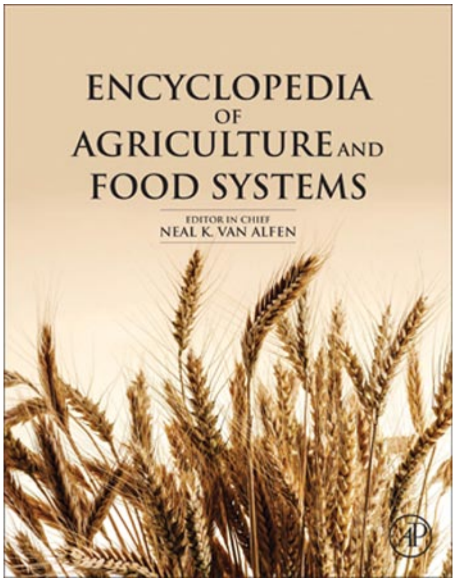

Kaffka S.R., and Grantz D.A. Sugar Crops. In: Neal Van Alfen, editor-in-chief. Encyclopedia of Agriculture and Food Systems, Vol. 5, San Diego: Elsevier; 2014. pp. 240-260.

Sugar Crops

SR Kaffka, University of California, Davis, CA, USA
DA Grantz, University of California, Riverside, CA, USA

Glossary

Bagasse Fibrous material remaining after crushing and extracting juice from sugarcane stalks.
Biomass Dry matter produced by plants.
Bolting The formation of seed stalks by sugar beet.
C3 Photosynthetic system of most plants of temperate regions.
C4 Photosynthetic system of many important tropical crop plants, including grasses, such as maize, sorghum, and sugarcane.
Evapotranspiration The loss of water from a given area by evaporation from the soil surface and by transpiration from plants.
Mega grams per ha ($Mg\ ha^{-1}$) An equivalent to metric tons per ha; when multiplied by 0.446 equals short tons (2000 pounds) per acre.
Photosynthesis The process by which green plants utilize the sun's energy to produce carbohydrate from carbon dioxide and water.
Photosynthetically active radiation The spectral range of solar radiation from 400 to 700 nm used by plants for phtotosynthesis.
Stand The number and distribution of plants after emergence from seed or vegetative cuttings.
Sucrose ($C_{12}H_{22}O_{11}$) The sugar of world commerce.
Ton 2000 lb, when multiplied by 1.102 equals 1 MT (mg).

Overview

Sucrose, the common sugar of commerce, is synthesized in most plants as a temporary storage product for photosynthetically reduced carbon, and it is the principal form of carbon transported in plants. Sucrose is typically converted into starch for long-term storage, especially in the seeds of plants, but accumulates to an exceptional degree in unmodified form in sugar beet (*Beta vulgaris* L.) and sugarcane (*Saccharum officinarum* L.). These two crops produce nearly all of the world's supply of sucrose, the 'sugar' of commerce. Small amounts of sucrose and alternative sweeteners are produced from sorghum, agave, stevia, and other sources of natural sweeteners; from high fructose syrup derived from maize grain; and increasingly from noncaloric synthetic sweeteners. Sugar production is a global, agroindustrial enterprise, with 123 countries producing sugar (43 beet, 71 cane, and 9 both, Figure 1). In 2013, approximately 20% of the world's sugar supply was derived from beets and nearly 80% from sugarcane (FAOSTAT, 2013). The most recent estimate for world sugar (sucrose) production is 160 million metric tons. Sugar consumption has been growing at roughly the same rate as world population or 2% per year. There are substantial differences in per capita sugar consumption among nations worldwide. It is highest in Europe and lowest in China and Africa. Sucrose from cane and beets is also converted into ethanol and a wide range of consumer products and feedstock chemicals, substituting for nonrenewable petroleum.

