Chapter 10

Sugar Beet (*Beta vulgaris* L) as a Biofuel Feedstock in the United States

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Sugar beet is a biennial plant, which produces an enlarged root and hypocotyl in the first year, in which it stores sucrose to provide energy to flower in the next season. Technically, conversion of sugar to ethanol is a simple process requiring only yeast fermentation. A 2006 USDA study calculated the yield of ethanol from the sucrose in a sugar beet was 103.5 L per tonne of root (wet weight). Life cycle analysis (LCA) indicates that bioethanol from sugar beet reduces green house gases as well or better than maize. Both nitrogen and water use efficiency may be superior to maize on average. However, sugar beet with an area of 465,000 ha in 2009, compared with about 32 million ha of maize, likely will not displace maize as the primary feedstock for bioethanol in the U.S. More likely, co-products like pulp and molasses will find use as bioenergy feedstocks, probably for high value specialty fuels or as feedstocks for a whole generation of petroleum plastic substitutes.

Introduction

Sugar beet (*Beta vulgaris*, L) is a biennial plant. In the first year, it produces an enlarged root and hypocotyl, in which it stores sucrose that provides energy used to flower in the next season. Sugar beet typically is cultivated in the northern temperate zones, between 30° and 60° (*1*), where it is primarily a spring

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planted crop. There also are areas of cultivation in the southern temperate zones, including Chile, Venezuela, and Uruguay (*2*). It also can be cultivated as a winter crop, "winter beet", (planted in the autumn and harvested the next summer) in Mediterranean regions and some arid tropical and sub-tropical areas, if irrigation water is available or rainfall is sufficient.

Although domestication of beet as a leafy vegetable and root crop took place in prehistoric times, sugar beet is a relatively new crop plant (*3*). The European beet sugar industry was able to develop once the technology to measure sucrose concentration in solution was discovered, and the spread of this industry was accelerated by increased demand for beet sugar caused by the British blockade of continental Europe in the early 19th century. Starting in France and Germany, the beet sugar industry spread throughout Europe, to North and South America, Asia, and North Africa (*2*).

About 35% of global sugar production and 50-55% of the domestic (U.S.) sugar production comes from sugar beet, equating to about 8.4 million metric tons (*4*). Some sugar beet currently is used for fuel ethanol production and, in Europe over the past three years, this has increased sharply because of restructuring of the European Sugar Regime (*5*). Production of sugar beet in 2009 in the U.S. was 26.7 million tonnes on 465.6 thousand hectares at a value of approximately $1.3 billion (*6*). Sugar beet was grown in 12 states and processed in 22 sugar beet factories.

Sugar beets are refined directly into white sugar at processing plants (see (*7*) for details of this process). Sucrose content in sugar beet ranges from 16-20% (wet weight). The major co-products from sugar beet processing are molasses, consisting of soluble impurities including some sucrose, which remains after sucrose extraction from the juice; and pulp, which consists of root material from which the sucrose has been extracted (*8*). Both are used as animal feed.

Technically, conversion of sugar to ethanol is a simple process requiring only yeast fermentation, whereas producing ethanol from maize, e.g., requires enzymes to convert starch to sugars (*9*).

The Sugar Beet Plant as a Biofuel Feedstock

Sugar beet is planted as early as possible in temperate areas because there is a direct correlation between the amount of solar radiation intercepted by sugar beet leaves and the sucrose stored in the root (*10*, *11*). However the sugar beet seedling is sensitive to cold and will not survive prolonged exposure to air temperatures below -2.5 °C (*12*).

The amount of sucrose extracted per area is dependent on three factors, the weight of the beets harvested, the percentage sucrose in those beets, and the amount of the sucrose that is extractable. Even though the beet root may contain up to 20% sucrose by fresh weight, the average percent extracted is less. Cations such as Na^+ and K^+ and small amino nitrogen compounds (e.g., glycine, betaine, and glutamine) interfere with the extraction and re-crystallization of sucrose (*13*). The average percent sucrose recovered from the U.S. crop from 2000-2009 was 15.3% (*6*). The portion of juice that is left over once all of the extractable sucrose

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has been removed is the molasses, which represents about 4% of the weight of one tonne of sugar beet and has a sucrose percentage of about 50% (*14*).

