operation include diesel fuel to power the equipment, as shown in Tables 3.19 and 3.20, water used in drain cleaning, and emissions to air from burning and operation of diesel equipment.

The quantity of water used for drain cleaning is unknown. An estimate of 4,658 liters/hectare-cleaning event is made in Equation 3.1. The combine harvesting operation requires 1 drain cleaning event. This water is assumed to be withdrawn and discharged to surface water with little lost to evaporation. The quality of the water would be degraded by the presence of suspended soils as well as chemical run-off (pesticides and fertilizers) from the surrounding cropland.

Emissions to air include criteria air pollutants (or precursors thereof) as well as greenhouse gas emissions. Criteria air pollutants that result from the burning of diesel fuel in the equipment listed in Tables 3.19 and 3.20 are calculated from the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004; EPA, 2005). The equipment population is based on lifetime expectancies for the equipment (Salassi and Deliberto, 2008) with most of the equipment at or near the median age. The expected lifetimes of harvesting equipment, which is self-propelled rather than being an implement pulled by a tractor, are typically 10 to 12 years. Therefore, in 2007, the model years 2001 to 2003 dominate and there is more Tier 1 technology equipment used (EPA, 2004) than in other unit operations. The sulfur content of the diesel is assumed to be 0.05 wt%. Additional details are provided in section 3.3.1.3.4 of this report. Emissions in grams per liter and grams per hectare for the land preparation unit operation are given in Table 3.21.

Table 3.21. Emissions in grams per liter (g/liter) of diesel fuel burned and grams per hectare (g/ha) for the harvesting unit operation (based on emission factors from the NONROAD model (EPA, 2004; 2005) and equipment data from Salassi and Deliberto (2008))

Equipment	Unit Power (HP)	Fuel Use liters/ha	Emissions g/liter					Emissions g/ha				
			VOC	CO	NOX	PM	SO2	VOC	CO	NOX	PM	SO2
Combine (billet)												
Billet Harvester *	225	78.6	1.65	5.97	21.37	1.03	0.80	130	469	1679	81	63
Billet Cane Wagon	150	142.9	1.70	6.52	19.79	1.21	0.76	242	932	2828	173	108
Drain Cleaner	75	2.9	2.40	19.64	24.56	2.01	0.93	7	56	70	6	3
TOTAL		224						379	1457	4578	259	174
Soldier (wholestalk)												
2 Row Harvester *	175	29.0	2.32	8.87	28.52	1.79	0.94	67	258	828	52	27
Burning Unit	75	7.5	1.70	13.91	17.39	1.43	0.66	13	105	131	11	5
2 Row Loader *	100	19.6	1.69	14.35	17.60	1.34	0.68	33	282	346	26	13
Cane Wagon	150	72.2	1.86	7.17	21.76	1.33	0.83	135	518	1571	96	60
Transloader *	60	11.0	1.92	12.82	17.85	2.03	0.61	21	141	196	22	7
TOTAL		139						269	1303	3072	207	112

* Unit power estimated from fuel use rate

Greenhouse gas emissions from burning of diesel fuel are estimated using IPCC emission factors (IPCC, 2006a). The default carbon dioxide (CO_2) emission rate for agricultural diesel operations is 74.1 kilograms (kg) of CO_2 per gigajoule (GJ) of fuel burned. If diesel is assumed to have a lower heating value (LHV) energy content of 0.0358 GJ/liter (ANL, 2009), this is equivalent to 2.65 kg CO_2 per liter of diesel burned. Similarly, the IPCC default value for methane (CH_4) is 4.15 kilograms per terajoule (TJ) and the default value for N_2O is 28.6 kg/TJ. These equate to emissions of 0.149 and 1.02 grams of CH_4 and N_2O, respectively, per liter of diesel combusted. Applying these values to the total fuel consumed during combine harvesting (224.4 liters per hectare), the operation of diesel powered equipment using this method results in per hectare emissions of 595 kg of CO_2, 0.0333 kg of CH_4, and 0.230 kg of N_2O. Wholestalk harvesting requires 139.4 liters per hectare with resulting per hectare emissions of 370 kg of CO_2, 0.0207 kg of CH_4, and 0.143 kg of N_2O.

In addition to emissions that are released through the use of diesel fuel, a number of gaseous species are emitted to the atmosphere during pre-harvest burning. Many of these may contribute to net greenhouse emissions and/or criteria air pollutant levels. The total emissions released depends upon the amount of matter that is available to be burned (fuel), the fraction that is actually burned (the combustion factor), and the emission factor for each species (the amount of a given compound that is release when a unit amount of biomass combusts.

Calculation of both criteria and greenhouse gas emissions due to burning is based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines, Volume 4, Equation 2.27 "Estimation of Greenhouse Gas Emissions from Fire" (IPCC, 2006), modified to reflect emissions per unit mass of cane harvested rather than per unit area.

$$E_{burn,k} = fraction_{BMF} * C_f * EF_{dm,\mathrm{k}} \tag{3.17}$$

where:

$E_{burn,k}$ is the mass of emissions for species *k* emitted per mass of cane harvested

$fraction_{BMF}$ is the mass fraction of biomass that acts as fuel; it replaces $A * M_B$ in IPCC Eq 2.27.

C_f is the combustion factor

$EF_{dm,\mathrm{k}}$ is the emissions factor for species k as given for agricultural residues per unit mass of dry matter. It is equivalent to factor G_{ef} in IPCC Eq 2.27.

The combustible material includes the tops and leaves of the cane stalks. Various estimates place the amount of matter available as fuel at between 20 and 40% of the above-ground biomass. Fageria and others (1997) state that the tops and leaves (non-millable cane) account for 30 to 40 wt% of the sugarcane plant at harvest; with roots at 10%. Irvine (2004) places the amount of extraneous matter at 25 to 35% of the standing cane (one-third to one-half of the mass harvested). Studies completed by others (Wiedenfeld, 2009; Gullett *et al*., 2006) suggest that US sugarcane in the field consists of about 20 to 25% combustible material. Macedo and others (2004) assumes that the ratio of leaves to cane is 0.28, which is equivalent to 21% of the above ground biomass. This study assumes that below-ground biomass is 10% of the total biomass and available combustible wet mass is equal to 25 wt% of the above-ground biomass (or 22.5% of the total biomass). This is equivalent to 0.33 kg of leaves and tops per kilogram of cane harvested. Leaves are typically 50% moisture by weight (Macedo *et al*., 2004; Jorapur and Rajvanshi, 1997); thus dry matter is estimated to be 0.167 kg per kg of cane harvested. Yields in the US average 73 Mg (tonnes) per hectare with an approximate 90^{th} percentile range of 53 and 88 Mg/ha-yr (based on data from ERS, 2009a). The available fuel in the US is thus estimated to range from 8.8 to 14.7 Mg/ha-yr with an average of 12.2 Mg/ha-yr.

In calculating the total amount that is actually consumed in the burn, an 80% combustion factor specific to sugarcane is given in the IPCC guidelines (IPCC, 2006b, Table 2.6). This factor is intended to account for the form of the biomass (surface area to mass), the moisture content, and the intensity of the fire. Macedo and others (2004) reduce the amount of emissions by an additional 10% through use of a burn efficiency factor of 0.90. A combustion factor of 80%, as recommended by the IPCC, is used in this study and is assumed to account for any inefficiency in the burning process.

Table 3.22 presents the emission factors and total emissions by species based on assumptions used in this study and three different yields of sugarcane that represent the US mean yield and 90^{th} percentile range (weighted by land area) over the past ten years (more detail on yield is provided in section (3.3.1.3.1). Both greenhouse gases and criteria air pollutants are included.

Emission factors are from Andre and Merlet, 2001, which are also used in the IPCC guidelines (IPCC, 2006b, Table 2.5). The carbon monoxide and VOCs emitted are expected to be quickly converted to CO2, and its associated carbon will be reabsorbed in the next growth cycle of the sugarcane. Therefore, the net contribution to greenhouse gases for these three species is assumed to be zero.

Table 3.22. Total emissions by species as kilograms per tonne cane harvested ($E_{burn,k}$) and as kilograms per hectare) for three different yields of sugarcane, where $fraction_{BMF}$ = 0.167 and C_f = 0.8. Emission factors $EF_{dm,k}$ from Andre and Merlet, 2001 and IPCC, 2006b).

Species	$EF_{dm,k}$ (g emitted / kg dry matter burned)	$E_{burn,k}$ (kg emitted / Mg cane harvested)	8.8 Mg/ha fuel; cane yield = 53 Mg/ha	12.2 Mg/ha fuel; cane yield = 73 Mg/ha	14.4 Mg/ha fuel; cane yield = 88 Mg/ha	Net contribution to GHG emissions (yield = 73 Mg/ha)
			Mass emitted (kilogram per hectare)			
CO2	1515	202.40	10,727	14,775	17,812	0
CH4	2.7	0.36	19	26	32	26.33
N2O	0.07	0.01	0	1	1	0.68
CO	92	12.29	651	897	1,082	0
NOX (as NO)	2.5	0.33	18	24	29	0
SO2	0.4	0.05	3	4	5	0
PM2.5	3.9	0.52	28	38	46	0
Total PM	13	1.74	92	127	153	0
VOC (as NMHC)	7	0.94	50	68	82	0

The harvesting unit operation does not apply to the fallow area. Harvesting of seed-cane is addressed in the seeding and planting unit operation. Therefore, the amount of land in any given year that is affected by harvesting is 70%. Within the harvesting unit operation, the type of practice taken to be representative of the US is 60% combine harvesting and 40% wholestalk. In weighting flows that are unique to each of these, 42% (60% of 70%) of the land is affected by combine harvesting and 28% is affected by wholestalk harvesting. The overall material and energy flows for this unit operation are summarized in Table 3.23.