Sugarcane is a perennial tropical grass with highly efficient C4 photosynthesis, high yields, and the ability to provide harvests for several years without replanting. It is suitable for low-technology hand planting and harvest as well as amenable to automation. Production is heavily concentrated in the countries of South America and Asia (Table 1). Brazil has the largest area devoted to sugarcane production for both sugar and ethanol and dominates world sugarcane production. A crop of temperate and Mediterranean regions (Figure 1), sugar beet is a biennial crop grown as an annual. For the most part, it is intensively farmed and is one of the most efficient crop plants. Over time, production technology has come to include a long list of innovations in plant breeding, mechanization, pest management, and fertilizer practice. Sugar beet-producing regions lie north and south of the 30th parallels. It must be grown in rotation with other complimentary crops. Most sugar beet and sugarcane production is rain fed, but in Mediterranean to arid regions, irrigation is necessary.

Origin and History of Sugar Crops

Sugar Beets

Sugar beet (*B. vulgaris* spp. *vulgaris,* L.), a genus of the family Amaranthaceae (formerly Chenopodiaceae), is one of the diverse and useful group of cultivars from the same species that includes Swiss chard, fodder beet, and red beet (McGrath, 2011). The first modern sugar beets originated as selections made in the middle of the eighteenth century from fodder beets grown in then German Silesia, but food and medicinal uses of the genus are much older. A precursor is known to have been used as food as early as dynastic times in ancient Egypt. In 1747 a German chemist, Andreas Marggraf, demonstrated that the crystals formed after a crude extraction from pulverized roots were identical to sugarcane crystals (sucrose). Attempts to derive sugar from beets, and the beet sugar industry itself, originated from this work. His student Karl Achard developed processing methods for sugar extraction from beet and made the first selections of higher sugar-type beets. The blockade of shipments of cane sugar to Europe by the British during the Napoleonic wars stimulated the industrialization of sugar production from