Pulp or marc remains after the sucrose and molasses have been extracted from the crop. The pulp represents the 22-28% of the dry mass of the sugar beet root that is not solubilized during the sugar beet extraction process (*15*). The weight of beet tops ranges from 4.6 to 7.5 tonnes per hectare (*15*), and beet tops have feed value, but are usually left in the field at harvest.

In a 2006 USDA study, it was estimated that the yield of ethanol from the sucrose in an average sugar beet crop was 103.5 L per tonne of root (wet weight) (*14*). This calculation was based on a refined sucrose recovery of 15.5% (of wet weight), and a yield of 20 kg of sucrose from a tonne of beet molasses (*14*). The authors based their calculations on a theoretical (stoichiometric) yield of 680 liters per metric tonne of sucrose and then assumed an obtainable yield of 86.6% (*14*).

In the 2006 USDA study, only sucrose or molasses was examined as a potential biofuel feedstock. The pulp contains 80 to 94% fermentable components (pentosans, pectins, and cellulose) and only 12 to 16% lignin, crude protein and mineral substances (*16*). Therefore, much of the pulp could provide additional biofuel feedstock if the sugars were released from the biomass. Atlantic Biomass Conversions (Frederick, MD) has reported that it is theoretically possible to solubulize 50-60% of the available sugars with an enzyme digestion method (*17*). The co-product of this process is a protein pellet of about 35% crude protein, which has value as animal feed (*17*). If pulp could be solubilized to fermentable sugar, it would provide an alternative feedstock source from sugar beet that was not considered into the 103.5 L/tonne calculation of Shapouri *et al.* (*14*).

The beet root dry weight is about 24% of the root yield fresh weight (*15*). The pulp of the sugar beet root is about 25% dry weight of the sugar beet root, (sucrose averaging about 75% of the dry root weight), therefore one tonne of sugar beet (fresh weight) yields about 6.0% pulp (fresh weight) (*15*). If 40% of a tonne of pulp (dry weight) could be converted to fermentable sugars (sucrose equivalent), the pulp would yield approximately 235 liters of ethanol (using the predicted yield of Shapouri *et al.* (*14*). One tonne (dry weight) of pulp is produced for every 17 tonnes (fresh weight) of beets harvested. The total ethanol yield per tonne of sugar beet than could equal 117 liters (assuming 40% conversion of the pulp) rather than the 103.5 liters estimated in the USDA study (*14*). The enzymatic digestion of the pulp would add a cost to the ethanol production, however, very little additional energy costs. Alternatively, von Felde (*18*) has estimated that a larger amount of energy is extractable from beets using anaerobic digestion methods for whole beets to produce bio-methane, compared to ethanol. This is a potential energy resource that should be studied in more depth.

Potential U.S. Sugar Beet Yields and Acreage

Sugar beet sucrose yield (all three components) or energy yield depends on a number of environmental and cultural factors. These include whether the crop is irrigated or rain fed, length of growing season, latitude (determining day length), disease pressure, soil type and fertility, and presence or absence of other abiotic stresses (drought, temperature, CO_2 levels, etc.) (*19*). Assuming no other significantly limiting factor, the sucrose concentration of the harvested root is proportional to the amount of solar radiation intercepted by a full canopy (*11*). Sugar beet is well adapted to a wide range of soil types and is able to thrive in soils with a pH above 6.5. In the United States sugar beet has been cultivated in soil types ranging from peat soils (San Joaquin Delta, CA) to rich loam soils of the Midwest and in low organic matter, slightly saline, mineral desert soils with a pH greater than 8.0. In arid to semi-arid sub-tropical areas, with sufficient irrigation, sugar beet will survive temperatures upwards of 40 °C. However, in humid tropical and sub-tropical areas, disease can limit production at high temperature.