Table 3.23. Direct material and energy flows for harvesting of US sugarcane cropland

Resource	Calculation	Value	Units
Land [1]	0.70 hectares / 1 hectare-year	0.3	1/yr
Diesel			
Volume	(0.42 / year * 224.4 + 0.28 / year * 139.4) liters / hectare	133	l/ha-yr
Mass [2]	133.3 liters / hectare-year * 0.837 kilograms / liter	112	kg/ha-yr
Energy [2]	133.3 liters / hectare-year * 35.8 megajoules / liter	4,771	MJ/ha-yr
Water			
Withdrawn	0.42 / year * 4,658 liters/ hectare	1,956	l/ha-yr
Consumed		0	l/ha-yr
Criteria Air Pollutants and Precursors			
VOC	(0.70 / yr * 85.4 + .42 / yr * 0.378 + 0.28 / yr * 0.269) kilograms / hectare	60.01	kg/ha-yr
CO	(0.70 / yr * 1122 + .42 / yr * 1.46 + 0.28 / yr * 1.303) kilograms / hectare	786.38	kg/ha-yr
NO_X	(0.70 / yr * 30.5 + .42 / yr * 4.58 + 0.28 / yr * 3.07) kilograms / hectare	24.13	kg/ha-yr
PM	(0.70 / yr * 127 + .42 / yr * 0.259 + 0.28 / yr * 0.207) kilograms / hectare	89.07	kg/ha-yr
SO_2	(0.70 / yr * 4.88 + .42 / yr * 0.174 + 0.28 / yr * 0.112) kilograms / hectare	3.52	kg/ha-yr
Greenhouse Gases			
CO_2	(0.70 / yr * 0 + .42 / yr * 595 + 0.28 / yr * 369) kilograms / hectare	353.22	kg/ha-yr
CH_4	(0.70 / yr * 26.3 + .42 / yr * 0.0343 + 0.28 / yr * 0.0208) kilograms / hectare	23.05	kg/ha-yr
N_2O	(0.70 / yr * 0.683 + .42 / yr * 0.229 + 0.28 / yr * 0.142) kilograms / hectare	0.73	kg/ha-yr

[1] 35% is organic wetland and 65% is mineral sandy soil, both are located in a warm temperate, moist climate.

[2] US conventional diesel (default inputs to GREET (ANL, 2009)

Density is 3167 grams per gallon, equivalent to 0.837 kg/liter.

Lower heating value (LHV) energy content is 128,450 Btu per gallon, equivalent to 35.8 MJ/liter

3.3.1.2.5 Waste Management

There are no known waste management activities for this life cycle stage.

3.3.1.2.6 Land Use, Organic Soils

Managed organic croplands have direct releases of greenhouse gases associated with them that cannot be assigned to a single unit operation. US sugarcane land is estimated to be grown on 35% organic soils and 65% sandy mineral soils, all in a warm temperate climate.

IPCC Guidelines (2006b) state that, given no changes in agricultural management systems over a 20-year time period, there are zero net emission of carbon from mineral soils. This condition is assumed for 65% of US sugarcane land. Croplands on organic soils are not classified into management systems. It is assumed that the drainage associated with use of this type of land, regardless of management system, stimulates oxidation of organic matter previously built up under a largely anoxic environment. The emission factor for annual losses of carbon (C) from organic soils located in a warm temperate climate is estimated to be 10.0 tonnes (10,000 kg) of C per hectare-year (IPCC, 2006b, Table 5.6). The atomic mass of carbon is 12 and that of oxygen is 16, thus the molecular mass of CO_2 is 44 and the mass ratio of CO_2 to C is 3.7 (44 divided by12). Assuming all carbon is present as CO_2 in the atmosphere, this equates to a CO_2 emission factor of 36.7 tonnes per hectare. Multiplying this by the percentage of organic soil land upon which sugarcane is grown in the US (35%) gives the expression:

$$0.35 \text{ / year} \; * \; 10{,}000 \text{ kg C / hectare} * \; 44/12 \; = \; 12{,}833 \text{ kilograms of } CO_2 \text{ / hectare-year} \quad (3.18)$$

The application of nitrogen fertilizer, the stools (below-ground biomass) left after the last ratoon crops, and use of organic soils to grow sugarcane in Florida all contribute to the production of direct emissions of nitrous oxide (N_2O), a particularly potent and long-lived greenhouse gas. Most nitrogen at or near the earth's surface is present as dinitrogen (N_2). In order to be useful to plants, the nitrogen must be "fixed" (i.e., the N to N triple covalent bond must be broken). Because of the strength of these bonds, breaking them is accomplished in only one of two ways, either through extreme heat (as is done in the manufacture of synthetic fertilizers) or through the activity of specific microbes (mostly bacteria) present in soils. Plants that are known as nitrogen "fixers" do not actually fix (break the bonds) of the nitrogen themselves, but instead attract and form symbiotic relationships with bacteria that do so. The initial form of fixed nitrogen is ammonia. Ammonia is converted to nitrate in a process referred to as nitrification. Nitrification may occur in the synthetic fertilizer manufacturing process or by through aerobic microbial activity. Ultimately, and on a relatively short time-scale, nitrate is converted back to N_2 in a process referred to as denitrification. N_2O is a gaseous intermediate in the reaction sequence of both nitrification and denitrification.

IPCC guidelines (IPCC, 2006b) are used to estimate the amount of N_2O released directly to the atmosphere as the result of nitrogen fertilization, crop residues, and cultivation of organic soils, as is the case in the Everglades. The general formula (IPCC, 2006b, Equation 11.1) accounts for both synthetic and organic fertilization (directly or through animal grazing). In the case of US sugarcane farming, only synthetic fertilization is considered. In this analysis, it is assumed that there is no grazing.

Eliminating those factors equal to zero, total direct N_2O emissions from managed soils as applied to US sugarcane farming is expressed in a simplified version of Equation 11.1 (IPCC, 2006b) as:

$$N_2O_{direct} = N_2O_{fert} + N_2O_{CR} * + N_2O_{OS} \quad (3.19)$$

where

N_2O_{direct} is the mass of annual direct nitrous oxide emissions per unit area

N_2O_{fert} is the mass of annual direct nitrous oxide emission per unit area due to the application of nitrogen fertilizer, as calculated in equation 3.14

N_2O_{CR} is the mass of annual direct nitrous oxide emission per unit area due to crop residues, as calculated in equation 3.4

N_2O_{OS} is the mass of annual direct nitrous oxide emission per unit area due to growing crops on organic soil in a temperate climate, as calculated in equation 3.20

The mass of annual direct nitrous oxide emission per unit area due to use of organic soils to grow sugarcane in the US is calculated as

$$N_2O_{OS} = A_{OS} * EF_{OS} * N_2O_{mw} /(2 * N_{aw}) \quad (3.20)$$

where

N_2O_{OS} is the mass of annual direct nitrous oxide emission per unit area due to growing crops on organic soil in a temperate climate

A_{OS} is the area fraction of land per year consisting of organic cropland

EF_{OS} is the emission factor for managed organic cropland in a temperate environment, , taken to be 8 kg N per ha per IPCC guidelines

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Given that in any one year, 35% of US sugar cane is grown on organic soils, the amount of annual direct emissions of N_2O per hectare due to this activity is:

0.35 / year * 8 kilograms N / hectare* 44/28 =

4.40 kilograms of N_2O / hectare-year (3.21)

3.3.1.2.7 Summary of Direct Material and Energy Flows for Life Cycle Stage 1

Tables 3.24, 3.25, and 3.26 sum all of the direct flows accounted for in sections 3.3.1.2.1 through 3.3.1.2.6 of this report.

Table 3.24. Direct flows of energy and water for life cycle stage one, raw material acquisition, in production of sugarcane ethanol

	Electricity		Diesel			Water	
			Volume	Mass	Energy	Withdrawn	Consumed
Unit Operation	kWh/ha-yr	MJ/ha-yr	l/ha-yr	kg/ha-yr	MJ/ha-yr	10^3 l/ha-yr	10^3 l/ha-yr
Land Preparation	0	0	60	50	2,136	5.8	0
Seeding and Planting	0	0	52	43	1,848	4.5	0
Tending	148	532	135	113	4,822	3576	6656
Harvesting	0	0	133	112	4,771	2.0	0
TOTAL	148	532	379	318	13,578	3,588	6,656

Table 3.25. Direct emissions to air for life cycle stage one, raw material acquisition, in production of sugarcane ethanol.