 doi:10.1016/B978-0-444-52512-3.00150-9

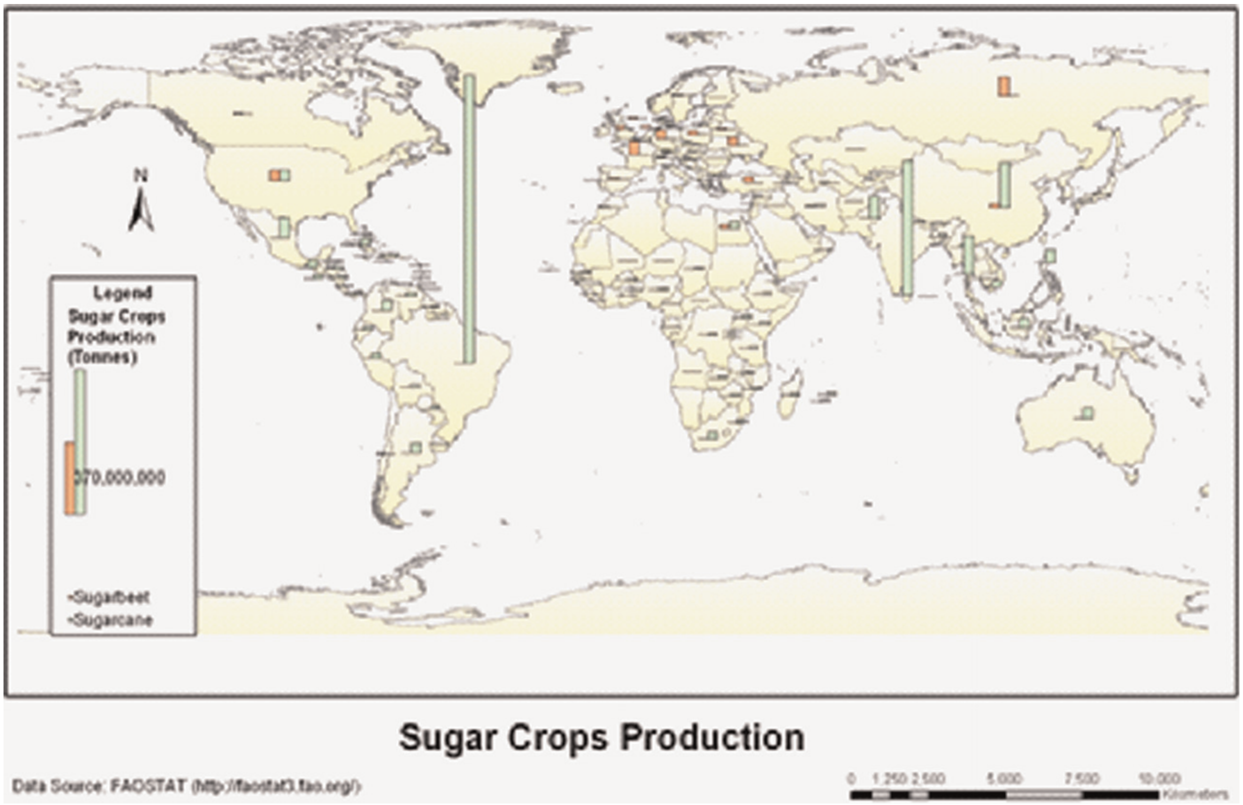

Figure 1 Sugar production from sugarcane and sugar beet by country. Reproduced from FAOSTAT, 2013. Food and Agriculture Organization of the United Nations. Available at: http://faostat.fao.org/default.aspx (accessed 18.02.14).

Table 1 Top 20 countries ranked by sugarcane production during the period 2001–12. Yields of recoverable sugar are approximately 8–12% of these fresh cane yields

Country	*Area harvested (ha)*	*Cane production (ton)*	*Cane yield (tons ha^{-1} year^{-1})*
	Average 2001–11	*Average 2001–11*	*Average 2001–11*
Brazil	6 715 370	507 308 916	74.7
India	4 417 324	296 284 500	66.9
China	1 496 251	98 746 750	65.6
Thailand	1 008 002	64 130 700	63.3
Pakistan	1 020 691	50 762 858	49.7
Mexico	669 208	49 023 541	73.3
Colombia	362 281	35 358 300	99.6
Australia	407 179	33 548 691	82.3
Philippines	389 918	31 078 416	79.9
United States of America	377 878	29 764 208	78.5
Indonesia	380 629	26 013 750	68.9
Argentina	313 960	23 055 833	73.4
Cuba	615 858	20 130 000	32.5
South Africa	315 416	19 962 458	63.2
Guatemala	211 612	19 213 150	91.3
Vietnam	287 233	16 147 566	56.4
Egypt	135 577	16 098 700	118.7
Venezuela	127 957	9 135 769	71.6
Peru	69 807	8 518 708	121.9
Myanmar	148 384	8 027 825	53.9

Source: Reproduced from FAOSTAT (http://faostat.fao.org/default.aspx).

beets, especially in France, through a more intensive search for sweeter beets, an innovative plant breeding program, and the construction of many crude factories in France and elsewhere in Europe. After the battle of Waterloo (1815) and the lifting of the British blockade, the incipient sugar beet industry in France declined for a time, but effectively a new crop had been created and the efficacy of sugar extraction from the beet had been demonstrated. The beet industry not only continued to expand in Europe, which remains the center of the industry, but also developed in other countries in the Middle East and North Africa; Central Asia and Japan; and North and South America. The first successful commercial factory in the United States was constructed by E. H. Dyer Alvarado, in California, in 1879. Soon after, sugar beet culture and factories expanded in many states.

Sugarcane

In contrast to sugar beet, sugarcane has been used as a sweetener in India and China for nearly three millennia. An early ancestor of commercial sugarcane spread from Asia into Papua New Guinea, which became a center of diversity and a major site of domestication. Selected sugarcanes spread throughout the Pacific Basin from around CE 8000, with eventual reintroduction of domesticated clonal materials to South and Southeast Asia. Domesticated clones spread throughout the Pacific islands with exploration and migration, reaching Hawaii by CE 750 (Barnes, 1974). Sugarcane was introduced to Europe from India in the fourth century CE by Alexander the Great and again from the Middle East by returning Crusaders in the Middle Ages. It came to the Americas with Columbus in CE 1493. Successful production was established in Haiti and the Dominican Republic (formerly Hispañola) in 1506, in Puerto Rico in 1515, and in Mexico by 1520 (Barnes, 1974; James, 2004).