Within the U.S., the four main growing regions have very different root yields per hectare (Figure 1) as well as total regional production based on total regional area cultivated (Figure 2). The per hectare yield differences are due to different agronomic practices and growing conditions. The highest yields are in the Far West, which consists primarily of Idaho, with smaller acreages in Oregon, Washington, and California. The only growing area left in California is in the Imperial Valley, where sugar beet is grown as a winter crop, i.e., planted in the fall and harvested early the next summer. The crop is irrigated in this area and the growing season is long (from mid-September until mid-July). The Far West region was about 17% of the 2009 growing area (*6*).

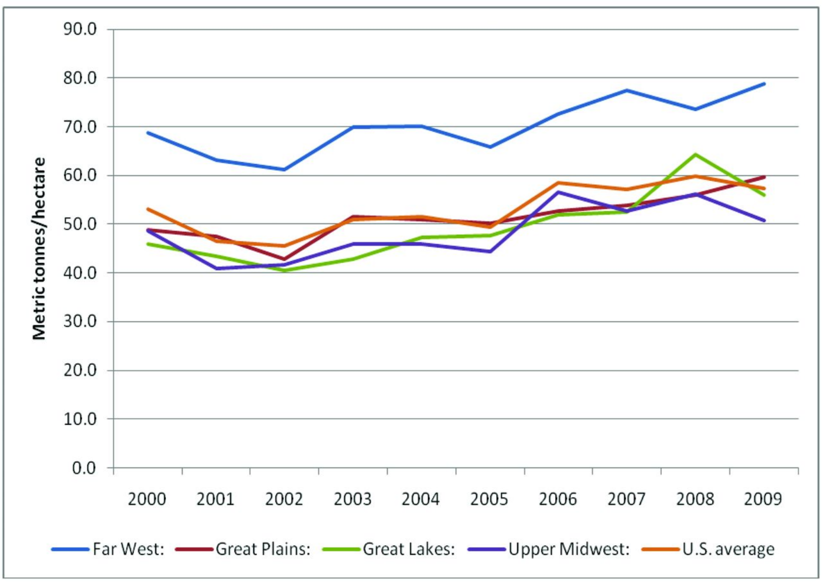

Figure 1. Yield per hectare in the four U.S. growing regions over the last ten years. Although there are year to year fluctuations, the general trend is increasing yield.

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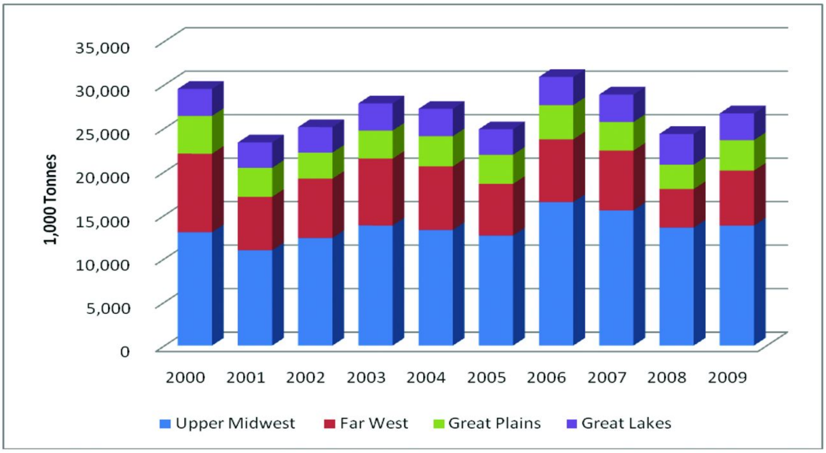

Figure 2. This graph indicates total production in metric tonnes in the United States over the last ten years by growing area. There is a trend toward higher yields even though the area cultivated is below historical highs.

The largest growing area in the U.S. is the Upper Midwest consisting of Minnesota and North Dakota. It is in the northernmost part of the continental U.S. and, therefore, has long summer days. The Great Lakes region consists of beets cultivated in Michigan (and Ontario, Canada). However the crop grown in both regions is not irrigated and has a short growing season, therefore. average yields are the lowest in these growing areas. Nonetheless, with about 58% of the 2009 growing area, the Upper Midwest's total production leads the U.S. (Figure 2). The Great Lakes area's production (12.6% of the U.S.) is similar to production in the Great Plains (Montana, Wyoming, Colorado, and Nebraska (11.8 % of the U.S.) (*6*). The yields of the two growing areas are similar despite the fact that the Great Plains' crop is grown with irrigation.