	Criteria Air Pollutants and Precursors					Net Greenhouse Gases		
	kg/ha-yr					kg/ha-yr		
Unit Operation	VOC	CO	NOX	PM	SO2	CO2	CH4	N2O
Land Preparation	0.11	0.45	1.30	0.07	0.05	185	0.01	0.44
Seeding and Planting	0.10	0.42	1.14	0.07	0.04	137	0.01	0.05
Tending	0.56	2.21	6.52	0.43	0.30	634	0.04	1.14
Harvesting (excluding burning)	0.23	0.98	2.78	0.17	0.10	353	0.02	0.14
Burning	47.79	628.08	17.07	88.75	2.73	0	18.43	0.48
Land Use (organic soils)						12,833		4.40
TOTAL	48.79	632.13	28.81	89.49	3.23	14,143	18.51	6.65
TOTAL without burning or organic soil use	1.00	4.05	11.74	0.73	0.50	1,309	0.07	1.77

Table 3.26. Application of chemicals to land in life cycle stage one, raw material acquisition, in production of sugarcane ethanol; all are attributed to the tending unit operation except as noted

Pesticides		Nutrients		Insecticides	
Type	kg/ha-yr	Type	kg/ha-yr	Type	kg/ha-yr
2,4-D amine	0.85	Dolomite [2]	56.00	Tebufenozide	0.40
Asulam	2.21	Slag [2]	84.00	Phorate	2.28
Atrazine [1]	3.02	Nitrogen (N)	56.73		
Dicamba	0.29	Phosphate (P_2O_5)	43.96		
Glyphosate [1]	0.83	Potash (K_2O)	78.69		
Metribuzin	0.58	Sulfur (S)	6.06		
Pendimethalin [1]	2.54	Micronutrients	0.67		
Trifluralin	0.81				
Unspecified surfactant	2.16				

[1] Land Preparation and Tending

[2] Land Preparation

3.3.1.3 Environmental Metrics

Four categories of environmental metrics are considered in the study: land use, net energy, water use, and emissions to air. Land use includes a quantitative assessment of the total amount of land required to support production of the crop. Net energy is the difference between quantity of energy required to produce the product less energy generated. Water use includes both consumption and withdrawals (i.e., that lost to evaporation and that returned to the source in an altered state). Emissions to air that are considered in the analyses include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), oxides of nitrogen (NO_X), and oxides of sulfur (SO_X). This section is also used to account for indirect flows and embodied inventories that occur due to activities upstream from the reference flow of sugarcane agriculture. In the case of the latter, only energy and emissions to air are considered.

3.3.1.3.1 Land Use, Area Requirements

The reference flow for the first life cycle stage in the production of ethanol from sugarcane is one hectare of land. The amount of sugarcane that can be produced on one hectare of land (yield) is dependent on several factors. The first is the location of the land, in particular the number of warm days, the second is the fraction of land left fallow at any given time, and the third is whether the sugarcane is irrigated or not. Of the three mainland states that produce sugarcane, Louisiana has significantly lower yields than either Florida or Texas. This is assumed to be because the land used is located further north and the sugarcane is not irrigated. Yields for each of the three states are taken for the past 10 years (seasons 1999/2000 through 2008/2009) (ERS, 2009a) and the 5^{th} and 95^{th} percentiles (roughly), in terms of amount of harvested land producing at a given yield, are determined (Figure 3.10).

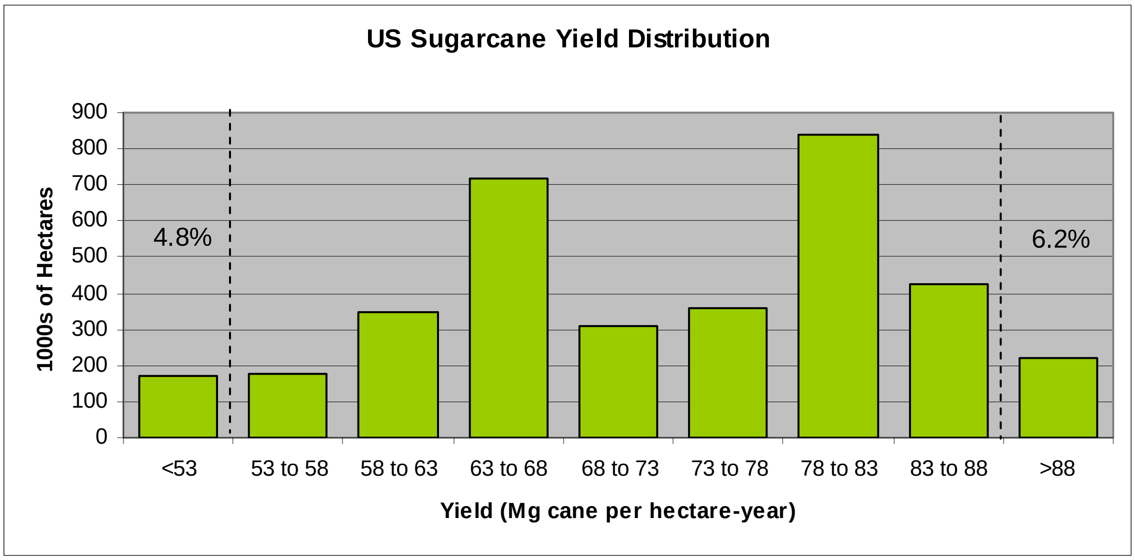

Figure 3.10. Sugarcane yields in the US exhibit a bimodal distribution about 66 and 79 Mg/ha-yr with 90% of US harvested cropland producing between 53 and 88 Mg/ha-yr (based on data from ERS, 2009a).

Based on this analysis, approximately 90% of US land harvested for sugarcane will yield between 53 and 88 Mg (tonnes) per hectare per year. The median is at 73 Mg/ha-yr, but the distribution is bimodal at about 66 and 79 Mg/ha-yr, reflecting Louisiana and Florida yields respectively. Noting that these figures represent only the land that is harvested for sugar, the total amount of land actually required to support these levels of production must be adjusted. The analysis assumes that 70% of sugarcane cropland is harvested for sugar; 25% is fallow (or planted in a rotation crop) and another 5% is used to grow seed-cane. In addition, land is needed to support access to fields and drainage systems. This is estimated to be an additional 15% of the actual cropland (Roka *et al*., 2009). Thus median amount of cane that is produced per hectare year (for all land required to support cultivation) is calculated as

$$(0.7 \;*\; 73 \text{ Mg sugarcane harvested for sugar / hectare- year}) \;/\; 1.15 \;=$$

$$44.4 \text{ Mg sugarcane / hectare-year} \qquad (3.22)$$

The range, at a 90% confidence interval, is similarly calculated to be 32.3 to 53.6 Mg sugarcane / hectare-year. This relationship stated in terms of the amount of cane harvested is a mean land use of 2.25 x 10^{-5} hectares per kilogram of sugarcane harvested for sugar, with a range of 1.87 x 10^{-5} to 3.10 x 10^{-5} hectares of land per kilogram of sugarcane.

3.3.1.3.2 Water Use

A total of 3.588 x 10^{6} liters per hectare is withdrawn annually in the US to support sugarcane agriculture. Less than 1% is used for cleaning drains. The remainder is used to irrigate crops or condition soil in Florida and Texas. In addition, because sugarcane requires a significant amount of water to grow, the amount consumed by the plants, either due to evapotranspiration or contained within the harvested stalks, is significant at an estimated average of 6.656 x 10^{6} liters per hectare in the continental US. The water lost through drainage to surface waters contains fertilizer, pesticides, and suspended solids.

Given an effective mean yield of 44.4 Mg sugarcane / hectare-year and a range of 32.3 to 53.6 Mg sugarcane / hectare-year, this translates to a mean embodied water use of 149.9 liters of water withdrawn and 80.8 liters consumed per kilogram of cane. The corresponding ranges are 124.2 to 206.1 liters withdrawn /kg cane and 66.9 to 111.1 liters consumed /kg cane.

3.3.1.3.3 Net Energy

There are no energy products produced during this stage of the life cycle, therefore, net energy is equivalent to all the direct energy inputs to sugarcane agriculture, plus the upstream energy required to generate the direct energy, as well as the embodied energy in the chemicals that are applied to the plants and soil.

Total direct energy, as shown in Table 3.24 is equal to 532 MJ/ha-yr from electricity and 13,578 MJ/ha-yr from diesel. Using the GREET model for electricity produced at the wall for stationary sources, the upstream energy to produce 532 MJ of electricity requires 2.56 times the energy delivered or 1364 MJ/ha-yr (ANL, 2009). Similarly, the energy required to produce 13,578 MJ of diesel fuel requires 0.1798 times the energy delivered or an additional 2442 MJ/ha-yr.

The amount of energy consumed in the production of agricultural chemicals (fertilizers and pesticides) is significant. The GREET model (ANL, 2009) is used to determine the values associated with the manufacture and transportation of fertilizers. Upstream energies of pesticides are taken from Bhat and others (1994); transportation energy requirements are from GREET.

Although not explicitly stated, the material cost and application methods described in the budgets provided by the state agricultural extension services (Salassi and Deliberto, 2008; TAES, 2007) suggests that nitrogen fertilizer used in Louisiana and Florida (90% of sugarcane production) is in the form of ammonia. Therefore, ammonia is assumed in calculating the upstream energies associated with the production and transportation of nitrogen fertilizer. Dolomite is essentially the same as limestone (calcium carbonate) in terms of mode of occurrence and density, thus the energies associated with mining and transporting of dolomite should be indistinguishable from that for calcium carbonate ($CaCO_3$). Calcium carbonate is also used as a surrogate for slag.

Upstream energy inputs for sulfur are estimated assuming sulfuric acid is the source with sulfur at 50 wt%. There are no data for micronutrients. As the mass fraction is small and the specific composition is unknown, the upstream energies associated with micronutrients are not included in the analysis. Total estimated upstream energies for each of the fertilizers are presented in Table 3.27.