Sugar was a luxury in European economies until extensive cultivation of sugarcane began in the Caribbean islands and Central and South America (James, 2004; Galloway, 1989). This allowed a more than hundred-fold increase in English sugar consumption between the mid-1600s and mid-1900s. Sugar use increased along with the Industrial Revolution and the broad appeal of inexpensive and rapidly prepared calories to support urban factory workers who no longer produced their own food. Per capita consumption was also fostered by the increased availability of newly introduced beverages, including coffee, cocoa, and, in England especially, tea, all typically consumed with sugar. Sugarcane provided nearly all sugar in world commerce until the commercialization of sugar beet in the nineteenth century.

Impacts of sugarcane production had substantial impacts on the global labor force. The development of a global sugar market based on sugarcane was closely associated with development of a global market in slave and later indentured labor. Sugarcane production throughout the Americas was dependent on importation of African slaves beginning in the early sixteenth century (James, 2004). By the eighteenth century a major component of international commerce was the exchange of slaves for sugar, molasses, and rum. Slavery was abolished over a prolonged period, ending in the British colonies by 1838, in United States' sugarcane-producing areas in 1863, and in Brazil by 1888. With the abolition of slavery, and advent of wage labor, production in many areas declined precipitously.

This situation was addressed in many production systems by institution of indentured contract labor, fostering immigration of large numbers of workers, especially from China and India. Some of these laborers were eventually repatriated, but most remained as settlers after their period of indentured servitude. These social and economic forces had substantial impact on the demographics of sugarcane-producing countries, contributing to large present day communities of African, Indian, and Chinese descent in many current and former sugarcane-producing countries. More recently, labor in sugarcane enterprises has been on a more conventional wage basis, or by small holders working their own or leased plots.

Production Environments

Sugar Beets

Cultivated sugar beet is a crop of temperate and Mediterranean regions predominantly and has a C_3 photosynthetic system. It is biennial and when the growing plant undergoes prolonged exposure to cold temperatures (approximately 90 days at 5–7 °C, followed by warmer temperatures and longer days), seed stalk production ('bolting') takes place. Wild beet relatives (*B. vulgaris*, spp. *maritima*) do not require vernalization to flower, only increasing day length. Sugar beet seed will germinate and emerge at low soil temperatures (4–5 °C), but emergence is much greater at temperatures greater than 10 °C. Mature plants tolerate modest freezing temperatures, but extended exposure to temperatures below approximately −4 to −5 °C results in cell disruption and death leading to rotting, requiring harvest and storage before severely freezing temperatures occur. These limits affect the length of the growing season of beets in northern latitudes with cold winters. The farthest northern production regions with sugar industries are located in Finland and Sweden in Europe. In Mediterranean locations, like California's central valley and parts of Turkey, Egypt, and Morocco, sugar beets grow year round, but overwintered crops must be harvested by late spring to prevent vernalization-induced flowering from occurring. In arid desert regions with irrigation, like California's Imperial Valley and parts of the Middle East, extremely hot temperatures increase the susceptibility of roots to pathogens like root rots and insect pressures and reduce water-use efficiency, creating other seasonal limits to efficient production. Where successful sugar beet-based industries have developed, diverse adjustments to these effective physiological limits to crop growth have been made. In addition, pest and disease management issues, like the threat of insect-vectored virus diseases, interact with the crop's agroecological requirements in locally diverse ways to set other practical limits to crop production that are regionally specific (Section Crop Management). These factors result in a large number of different cropping patterns worldwide.