Sugar beet production in the United States is determined by domestic marketing allotments allowing the Cooperatives producing sugar to market an amount of sugar based on historical production in their growing area (*20*). For this reason, sugar beets are planted only if the grower has a contract for processing. Current sugar prices are high and projected to stay that way throughout 2010 (*21*) and, therefore, there is little interest in diverting refined sucrose into biofuel processing. However, sugar beet cultivation has moved into the Upper Midwest over the past 20 years due, at least in part, to the lower cost of production in this region. Therefore many former growing areas have less area cultivated for sugar beet than their historical highs.

If sugar beet were grown exclusively as an energy beet, many of the areas where it has been grown in the past would be the logical first places to look to for increased production. A recent study for the Washington State Department of Agriculture (*22*) looked at the feasibility of ethanol production from a sugar beet feedstock. In the past, sugar beet has been produced on 37,000 hectares in Washington State (*6*), however, only about 650 hectares were grown in 2008 and none in 2009. Nonetheless, Washington State has had high yields, comparable

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to California, which has had the highest in U.S. (Table I) (*6*). The report concludes that three factors would have to converge to increase the likelihood of successfully producing ethanol from sugar beet in Washington State. They are: the simultaneous (i) increase of the price of oil, (ii) increase of the cost of corn (maize), and (iii) the decrease of the price of refined sugar (*22*). This would increase the economic competitiveness of sugar beet as an ethanol feedstock nationwide.

Table I. Area Harvested and Average Yield for the Last Three Years by U.S. State within Growing Region

	Hectares Harvested			*Yield Mg/ha*		
	2009	*2008*	*2007*	*2009*	*2008*	*2007*
Great Lakes:						
Michigan	55039	55039	60300	56.0	64.3	52.4
Upper Midwest:						
Minnesota	184139	161475	194661	51.5	55.3	53.3
North Dakota	87415	79726	99961	49.3	58.0	51.7
Great Plains:						
Colorado	14165	11574	11817	62.1	59.4	58.7
Montana	13315	12424	19021	65.4	60.0	55.3
Nebraska	21247	15095	17928	54.9	50.6	52.6
Wyoming	10118	10967	12222	58.2	54.9	48.8
Far West:						
California	9956	10279	15824	89.6	88.9	79.5
Idaho	65966	46945	67585	76.8	69.9	77.1
Oregon	4249	2388	4452	82.3	74.0	71.5
Washington	---	648	809	---	93.8	94.1

Winter Beets

Another area, in which the production of biofuels from sugar beet is being considered, is California (Figure 3). Storing the harvested sugar beet roots is one of the largest obstacles to using only sugar beet as a biofuel feedstock, because they degrade in quality much more quickly than does grain in storage. The Sacramento and San Joaquin Valleys of California are climates in which beets can be grown as both spring and fall planted crops, and harvested daily for 6 to 7 months. If anaerobic digestion were the primary conversion technology, additional beets might be ensiled to allow additional months of operation.

When sugar beet is treated as a fall planted crop in some areas of the world (sub-tropical and tropical, plus arid), including the Imperial Valley of California, it is planted late summer and harvested the following late spring and summer (210 to 300 days from planting). The advantage to growing winter beet is that yields can be much higher due to longer growing season (nine months instead of six or seven). In Mediterranean climates, Fall-planted beets have better water use efficiency than spring planted beets due to greater water use efficiency during periods with cooler temperatures and more frequent rainfall throughout the winter. Disease pressure also may be reduced. Disadvantages to growing winter beet include breeding for extreme tolerance to bolting because the cooler winter temperatures may approach the temperature needed for vernalization and flowering. Although the disease pressure may be reduced, there often is a different spectrum of disease and insect problems than seen in spring planted sugar beet, and winter beet hybrids must contain a different suite of resistances to these pests and diseases. Finally the logistics of harvest are more complicated because roots cannot be stored for more than a few days before processing (*23*, *24*). Many of the specific practices are reviewed in Cooke and Scott (*25*) and Draycott (*19*). Irrigation of winter beet has been reviewed (*26*, *27*).