Table 3.27. Upstream energies associated with the manufacture and transportation of fertilizer (based on data from ANL, 2009)

Nutrient	Use Rate	MJ/kg nutrient		Total Upstream Energy
	kg/ha-yr	Feedstock + Production	Transportation	MJ/ha-yr
Nitrogen (N) as ammonia	56.73	45.01	1.03	2,611
Phosphate (P2O5)	43.96	13.98	0.93	656
Potash (K2O)	78.69	8.77	0.91	762
Sulfur (S)	6.06	0.49	0.81	8
Dolomite	56.00	8.01	0.16	458
Slag	84.00	8.01	0.16	686
TOTAL				5,181

Energy requirements for production of pesticides are taken from a report produced by the US Department of Energy (Bhat *et al*., 1994). While the information is dated, it is the most complete available and is a key source of data in many life cycle inventory databases for the energy associated with pesticide manufacturing. A summary is presented in Table 3.28.

Table 3.28. Upstream energies associated with the manufacture and transportation of pesticides (based on data from Bhat *et al*., 1994)

Pesticide	Pesticide Use	Production Energy		Production plus Transportation
	kg/ha-yr	MJ/kg	MJ/ha-yr	MJ/ha-yr
2,4-D amine	0.85	85	72	73
Asulam *	2.21	214	474	476
Atrazine	3.02	190	574	577
Dicamba	0.29	295	86	87
Glyphosate	0.83	454	375	375
Metribuzin	0.58	200	115	116
Pendimethalin	2.54	150	381	383
Trifluralin	0.81	150	121	122
Tebufenozide **	0.40	245	98	98
Phorate **	2.28	245	559	561
TOTAL			2,855	2,867

* Average herbicide

** Average insecticide

Assume transportation energy for all is 0.919 MJ/kg (based on ANL, 2009)

The annual net energy balance per hectare for sugarcane grown in the continental US in 2007 is estimated to be the sum of the following: 532 MJ/ha-yr from electricity and 13,578 MJ/ha-yr from diesel; 1364 MJ/ha-yr to produce the electricity and 2442 MJ/ha-yr to produced the diesel;

5,181 MJ/ha-yr to manufacture and distribute fertilizer and an additional 2,867 MJ/ha-yr to manufacture and distribute pesticides. This yields a total energy requirement of 26.0 GJ/ha-yr (Figure 3.11).

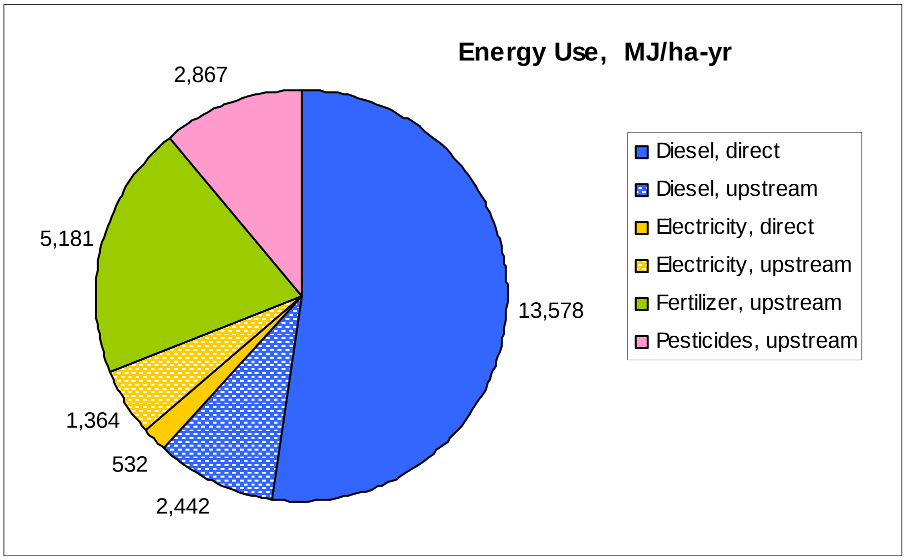

Figure 3.11. US sugarcane has a total energy requirement of 26.0 GJ/ha-yr, with nearly half due to upstream requirements in the production of electricity, diesel, fertilizer, and pesticides.

Accounting for land that is fallow (including that cropped in a cover crop), that used for seed-cane, and space required for roads and drainage gives an effective mean yield for the continental US of 44.4 Mg / hectare-year and a range of 32.3 to 53.6 Mg / hectare-year (see section 3.1.3.1). This translates to a mean embodied energy of 0.584 MJ/kg of harvested cane, with a range of 0.484 to 0.803 MJ/kg of cane.

3.3.1.3.4 Emissions to Air

Emissions to air include all of the direct emissions that can be attributed to specific unit operations as well as those related to managing sugarcane cropland on organic soils. In addition, there are indirect emissions of greenhouse gases due to use of nitrogen fertilizers. Production of energy, fertilizers, and pesticides also result in emissions to air. This analysis considers only emissions related to upstream energy inputs used to produce energy and to manufacture nutrients and pesticides (Figure 3.8).

3.3.1.3.4.1 Greenhouse Gases

Direct Emissions

The direct net emissions of greenhouse gases released due to sugarcane farming in the continental US include 14,143 kilograms of CO_2 per hectare-year, 18.5 kg CH_4/ha-yr, and 6.7 kg N_2O/ha-yr (Table 3.25). Most of the CO_2 and N_2O emissions (90% and 65% respectively) are the result of using the organic soils of the Florida Everglades, which accounts for 35% of sugarcane cropland. Virtually all of the CH_4 emissions are due to pre-harvest burning. Elimination or reduction of these practices would have a significant impact on the greenhouse gas inventory related to sugarcane agriculture (Table 3.25).

<u>Indirect Emissions</u>

In addition to N_2O emissions that are released directly from fertilized cropland, indirect emissions occur in one of two ways. In the first, N is volatilized as NH_3 or oxides of nitrogen (NO_X) and subsequently deposited either in its gaseous form or as NH_4^+ and NO_3^- onto soil, water, or plant surfaces. The second pathway occurs when N is removed from soils by leaching or runoff before being taken up into biological systems. Nitrification and denitrification are the mechanisms by which N_2O is formed, just as in direct emissions, but the reactions occur in water and soils that are peripheral to the agricultural land that was originally enriched in nitrogen (the target area).

The indirect emissions of nitrous oxide are accounted for using IPCC guidelines. Sources of nitrogen that contribute to indirect emissions of N_2O from sugarcane farming include synthetic fertilizer application and crop residues (stools remaining after the final ratoon crop). IPCC Equation 11.9 accounts for N_2O emissions that result from atmospheric deposition of volatilized N. Equation 11.10 accounts for N_2O emissions that result from leaching and runoff (IPCC, 2006b).

After eliminating factors that are equal to zero for US sugarcane and converting nitrogen to N_2O, Equation 11.9 can be written as

$$N_2O_{atm\ dep} = N_{fert,\ N} * fraction_{GASF} * EF_{atm\ dep} * N_2O_{mw} /(2 * N_{aw}) \tag{3.23}$$

where

$N_2O_{atm\ dep}$ is the mass of annual nitrous oxide emissions per unit area produced from atmospheric deposition of nitrogen volatilized from cropland

$N_{fert,\ N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$fraction_{GASF}$ is the fraction of synthetic fertilizer that volatilizes, assumed to be 0.10 per IPCC guidelines (IPCC, 2006b, Table 11.3).

$EF_{atm\ dep}$ is the mass of annual direct nitrous oxide emission per unit area due to the application of nitrogen fertilizer; assumed to be 0.01 per IPCC guidelines (IPCC, 2006b, Table 11.3, EF_4).

$N_2O_{mw} /(2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

Substituting in the rate of nitrogen fertilizer application, as nitrogen, from Table 3.26, the expression becomes

56.73 kg / ha-yr * 0.10 * 0.01 * 44/28 =

$$0.0891 \text{ kilograms } N_2O \text{ / hectare-year} \quad (3.24)$$

Similarly, after eliminating factors that are equal to zero for US sugarcane and converting nitrogen to N_2O, Equation 11.10 (IPCC, 2006b) can be written as

$$N_2O_{leach} = (N_{fert,N} + N_{b\text{-}g\ BM,N}) * fraction_{LEACH} * EF_{leach} * N_2O_{mw} / (2 * N_{aw}) \quad (3.25)$$

where

N_2O_{leach} is the mass of annual nitrous oxide emissions per unit area produced from leaching and runoff of nitrogen from cropland

$N_{fert,N}$ is the mass of nitrogen fertilizer, as nitrogen, applied annually per unit area

$N_{b\text{-}g\ BM,N}$ the mass of nitrogen in biomass remaining below ground per unit area

$fraction_{LEACH}$ is the fraction of added nitrogen that volatilizes, assumed to be 0.30 per IPCC guidelines (IPCC, 2006b, Table 11.3).

EF_{leach} is the mass of annual direct nitrous oxide emission per unit area due to the leaching of nitrogen; assumed to be 0.0075 per IPCC guidelines (IPCC, 2006b, Table 11.3, EF_5).