Sugarcane

Sugarcane is a tropical plant with a highly efficient nicotinamide adenine dinucleotide phosphate-malic enzyme type C_4

Table 2 Top 10 countries ranked by yield of sugarcane per land area during the period 2001–12. Yields of recoverable sugar are approximately 8–12% of these fresh cane yields

Country	*Area harvested (ha)*	*Cane production (ton)*	*Cane yield (ton ha^{-1} year^{-1})*
Peru	69 807	8 518 708	121.9
Egypt	135 577	16 098 700	118.7
Senegal	7 307	837 038	114.6
Ethiopia	21 775	2 399 600	112.1
Malawi	22 041	2 370 833	107.5
United Republic of Tanzania	20 125	2 113 750	104.8
Zambia	23 875	2 498 333	104.6
Burkina Faso	4 458	445 833	100.0
Colombia	362 281	35 358 300	99.6
Chad	3 797	376 916	99.2

Source: Reproduced from FAOSTAT (http://faostat.fao.org/default.aspx).

photosynthetic pathway. This photosynthetic pathway is generally associated with adaptation to high temperature and high light environments, and to efficient use of water as well as light, while maintaining high productivity (Sage and Kubien, 2007). The optimal environment for cultivation of sugarcane was described as one having a "long warm growing season with adequate rainfall, fairly dry and cool but frost-free ripening and harvesting season, [and] freedom from tropical storms" (Mangelsdorf, 1950). However, with irrigation this ideal changes to one with an absence of clouds, and diurnal and seasonal gradients in temperature, but still free from frost or hurricanes. These requirements are met primarily in lowland subtropical areas and in the tropical highlands, and the highest yields per land area are achieved in such environments (**Table 2**), with high irradiance, irrigation, and a cool dry season to stimulate sugar accumulation, known as ripening.

A major limitation to the expansion of sugarcane as a sugar or biofuel crop is its natural limitation to the latitudes where native *Palmaceae* (palm trees) are found (**Figure 1**). This palm zone, approximately 30° N to 30° S, accommodates the limited cold tolerance of commercial sugarcane clones and avoids the occurrence of freezing night temperatures (Ming *et al.*, 2001) that absolutely limit the current production region. Visible cold damage is not generally observed above 0 °C (Irvine, 1983), when cold chlorosis may be observed as bleached stripes across the leaf lamina. In Louisiana and Florida, risk of freezing nights dictates short growing seasons of approximately 9 months, compared with 12 months in tropical and subtropical environments. A large number of producing countries experience freezing temperatures during the off-season.

Even in the mild, subtropical, marine environment of Hawaii, sugarcane exhibits a strongly bimodal growth pattern, with substantial reduction in the cool (but not cold) winters. Physiological acclimation to progressively cooling temperatures may extend this range. Even moderate chilling may be deleterious (Moore, 1987). In sugarcane fields in Hawaii, excursions below average nocturnal temperatures of only a few degrees Celsius were sufficient to depress stomatal conductance and to substantially inhibit photosynthesis for several days (Grantz, 1989). Chilling effects on mesophyll function dominated these responses, and conductance and photosynthesis were uncoupled. This was most pronounced in summer when rates were greatest and least acclimated to chilling. The effect was also observed in spring, but not in winter, although rates were lower in winter relative to their levels in spring or summer. Extreme heat may also limit production. Sugarcane trials in the low desert of California, where summer temperatures exceed 45 °C, resulted in mid-summer bleaching of leaves in some clones. At both high and low temperatures, stomatal control of water loss may be disrupted (Grantz, 2014).

Under production conditions, flowering of sugarcane is to be avoided as it reduces growth, consumes sugar, and reduces yield. Most modern commercial clones are not heavily flowering in their adapted production environments. Flowering is required for traditional breeding but is often difficult to induce. Shortening days are required, but not sufficient. Conditions with photoperiods just exceeding 12 h, moderate day and night temperatures, and reduced fertility and water supply have been considered essential (James, 1980). For example, in Hawaii, a breeding station on the windward side of the island of Oahu provided a far more favorable environment for flowering than locations at the same latitude on the leeward side.

The Sugar beet Crop

Sugar Beet Breeding and Genetics

In countries with intensive agriculture, hybrid varieties are used for production. Hybrid creation in sugar beets is complex and is made difficult by both physiological and genetic characteristics particularly associated with sugar beets (Bosemark, 2006). These have to do with the crop's biennial character, self-incompatibility, multigerm seed formation in the Beta genome, and the wide range of environments, pest, and diseases affecting the crop in diverse production regions. Creating a new hybrid is a multiyear process. Sugar beets are self-sterile, but mating between close genetic relatives is possible. Cytoplasmic male sterility is found commonly in the Beta genome (Owen, 1945) and is used for hybrid production. However, to obtain offspring from male sterile plants that are themselves male sterile, maintainer lines (called O-types) must be produced as part of the hybrid development process, adding to the complexity of hybrid creation and plant breeding in general. In 1950, Savitsky (1952) laboriously identified a few plants that formed single embryos (monogerms) which have become the basis for the seed industry worldwide outside of Russia, where separate lines were identified. All commercial hybrid seeds are monogerm.