Figure 3. Harvesting over-wintered beets in Brawley, California, in June, 2008.

Table II. Imperial Valley of California Harvest Results from 1998 – 2007 (Personal Communication, Ben Goodwin)

Crop Year	*Hectares Harvested*	*Tonnes/ha*	*% Sucrose*	*Kg Refined sucrose/ha*
2007	9620.9	85.2	17.3	14739.2
2006	9616.5	82.9	16.8	13932.8
2005	9471.6	86.4	16.7	14441.3
2004	10439.2	96.3	16.5	15921.9
2003	10565.5	96.7	16.2	15633.0
2002	10367.2	95.0	16.7	15904.0
2001	10634.7	93.3	15.5	14416.6
2000	12750.5	86.5	16.3	14050.4
1999	12902.6	90.3	17.0	15374.2
1998	13822.9	80.9	17.2	13932.8
Average	11019.2	89.3	16.6	14834.6

Yields in California averaged 86.0 tonne/ha during the years of 2007 through 2009 (Table I). In the Imperial Valley, where only fall-planted beets are grown, that average over 10 years was 89 tonnes/ha (Table II, Ben Goodwin, personal communication). However, there is an approximate doubling of yield between the fields harvested in April (60 t/ha) and early August (120 t/ha) because the beet crop continues to accumulate dry matter until harvest (*28*). For this reason, the winter beet yield potential is much greater in irrigated Mediterranean and semi-arid to arid conditions with modern agronomic practices than in regions with more temperate or continental climates. For example, the highest known commercial yield (142.4 tonnes/ha) was observed in 2004 in the Imperial Valley of California from a 33 ha field (80 acres), harvested in July, which produced an average 23.5 tonnes/ha gross sugar (*28*). This is a tremendous potential ethanol yield per hectare.

The theoretical ethanol yield from crops with such high yields is very large. For 2007 average yields in the Imperial Valley, approximately 9,400 L of ethanol can be produced per ha on average (1000 gal/ac). This is more than double average ethanol yields from United States maize in 2009 (4660 L/ha), average estimated sugarbeet ethanol yields (5,100 L/ha), or average sugarcane ethanol yields in Brazil of 6,800 L/ha) (*14*, *29*, *30*).

Life Cycle Analysis (LCA)

Life cycle analysis is a methodology that attempts to evaluate the net green house gas (GHG) effects generated from the extraction of the raw materials to the end of their use during the production of a product or service. There are international standards that provide the framework, guidelines, principles,

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requirements, etc. for conducting LCA studies (ISO 14040:2006 and 14044:2006) (*31*). LCAs are used by a number of governmental agencies to make decisions to promote or mandate biofuels (*32*). LCA calculates the direct effects of biofuel production and use from feedstock production and assembly to transformation and ultimate use in vehicles. Based on the analysis of direct effects, most LCAs indicated that first generation biofuels result in GHG savings compared to petroleum based gasoline or diesel. There is debate, however, that calculating only direct effects misses other important consequences from crop use for biofuels, resulting from market-mediated pressures to convert new lands to agriculture to substitute for land diverted from traditional food or feed production (*33*, *34*). This issue is in dispute and discussion is beyond the scope of this review. First generation biofuels (bioethanol from maize or sugarcane) and biodiesel from fats, oils, and greases (FOG) (principally soybean oil) have been subjected to a number of LCAs (*31*, *35*). Some second generation biofuels like switchgrass also have received attention. Since LCA methods and assumptions differ, they are not easily compared with each other. A recent and thorough assessment estimates that direct green house gas emissions from sugar beet produced in Europe on average are 40 g CO /MJ of fuel energy. This compares in the same analysis 70 for ethanol made from wheat, 43 for maize and 24 for Brazilian sugarcane (*36*). Based on this analysis and excluding any calculations for indirect GHG emissions, sugar beet would qualify as an advanced biofuel under US EPA's classification system (*32*).