$N_2O_{mw} / (2 * N_{aw})$ is the conversion factor for nitrogen to nitrous oxide, equal to 44/28

The mass of nitrogen fertilizer, as nitrogen, is 56.73 kg / ha-yr (Table 3.26). The mass of nitrogen present in below-ground biomass is 97.2 kilograms /hectare-year (as in equation 3.5), but only on fallow land. If this is assumed to be 25% of the cropland, the effective concentration is 24.3 kg/ha and the expression becomes

$$(56.73 \text{ kg / ha-yr} + 24.3 \text{ kg / ha-yr}) * 0.30 * 0.0075 * 44/28 =$$

$$0.286 \text{ kilograms } N_2O \text{ / hectare-year} \quad (3.26)$$

The total indirect emissions of N_2O are the sum of equations 3.24 and 3.26 or 0.376 kilograms N_2O / hectare-year.

Upstream Emissions

Upstream greenhouse gas emissions related to the energy, fertilizers, and pesticides used directly in sugarcane agriculture are estimated only as functions of the energy required to produce and deliver these resources. The GREET model (ANL, 2009) is used to determine these values. For pesticides, only one of those used on sugarcane, atrazine, is included in the GREET model. Emissions are scaled in proportion to the energy used to produce them (Table 3.28) for the other pesticides.

Upstream emissions related to energy and fertilizer production are presented in Table 3.30; those related to pesticide production are given in Table 3.31.

Table 3.30. Upstream greenhouse gas emissions from production of energy and nutrients

Inputs	Electricity, kWh/ha-yr	Diesel, MJ/ha-yr	Nitrogen (N) as ammonia, kg/ha-yr	Phosphate (P2O5), kg/ha-yr	Potash (K2O), kg/ha-yr	Dolomite and Slag, kg/ha-yr	
	147.84	13,578	56.73	43.96	78.69	140	
Species	Upstream Emissions kg/ha-yr						TOTAL
CH_4	0.145	1.331	0.141	0.078	0.076	0.126	1.896
N_2O	0.001	0.003	0.001	0.001	0.001	0.001	0.008
CO_2	107	186	144	43	51	83	615

Table 3.31. Upstream greenhouse gas emissions from production of pesticides

Inputs	2,4-D amine	Asulam	Atrazine	Dicamba	Glyphosate	Metribuzin	Pendimethalin	Trifluralin	Insecticide	
	0.848	2.214	3.02	0.293	0.825	0.577	2.5395	0.808	2.68	
Species	Upstream Emissions kg/ha-yr									TOTAL
CH_4	0.0026	0.0439	0.0725	0.0011	0.0129	0.0028	0.0405	0.0041	0.0943	0.2745
N_2O	0.0000	0.0003	0.0006	0.0000	0.0001	0.0000	0.0003	0.0000	0.0008	0.0022
CO_2	2	30	50	1	9	2	28	3	64	189

Calculation of greenhouse gas emissions for the purpose of estimating total global warming potential requires that the each gas be scaled according to its global warming potential relative to carbon dioxide as given in the Fourth Assessment Report of the IPCC (IPCC, 2007). These factored emissions are then summed to give total greenhouse gas emissions in terms of carbon dioxide equivalents (CO_2e). In addition, CO and VOCs are assumed to oxidize readily to CO_2. VOCs are assumed to have a relatively low molecular weight and consist of 83 wt% C (e.g., pentane). The sum of the mass of greenhouse gas emissions expressed as CO_2 equivalents is thus calculated as:

$$GHG = \sum_{k} E_{k} * GWP_{k} + [E_{CO} * CO2_{mw} / CO_{mw}] + [0.83 * E_{VOC} * CO2_{mw} / C_{aw}] \quad (3.27)$$

where:

GHG is the sum of the mass of greenhouse gas emissions expressed as CO_2 equivalents

E_k is the mass of emissions of GHG species k

GWP_k is the global warming potential for GHG species k (IPCC, 2007)

E_{CO} is the mass of CO emissions

$CO2_{mw} / CO_{mw}$ is the conversion factor for CO to CO_2, equal to 44/28

E_{VOC} * is the mass of VOC emissions

$CO2_{mw} / C_{aw}$ is the conversion factor for C to CO_2, equal to 44/12

Total emissions of species contributing to the greenhouse gas inventory are given in Table 3.32 as net emissions as well as in terms of CO_2 equivalents.

Table 3.32. Greenhouse gas emissions (net and as carbon dioxide equivalents (CO_2e)) in kilograms per hectare-year (kg-ha-yr) released during life cycle stage one, raw material acquisition, in the production of sugarcane ethanol

	Net Emissions of GHG kg/ha-yr					Emissions of GHG in CO_2e kg/ha-yr					
Source	CO_2	CH_4	N_2O	CO	VOC	CO_2	CH_4	N_2O	CO	VOC	TOTAL CO_2e
GWP (CO2e factor)	1	25	298	1.57	3.04						
Burning	0	18.4	0.5	0	0	0	461	142	0	0	603
Land Use (organic soils)	12,833	0	4.40	0	0	12,833	0	1,311	0	0	14,144
All other direct emissions	1,310	0.07	1.77	4.18	0.91	1,310	2	527	7	3	1,849
Indirect emissions	0	0	0.38	0	0	0	0	112	0	0	112
Upstream emissions	803	2.17	0.01	0.71	0.50	803.5	54	3	1	2	863
TOTAL	14,980	21	7	5	1	14,980	521	2,096	8	4	17,609
TOTAL (excluding burn)	14,980	2	7	5	1	14,980	60	1,954	8	4	17,006
TOTAL (excluding organic soil)	2,147	21	3	5	1	2,147	521	785	8	4	3,465
TOTAL (w/o burn and organic soil)	2,147	2	2	5	1	2,147	60	643	8	4	2,862

As is evident in examining the totals presented in Table 3.32, the practice of growing sugarcane on the organic soils of the Florida Everglades is by far the most significant contributor to greenhouse gas emissions in the growing of sugarcane in the continental US. This is shown graphically in Figure 3.12.

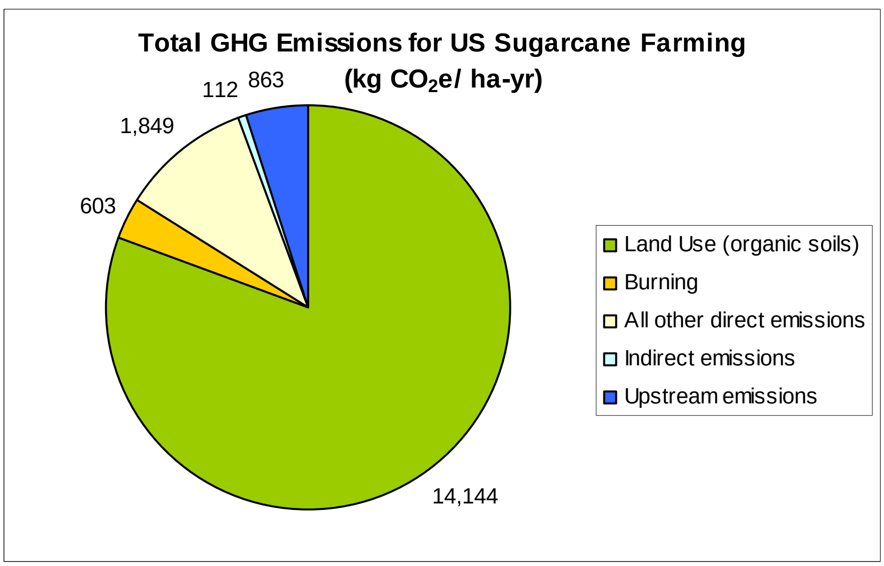

Figure 3.12. More than three-quarters (80%) of the greenhouse gas emissions associated with US sugarcane farming, as measured in carbon dioxide equivalents (CO2e) per hectare-year, is due to cultivation of organic soils.

If emissions produced by growing on organic soil are excluded from the analysis, emissions from other direct activities are clearly dominant (Figure 3.13). Roughly 20% of these emissions are released as the result of nitrogen fertilization, but most are the consequence of diesel fuel combustion. Thus, while a decrease in cultivation of organic soils might cause a slight increase in N_2O emissions because of increased fertilization, these would be more than offset by a decrease in both CO_2 and N_2O emissions that result when organic soils are managed.

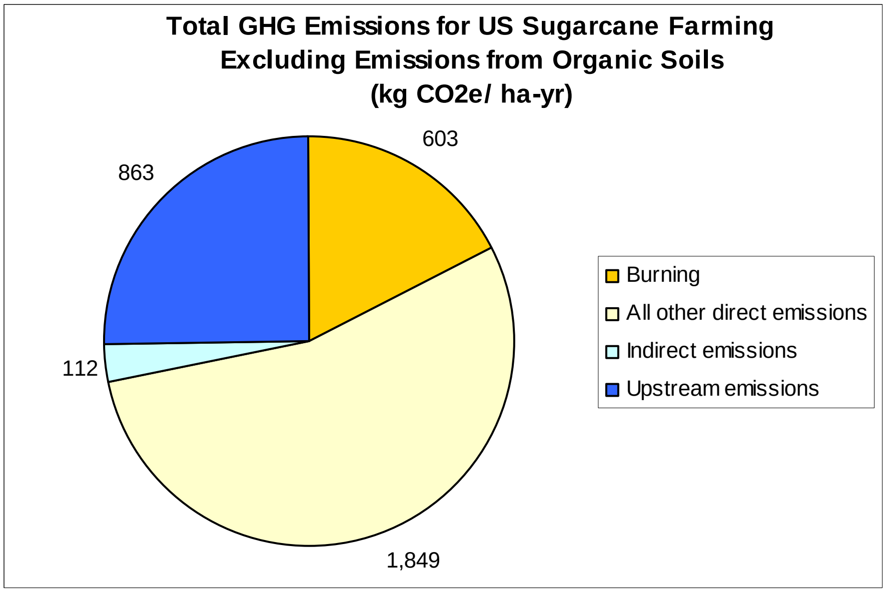

Figure 3.13. If emissions due to management of organic soils are excluded from the analysis, direct emissions, largely from the burning of diesel fuel, dominate.