In both Europe and the United States, sugar beet variety improvement and seed production are carried out primarily by private companies. However, the US Department of Agriculture (USDA) developed most of the varieties grown in the first half of the twentieth century in the United States and current variety development often uses genetic lines derived from USDA research (Panella *et al.*, 2013). Both diploid ($n=9$) and triploid hybrids are available, but increasingly, diploid hybrids are being developed due to greater ease and better adaptability to rapid incorporation of new traits (Bosemark, 2006), most recently resistance to a virus disease (Beet necrotic yellow vein virus) called rhizomania (vectored by *Polymyxa betae*) that spread rapidly to all growing regions of the world in the 1980s (Wisler and Duffus, 2000). Plant biotechnology, such as marker-assisted selection, has been used to assist the development of new sugar beet hybrids (Panella *et al.*, 2013; McGrath *et al.*, 2007). In North America, herbicide-tolerant sugar beets are now grown commercially, but their adoption in other parts of the world has been delayed by regulatory restrictions.

For most of the world, sugar beet seed is produced in narrow latitudinal ranges (44°–46° N) in northern Mediterranean areas in Italy and Southern France that have appropriate day length conditions and mild winter temperatures for seed production. Similarly in the United States, sugar beet seed is produced most efficiently in the Willamette Valley of Oregon at similar latitude. In all these locations, winter temperatures are low, but the roots do not freeze, allowing seed producers to manipulate the plant's biennial habit, and day-length conditions support selection of types less likely to flower ('bolt') during the growing season.

Most countries have a variety of testing programs to ensure the use of cultivars that are productive and well adapted to local conditions. Sugar beet breeding, together with improvements in agronomic and pest management practices, has allowed continuous yield and efficiency improvements over time (especially root yield, (**Figure 2**; Panella *et al.*, 2013; Jaggard *et al.*, 2012; Zimmerman and Zeddies, 2000). In countries with less intensive agriculture or where larger numbers of small-scale producers grow beets using less than optimal technology, yields have not risen as much indicating that there is substantial room for yield increases if supporting conditions are established.

Sugar Beet Industry Organization

Worldwide, sugar beet production, sugar processing, and marketing are carefully integrated. In North America, all the companies are grower-owned cooperatives. In other regions, either privately held or state-owned companies are found. Of necessity, there is a closer and more cooperative relationship among growers and companies than is found with many other agronomic commodities, which results in careful organization of all aspects of production from area planted, scheduling of harvest of individual fields, and through sale of the final product. Commonly, contracts between sugar processors and growers contain quality incentives (see Section Sugar Beet Growth and Management; **Figure 8**).

Sugar beet root yields (**Figure 2**) and sucrose concentrations vary widely. This variance is most strongly related to the climate where they are produced, especially the length of the growing season, local soil types, and the level of agricultural development in each region. A surprisingly diverse set of production, harvest, and processing arrangements is possible. In temperate sugar beet production regions like