Because the commercial production of biofuel (ethanol) from sugar beet occurs in Europe (*37*), most LCAs for sugar beet have been done for central European conditions (*31*, *38*, *39*). In these evaluations, GHG reduction from sugar beet is comparable or better than that of maize or sugarcane (see Table 5.1, p 85 in Menichetti and Otto (*31*) comparing maize, sugarcane, wheat and sugar beet). However, both sugar beet and maize production in central Europe is different from production in the United States. Maize yields in the United States are typically higher and sugar beet growing areas in the western U.S. are irrigated. Sugar beet production in western, irrigated regions like California and Washington have both higher yields and additional, regionally variable energy costs associated with irrigation that are not accounted in most European estimates. The need to qualify LCA analysis under different environmental conditions is noted in the literature (*35*, *40*).

Nitrous oxide (N_2O) is a more potent GHG than CO_2. It is released in small amounts from soils and is related to fertilizer, manure or cover crop use in farming (*41*), but since it is 300 times more effective at atmospheric warming than CO_2, its loss is important. In a broad-scale analysis, Smeets et al. (*41*) concluded that sugar beet and sugarcane reduced N_2O emissions more than maize, with resulting greater GHG savings (*41*). Sugar beet production was based on estimates from the EU25 nations or East Europe, and the authors emphasized that 'optimized management' for cultivation of the crop had a significant effect on N_2O generation, especially optimization of nitrogen fertilization (*41*). Increased fertilizer use efficiency, resulting in greater biomass yields at the same or reduced levels of fertilizer use has been reported for sugar beets in Europe and California (*42*, *43*). Increasing resource use efficiency, where it occurs, is a positive basis for the use of crops and crop residues for biofuels, while static or declining resource

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use efficiency would make it unwise to use sugar beets or any other crop for bioenergy purposes (*43*).

Another resource requirement that has been evaluated is the water needed (or water footprint) for bioenergy crop production. Gerbens-Leenes *et al.* (*44*), in a country-scale study, found sugar beet and potato, followed by sugarcane to be more efficient than maize and sorghum as sources for biofuels in most regions of the world. In most respects, bioethanol from sugar beet compares favorably with maize in most environments.

Breeding an Energy Beet for Production in the United States?

In the United States over the next few years, economic conditions imply that sugar beet will be grown as a sugar crop. However, if sugar beet is eventually used solely as a biofuel feedstock, depending on the conversion technology used, biomass yield may become a more important breeding goal than sucrose yield (*18*). Previous research has shown that higher biomass yields are obtainable using fodder beet germplasm as a parent in hybrids with sugar beet (*45*, *46*). In an older study, Geng *et al.* (*47*) compared fodder beet, sugar beet, sweet sorghum, and maize for potential ethanol yields and reported that fodder beet resulted in the largest ethanol yields of the group under equivalently well-managed conditions. This research should be repeated with modern sugar beet and fodder beet germplasm. Because the potential yield of biomass is correlated with interception of solar radiation (*48*), winter beets, typically with a longer growing season than spring-planted beets, have a much higher yield potential. This is one reason that sugar beet is being investigated throughout the semi-arid tropics as a potential bioenergy feedstock (*49*) as well as in temperate regions of Asia (*50*, *51*).

Even though LCA may indicate that sugar beet is a better feedstock than maize, because area of sugar beet cultivation in the United States in 2009 was about 465 thousand hectares (*6*) and the area of maize cultivation about 32 million hectares (*52*), sugar beet cannot displace maize as a feedstock for bioethanol. Beets also are more costly to produce than maize in the United States and result in larger estimated per unit costs of ethanol, while sugar also remains a more valuable commodity than ethanol (*14*).

Sucrose is a source for many value-added feedstock chemicals or sucrose derivatives, but currently only about 2% of sucrose worldwide is used for such purposes (*7*). In addition to sucrose, sugar beet roots contain about one-third each of cellulose, hemicelluloses, and pectin, with very little lignin (*8*). Each compound is used or can be used as the source of several important industrial feedstock chemicals, and use for this purpose has significant potential for growth (*53*). For example, Fishman and co-workers (*54*, *55*) recently reported on the use of sugarbeet pulp as a source of carboxyl methyl cellulose and polysaccharides with industrial uses. As modern economies reduce or transform their use of oil, it is possible that sugar beets will become a feedstock for a range of chemicals and new biomass-derived specialty materials.

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