3.3.1.3.4.2 Criteria

Direct Emissions

Criteria pollutants and their precursors are released primarily during pre-harvest burning. Totals (Table 3.25) include 48.8 kg of VOCs per hectare-year, 632 kg CO/ha-yr, 28.8 kg NO_X/ha-yr, 89.5 kg PM/ha-yr, and 3.23 kg SO_2/ha-yr. The totals due to operation of diesel power equipment alone are 60.69 kg of VOCs per hectare-year, 789.6 kg CO/ha-yr, 31.92 kg NO_X/ha-yr, 33.98 kg PM/ha-yr, and 3.82 kg SO_2/ha-yr.

Emissions to air from diesel powered field equipment are calculated from the formulas and emission factors used in the US Environmental Protection Agency's NONROAD model (EPA, 2004). For HC, CO, and NO_X, the exhaust emission factors for a given diesel equipment type in a given model year and of a specified age are calculated as:

$$EF_{adj\ (HC,CO,NOx)} = EF_{SS} * TAF * DF$$

where:

EF_{adj} is final emission factor adjusted to account for transient operation and deterioration in grams per horsepower-hour (g/hp-hr)

EF_{SS} is the zero-hour, steady-state emission factor (g/hp-hr)

TAF is the transient adjustment factor

DF is the deterioration factor

Determination of EF_{SS} and DF requires that age and the technology of the equipment be known or assumed along with the horsepower of the diesel engine. In the model developed for sugarcane farming, almost all of the equipment consists of implements pulled by a tractor which Salassi and Deliberto (2008) estimate to last 8 years, giving a median model year of 2003/4 in 2007 and a median age of 4 years. The oldest model year would be 2000 and the newest 2007. The exceptions to this are the transloader and 2 row harvester which are expected to last 12 years and the 2 row loader and billet harvester which have an expected lifetime of 10 years.

All of the equipment listed under the various unit operations (Tables 3.4, 3.8, 3.11, 3.19, and 3.20 are grouped by horsepower and life expectancy. Technology distribution profiles are assumed for each (Table 3. 29) using Table A1 from the EPA (2004) documentation. An equipment population profile is generated assuming that approximately 10% of the equipment is close to the maximum age, another 10% is close to the minimum age, and the remaining 80% is close to the median age.

Table 3. 33. Technology distribution assumed in estimating emissions from diesel exhaust (based on Salassi and Deliberto, 2008 and EPA, 2004)

Unit Power (HP)	Useful life (years)	Oldest Model Year	Median Model Year	Newest Model Year	Technology Distribution		
					Tier 1	Tier 2	Tier 3
60	12	1996	2001/2	2007	0.9	0.1	0
75	8	2000	2003/4	2007	0.3	0.7	0
100	10	1998	2002/3	2007	0.2	0.8	0
150	8	2000	2003/4	2007	0.3	0.6	0.1
170	8	2000	2003/4	2007	0.3	0.6	0.1
175	12	1996	2001/2	2007	0.5	0.5	0.1
190	8	2000	2003/4	2007	0.3	0.6	0.1
225	10	1998	2002/3	2007	0.4	0.5	0.1

Upstream Emissions

Emissions of criteria air pollutants and their precursors that are released in the production and delivery of electricity, diesel, fertilizers, and pesticides used in sugarcane agriculture are estimated only as functions of the energy required to produce and deliver these resources. The GREET model (ANL, 2009) is used to calculate these values. Only one of the pesticides used on sugarcane, atrazine, is included in the GREET model. Emissions for the other pesticides are estimated assuming that they are proportional to the energy used to produce them (Table 3.28) and scaling them relative to emissions for atrazine. Emissions related to energy and fertilizer production are presented in Table 3.30A; those related to pesticide production are given in Table 3.31A.

Table 3.34. Upstream criteria air pollutants and precursors from production of energy and nutrients

Inputs	Electricity, kWh/ha-yr	Diesel, MJ/ha-yr	Nitrogen (N) as ammonia, kg/ha-yr	Phosphate (P2O5), kg/ha-yr	Potash (K2O), kg/ha-yr	Dolomite and Slag, kg/ha-yr	
	147.84	13,578	56.73	43.96	78.69	140	
Species	Upstream Emissions kg/ha-yr						TOTAL
VOC	0.010	0.099	0.334	0.016	0.009	0.010	0.491
CO	0.028	0.157	0.306	0.055	0.034	0.037	0.638
NO_X	0.113	0.534	0.120	0.316	0.144	0.117	1.417
PM10	0.145	0.103	0.029	0.075	0.049	0.083	0.513
PM2.5	0.038	0.042	0.010	0.046	0.017	0.028	0.190
SO_X	0.249	0.256	0.072	2.804	0.105	0.132	3.675

Table 3. 35. Upstream criteria air pollutants and precursors from production of pesticides

Inputs	2,4-D amine	Asulam	Atrazine	Dicamba	Glyphosate	Metribuzin	Pendimethalin	Trifluralin	Insecticide	
	0.848	2.214	3.02	0.293	0.825	0.577	2.5395	0.808	2.68	
Species	Upstream Emissions kg/ha-yr									TOTAL
VOC	0.0002	0.0037	0.0062	0.0001	0.0011	0.0002	0.0034	0.0003	0.0100	0.0253
CO	0.0008	0.0139	0.0230	0.0003	0.0041	0.0009	0.0128	0.0013	0.0387	0.0959
NO_X	0.0029	0.0491	0.0811	0.0012	0.0145	0.0031	0.0453	0.0046	0.1119	0.3135
PM10	0.0014	0.0240	0.0396	0.0006	0.0071	0.0015	0.0221	0.0022	0.0496	0.1480
PM2.5	0.0006	0.0110	0.0181	0.0003	0.0032	0.0007	0.0101	0.0010	0.0236	0.0686
SO_X	0.0027	0.0461	0.0761	0.0011	0.0136	0.0029	0.0425	0.0043	0.0650	0.2543

3.3.1.4 By-Products

There are no by-products associated with the growing of sugarcane.

3.4 Sugarcane Ethanol Glossary

2,4-D amine: An herbicide**,** typically sold under a trade name that includes 2,4-D amine

asulam: An herbicide sold under the names Asulox or Asulam.

atrazine: An herbicide sold under the names Atrazine 4L or Atrazine 90DF

bagasse: The fibrous, structural matter of the sugarcane stem; cellulosic material that remains after sugar containing juice has been squeezed from the cane. It also includes any other biomass material inadvertently brought to the mill.

billet: A 20 to 24 inch (50 to 60 cm) length of sugarcane stalk.

Conservation Reserve Program: A voluntary program managed by the US Department of Agriculture's Natural Resource Conservation Service and the Farm Service Agency whereby agricultural landowners receive annual payments in return for establishing approved conservation practices on their land. The primary purpose is to control soil erosion.

CRP: Conservation Reserve Program

dicamba: An herbicide sold under various trade names such as Clarity or Vanquish or as a mixture with other herbicides (e.g. Weedmaster)

ET: evapotranspiration

evapotranspiration: The combined release of water from the surface of soil and plants to the atmosphere.

glyphosate: An herbicide sold under many different formulations and names including Accord, Glyfos, and Touchdown, but most commonly known under the Monsanto trade name of Roundup. Also sold as a sugarcane ripener under the names Polado and Touchdown.

imbibition: The process by which cane juice is displaced with water during the final milling steps in order to increase juice yield.

inflorescence: A tassel consisting of thousands of tiny flowers that may appear at the top of the sugarcane plant.

internode: The section of sugarcane stalk located between two nodes

joint: A section of sugarcane stalk consisting of the node and the internode.

metribuzin: An herbicide sold under several trade names including Sencor , DF

MFWD: mechanical front wheel drive

node: The part of the stalk that connects joints together and which contains the bud from which new growth, including leaves, emerges.

pendimenthalin: An herbicide sold under several trade names including Prowl and Pendimax

plant cane crop: The first crop of cane grown from seed-cane.

Poaceae: Botanical family to which sugarcane belongs; includes corn and most cereal crops

ratoon: A sprout or shoot that emerges from the root of sugarcane after the primary stalk has been harvested (noun); to send out new sprouts (verb).

ratoon crop: The second and subsequent seasonal crops of cane grown from the initial seed-cane (also stubble crop)

ripening: The process by which the sugarcane plant stores sucrose in its stalk.

***Saccharum**:* Genus to which sugarcane plants belong.

seed-cane: Either a whole stalk or cutting from a stalk of sugarcane that is used to propagate new plants.

stillage: The residue from ethanol distillation containing non-fermentable solids and water; also vinasse

stools: Residual pieces of cane left after the final ratoon crop has been harvested.

stubble crop: The second and subsequent seasonal crops of cane grown from the initial seed-cane (also ratoon crop)

subirrigation: A system of irrigation that relies on relatively precise control of the depth of the water table beneath the crop. The water table typically is not naturally occurring, but rather created (engineered) by perching it on top of an impermeable layer of soil. The level of the water table is maintained by pumping in water when needed or by draining excess water out through lateral ditches that are excavated adjacent to the fields.

sucrose ($C_{12}H_{22}O_{11}$),

tillers: Secondary shoots that emerge from buried seed-cane.

tillering: The development of secondary shoots.

trash: All parts of the harvested plant other than the targeted portion of the crop (i.e., cane)

trifluralin: An herbicide sold under several trade names including Treflan.

vegetative propagation: The growing of new plants from pieces of existing plants without the use of true seed.

vinasse: The residue from ethanol distillation containing non-fermentable solids and water; also stillage.

3.5 Sugarcane Ethanol References

Achenbach, 2008: Achenbach, Joel, 2008. Florida Moves to Restore Wetlands: Sugar Corp. Purchase Would Aid Everglades. Washington Post, June 25, 2008.

AHS, 1997. American Horticultural Society, 1997. Plant Heat-Zone Map. Complied by Meteorological Evaluation Services Co., Inc. Retrieved December 2009 from http://www.ahs.org.pdfs/05_heat_map.pdf.

AMSCL, 2009. American Sugar Cane League, 2009. The Louisiana Sugar Industry. Retrieved November 2009 from http://www.amscl.org/SugarIndustry.pdf

Andreae, M.O. and Merlet, P., 2001. Emission of Trace Gases and Aerosols from Biomass Burning, *Global Biogeochemical Cycles* 15 (4) 955-966.

ANL, 2009a: Argonne National Laboratory, 2009. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, GREET 1.8c.0, Fuel Specs, Argonne National Laboratory, US Department of Energy. Available at http://www.transportation.anl.gov/modeling_simulation/GREET/greet_1-8c_beta.html

ANL, 2009b: Argonne National Laboratory, 2009. Detailed California-Modified GREET Pathways for Brazilian Sugarcane Ethanol: Average Brazilian Ethanol, with Mechanized Harvesting and Electricity Co-product Credit, Version 2.2, Stationary Sources Division, Argonne National Laboratory, US Department of Energy, July 20, 2009. Available at http://www.arb.ca.gov/regact/2009/lcfs09/sugar.pdf.

Baucum and Rice, 2006: Baucum, L.E. and Rice, R.W, 2006, An Overview of Florida Sugarcane in *Sugarcane Handbook*, Gilbert, R.A., ed., Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS-AGR-232, Original publication date July 1992, Revised May 2006. Available at http://edis.ifas.ufl.edu/sc032.

Bhat *et a*l., 1994: Bhat, Mahadev; English, Burton, C.; Turhollow, Anthony F.; and Nyangito, Hezron, O., 1994. Energy in Synthetic Fertilizers and Pesticides: Revisited, Oak Ridge National Laboratory (ORNL), US Department of Energy, ORNL/Sub/90-99732/2, January 1994. Available at http://www.osti.gov/bridge/servlets/purl/10120269-p6yhLc/webviewable/10120269.pdf

Cheesman, 2004: Cheesman, Oliver D., 2004. *Environmental Impacts of Sugar Production: The Cultivation and Processing of Sugarcane and Sugar Beet*, Cambridge, MA: CABI Publishing.

Clarke, 2000: Clarke, Margaret A., 2000. Sugar, Cane Sugar in *Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed*, John Wiley & Sons, Inc.

Dauriat and Gnansounou, 2007: Dauriat, Arnaud and Gnansounou, Edgard, 2007. Ethanol-based Biofuels in *Life Cycle Inventories of Bioenergy*, Jungbluth, Neils, ed., Swiss Centre for Life Cycle Inventories, ecoinvent report No.17, Uster, December 2007.

Duke, 1983: Duke, James A., 1983. *Saccharum officinarum L.* in Handbook of Energy Crops, unpublished. Retrieved December, 2009 from http://www.hort.purdue.edu/newcrop/duke_energy/Saccharum_officinarum.html

EIA, 2009: Energy Information Administration, 2009. Annual Energy Review 2008. US Department of Energy, DOE/EIA-0384(2008), June 2009. Available at http://www.eia.doe.gov/emeu/aer/

Ellis and Merry, 2004: Ellis, R.D. and Merry, R.E., 2004. Sugarcane Agriculture in *Sugarcane*, 2nd edition, James, Glyn, ed., World Agriculture Series, Ames, Iowa: Blackwell Science Ltd.

EPA, 1996: US Environmental Protection Agency, 1996. AP-42, Fifth Edition, Compilation of Air Pollutant Emission factors, Volume 1: Stationary Point and Areas Sources, Section 3.3, Stationary Internal Combustion Sources, Gasoline and Diesel Industrial Engines, Final Section, Supplement B, October 1996. Available at http://www.epa.gov/ttn/chief/ap42/ch03/final/c03s03.pdf

EPA, 1997: US Environmental Protection Agency, 1997. Emission Factor Documentation for AP-42 Section 9.10.1.1, Sugarcane Processing, Final Report, June 1997. Available at http://www.epa.gov/ttn/chief/ap42/ch09/bgdocs/b9s10-1a.pdf

EPA, 2004: US Environmental Protection Agency, 2004. Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling--Compression-Ignition, EPA420-P-04-009, April 2004, NR-009c. Available at http://www.epa.gov/oms/models/nonrdmdl/nonrdmdl2004/420p04009.pdf.

EPA, 2005: US Environmental Protection Agency, 2005.Conversion Factors for Hydrocarbon Emission Components, EPA420-R-05-015, December 2005, NR-002c. Available at http://www.epa.gov/oms/models/nonrdmdl/nonrdmdl2004/420r05015.pdf.

EPA, 2009a: US Environmental Protection Agency, 2009. Agriculture, Ag 101, Crop Production. Retrieved December 2009 from http://www.epa.gov/agriculture/ag101/printcrop.html.

ERS, 2009a: Economic Research Service, 2009. Sugar and Sweeteners Yearbook Tables: Excel Spreadsheets, Economic Research Service, US Department of Agriculture. Retrieved November 2009 from http://www.ers.usda.gov/briefing/sugar/data.htm .

Fageria *et al.*, 1997: Fageria, N.K.; Baligar, V.C.; Jones, Charles Allan, 1997. Growth and Mineral Nutrition of Field Crops, 2nd edition, New York: Marcel Dekker.

Gilbert and Rice, 2006: Gilbert, R.A. and Rice, R.W., 2006. Nutrient Requirements for Sugarcane Production on Florida Muck Soils, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS-AGR-228. Original publication date August 1993. Revised August 2006. Available at http://edis.ifas.ufl.edu/sc0286

Haley and Dohlman, 2009. Haley, Stephen and Dohlman, Erik, 2009. Sugar and Sweeteners Outlook, Economic Research Service, US Department of Agriculture, SSS-256, October 5, 2008. Available at http://www.ers.usda.gov/publications/SSS/2009/SSS256.pdf.

Hodges *et al*., 2008: Hodges, Alan W.; Mulkey, W. David; Spreen, Thomas H.; Clouser, Rodney L., 2008. Economic Impacts of the U.S. Sugar Corporation in Florida: Implications of the Purchase by the State of Florida, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report FE754. October 2008. Available at http://edis.ifas.ufl.edu/pdffiles/FE/FE75400.

Hugot, 1972: Hugot, E., 1972. *Handbook of Cane Sugar Engineering*, New York: Elsevier Publishing Company.

IPCC, 2006a: Intergovernmental Panel on Climate Change, 2006. Energy, Volume 2 in 2006 IPCC Guidelines for National Greenhouse Gas Inventories, NGGIP Publications. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

IPCC, 2006b: Intergovernmental Panel on Climate Change, 2006. Agriculture, Forestry and Other Land Use, Volume 4 in 2006 IPCC Guidelines for National Greenhouse Gas Inventories, NGGIP Publications. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC, 2007: Intergovernmental Panel on Climate Change, 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press.

IPM, 2008: Integrated Pest Management National Center, US Department of Agriculture. Retrieved, December 2009 at http://www.ipmcenters.org.

Irvine, 2004: Irvine, James E., 2004. Sugarcane Agronomy in *Sugarcane*, 2nd edition, James, Glyn, ed., World Agriculture Series, Ames, Iowa: Blackwell Science Ltd.

James, 2004: James, Glyn, L, 2004. An Introduction to Sugarcane in *Sugarcane*, 2nd edition, James, Glyn, ed., World Agriculture Series, Ames, Iowa: Blackwell Science Ltd.

Jorapur and Rajvanshi, 1997: Jorapur, Rajeev and Rajvanshi, Anil K. 1997: Sugarcane Leaf-bagasse Gasifiers for Industrial Heating Applications, *Biomass and Bioenergy*, 13 (3) 141-146.

Junker, 2004: Junker, Beth, 2004. Fermentation in *Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed*, John Wiley & Sons, Inc.

Lang *et al*., 2002: Lang, T. A.; Daroub, S. H.; and Lentini, R. S., 2002. Water Management for Florida Sugarcane Production in *Sugarcane Handbook*, Gilbert, R.A., ed., Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida, Report SSAGR231, First printed August 1993 Revised May 2002. Available at http://edis.ifas.ufl.edu/sc031.

Macedo *et al*., 2004: Macedo, Isaias de Carvalho; Leal, Manoel Regis Lima Verde; and da Silva, João Eduardo Azevedo Ramos, 2004. Assessment of Greenhouse Gas Emissions in the Production and Use of Fuel Ethanol in Brazil, Government of the State of São Paulo, March 2004. Available at http://www.wilsoncenter.org/events/docs/brazil.unicamp.macedo.greenhousegas.pdf.

Marella, 2008: Marella, Richard L., 2008. Water Use in Florida, 2005 and Trends 1950-2005. U.S. Geological Survey, U.S. Department of the Interior, Fact Sheet 2008-3080. Available at http://pubs.usgs.gov/fs/2008/3080/.

Miller and Gilbert, 2006: Miller, J.D. and Gilbert, R.A., 2006. Sugarcane Botany: A Brief View in *Sugarcane Handbook*, Gilbert, R.A., ed., Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS-AGR-234. Original publication date August 1993. Revised May 2006. Available at http://edis.ifas.ufl.edu/sc034.

Muchovej, 2008: Muchovej, R.M., 2008. Rotational Crops for Sugarcane Grown on Mineral Soils in *Sugarcane Handbook*, Gilbert, R.A., ed, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SSAGR169l, April, 2008. Available at http://edis.ifas.ufl.edu/sc053.

MWSC, 2009: Mississippi Weed Science Committee, 2009 Weed Control Guidelines for Mississippi, Mississippi State University Extension Service, Publication 1532, rev-1000-02-09. Available at http://msucares.com/pubs/publications/p153209whole.pdf.

Nemeck and Kägi, 2007: Nemeck, Thomas and Kägi, Thomas, 2007. *Life Cycle Inventories of Agricultural Production Systems*, Swiss Centre for Life Cycle Inventories, ecoinvent report No.15, Uster, December 2007.

NRCS, 2007: Natural Resources Conservation Service, 2007, Data in National Resources Inventory, 2003 Annual NRI, State Report, USDA, February 2007. Available at http://www.nrcs.usda.gov/technical/NRI/2003/statereports/2003summaryreport.txt

NRCS, 2009: Natural Resources Conservation Service, 2009. *Saccharum* L., in Plants Database, US Department of Agriculture. Retrieved December, 2009 from http://plants.usda.gov/java/profile?symbol=SACCH

Ohyama *et al*., 2008: Ohyama, Takuji; Momose, Atsushi; Ohtake, Norikuni; Sueyoshi, Kuni; Sato, Takashi; Nakanishi, Yasuhiro; and Akao, Shoichiro, 2008. Nitrogen Fixation and Translocation in Sugarcane. *Nature Precedings*. Available at http://precedings.nature.com/documents/2360/version/1.

Parish, 2005: Parish, Richard L., 2005. Implements for Compact Tractors: Selection, Use, Maintenance and Safety, Louisiana State University Agricultural Center, Publication 2917, May, 2005. Available at http://www.lsuagcenter.com/NR/rdonlyres/C705F0EB-DF80-4EFB-963B-31C4721758AE/11557/pub2917tractorimplements1.pdf

Rahmani and Hodges, 2006: Rahmani, Mohammad and Hodges, Alan, 2006. Potential Feedstock Sources for Ethanol Production in Florida, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS-AGR-650, July 2006. Available at http://edis.ifas.ufl.edu/fe650.

Rainbolt and Gilbert, 2008: Rainbolt, Curtis and Gilbert, Robert, 2008. Production of Biofuels Crops in Florida: Sugarcane/Energycane, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS AGR 298. Available at http://edis.ifas.ufl.edu/ag303.

Rice *et al*., 2006: Rice, R.W.; Gilbert, R.A; and Lentini, R.S., 2006. Nutritional Requirements for Florida Sugarcane, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SS-AGR-228. Original publication date August 1993. Revised August 2006. Available at http://edis.ifas.ufl.edu/sc028.

Roka *et al*., 2009: Roka, Fritz M.; Alvarez, Jose; and Baucum, Leslie E., 2009. Projected Costs and Returns for Sugarcane Production on Mineral Soils of South Florida, 2007-2008, Institute of Food and Agricultural Sciences (IFAS) Extension, University of Florida. Report SC087, September 2009. Available at http://edis.ifas.ufl.edu/sc087.

Salassi and Champagne, 1998: Salassi, Michael E. and Champagne, Lonnie P., 1998. A Spreadsheet-based Cost Model for Sugarcane Harvesting Systems, *Computers and Electronics in Agriculture*, 20 (3) 215-227.

Salassi and Deliberto, 2008: Salassi, Michael E. and Deliberto, Michael, 2008. Sugarcane Production in Louisiana: 2008 Projected Commodity Costs and Returns, Farm Management Research and Extension, Department of Agricultural Economics and Agribusiness, A.E.A. Information Series No. 253, January 2008. Available at http://text.lsuagcenter.com/NR/rdonlyres/7586D630-9D92-42D4-ADE6-3E5965CA0DEE/42547/SugarBudgets2008.pdf

Salassi and Deliberto, 2009: Salassi, Michael E. and Deliberto, Michael, 2009. Sugarcane Production in Louisiana: 2009 Projected Commodity Costs and Returns, Farm Management Research and Extension, Department of Agricultural Economics and Agribusiness, A.E.A. Information Series No. 260, January 2009. Available at http://www.lsuagcenter.com/NR/rdonlyres/F1FC7937-B95B-47F9-BAE2-3F4F12A0B6BB/54641/2009SugarcaneProjectedBudgets.pdf

SFWMD, 2009. South Florida Water Management District, DBHYDRO Environmental Monitoring database. Available at http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_era/pg_sfwmd_era_dbhydrobrowser.

Shaffer *et al*., 2009: Shaffer, Steve; Paredes, Lauro; Summers, Matthew; Kim, Dae Hyuan, 2009. Feasibility of Biomass Energy Production to Support Local Water Self-Sufficiency, Report to the Western Governors Association, January, 2009. Available at http://www.westgov.org/index.php?option=com_content&view=article&id=218&Itemid=80.

Shapouri and Salassi, 2006: Shapouri, Hossein and Salassi, Michael, 2006. The Economic Feasibility of Ethanol Production from Sugar in the United States. US Department of Agriculture, Office of Chief Economist, July 2006. Available at http://www.usda.gov/oce/reports/energy/EthanolSugarFeasibilityReport3.pdf.

Soreng, 2009. Soreng, Robert, 2009. *Saccharum L*. (Sugarcane), USDA-NRCS PLANTS Database, Smithsonian Institution, Department of Systematic Biology-Botony. Used with permission. Retrieved December, 2009 from http://plants.usda.gov/java/largeImage?imageID=sacch_001_avp.tif

Sutter, 2007a: Sutter, Jürgen, 2007: Sugarcane Production in Brazil in *Life Cycle Inventories of Bioenergy*, Jungbluth, Neils, ed. Swiss Centre for Life Cycle Inventories, ecoinvent report No.17, Uster, December 2007.

Sutter, 2007b: Sutter, Jürgen, 2007: Ethanol 99.7% in H_2O from Sugar Cane in *Life Cycle Inventories of Bioenergy*, Jungbluth, Neils, ed. Swiss Centre for Life Cycle Inventories, ecoinvent report No.17, Uster, December 2007.

TAES, 2007: Texas AgriLife Extension Service, 2007. Projected 2008 Texas Crop and Livestock Budgets, Extension Agricultural Economics. Available at http://agecoext.tamu.edu/resources/crop-livestock-budgets/by-commodity/fruits-and-vegetables.html

Thomas, 2009. Thomas, Mike, 2009. Governor Charlie Christ Fumbles Chance to Revive River of Grass, Commentary, Orlando Sentinel, December 26, 2009.

Uribe, 2006. Uribe, Rufino, 2006. Venezuelan Sugar Cane (*Saccharum*) Harvested for Processing. Originally posted http://www.flickr.com/photos/rufino_uribe/212125878/. Free content license. Retrieved December, 2009 from http://en.wikipedia.org/wiki/File:Cut_sugarcane.jpg.

USDA, 2009a: US Department of Agriculture, 2009. 2007 Census of Agriculture, Volume 1, Geographic Area Series, Part 51, AC-07-A-51, US Department of Agriculture. Issued February 2009, Updated, September 2009. Available at http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf

USNA, 2003. US National Arboretum, 2003. USDA Plant Hardiness Zone Map, US Department of Agriculture. Accessed November 2009 at http://www.usna.usda.gov/Hardzone/index.html

Wang *et al*., 2007: Wang, Michael; Wu, May; Huo, Hong; and Liu, Jiahong, 2007. Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Brazilian Sugarcane Ethanol Production Simulated by Using the GREET Model, Center for Transportation Research, Argonne National Laboratory, US Department of Energy, July 20, 2007..Available at http://www.dep.state.fl.us/ClimateChange/team/file/2007_0720_wang_suga_cane_ethanol_paper.pdf

Wiedenfled, 2004: Wiedenfled, Bob, 2004. Scheduling Water Application on Drip Irrigated Sugarcane, *Agricultural Water Management*, 64 (2) 169-181.

Wiedenfeld, 2009: Wiedenfled, Bob, 2009. Effects of Green Harvesting vs Burning on Soil Properties, Growth, and Yield of Sugarcane in South Texas, *Journal of the American Society of Sugar Cane Technologists*, 29: 102-109.

WorldClimate, 2008: WorldClimate database. Retrieved 2009 from www.worldclimate.com.