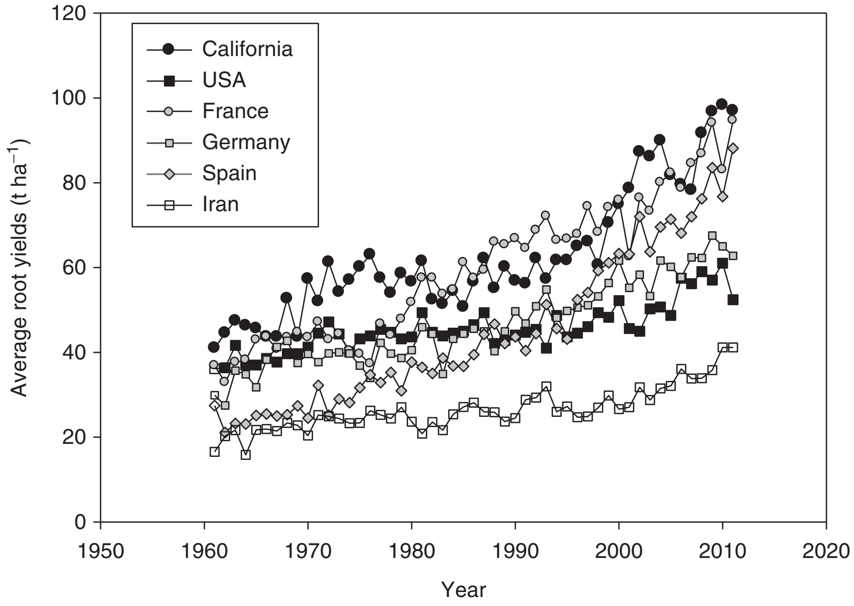

Figure 2 Root yield trends in selected sugar beet–producing countries (1961–2011). Reproduced from FAOSTAT, 2013. Food and Agriculture Organization of the United Nations. Available at: http://faostat.fao.org/default.aspx (accessed 18.02.14).

Northern Europe and most of North America, beets are planted as early as possible in spring after the danger of severe frost (usually March to April) and harvested in autumn (starting in September) for as long as soil conditions and the onset of continuously freezing weather allow. During a typical, concentrated autumn harvest campaign in Europe, factories process large amounts of raw beets to produce crystallized sugar and varying amounts of thick juice (sucrose syrup) that is stored and can be crystallized subsequently at a slower rate during the rest of the year. In the Red River Valley Region of Minnesota and North Dakota in North America, the early onset of extremely frigid temperatures shortens harvest of approximately 1 month but allows roots to be frozen in massive piles in autumn and processed until late spring, often for 200 days or more. In Mediterranean or semiarid to arid regions with milder winters, beets can grow for more than 6 months or even year round, and longer harvest campaigns are possible. In warm locations, roots must be processed shortly after harvest due to losses of sucrose from root respiration and to pathogens during storage.

Sugar Beet Growth and Management

A rapidly growing sugar beet crop is capable of high rates of sucrose accumulation. Dry matter (DM) accumulation and sugar yield are directly proportional to the amount of solar radiation absorbed by the crop (Jaggard and Qi, 2006). Other conditions being equal, the longer the growing season, the larger the yield potential. Under appropriate conditions, the plant develops quickly from seed with the seedling emerging from the soil within 5–10 days after planting under suitable soil temperature and moisture conditions. The taproot grows rapidly and may reach 30 cm or more by the time the first true leaf is developed. During the first 30 days, growth is confined primarily to its leaves and fibrous roots. After approximately 30 days both top and storage root growth proceeds rapidly, with tops reaching near maximum fresh weight in 60–90 days and canopy closure occurring at a leaf area index (LAI) of 3 (Milford, 2006). Subsequently, with favorable climate, top growth remains fairly constant but storage roots continue to grow rapidly for another 20–40 weeks (for a 10-month crop). As the crop develops, an increasing amount of DM accumulates in roots. While leaf number and area may remain relatively constant, in areas with longer growing seasons, roots consist of larger amounts of crown materials, so there is a tendency for impurities to accumulate as well. These impurities reduce sugar recovery from roots in factories (Harvey and Dutton, 1993).

As the storage root increases in size, there is a constant translocation of sucrose from the leaves to the root where it is stored primarily in concentric rings of vascular tissues derived from secondary cambium initiated early in the root's development and in root parenchyma cells that increase in number and enlarge during growth. Bell *et al.* (1996) and Milford (2006), summarizing a large number of studies, reported that DM partitioning in roots is regulated by the cells within the root and is independent of the photosynthate supply (**Figure 3**, Bell *et al.*, 1996; Milford, 2006). On a fresh weight basis, the sucrose content of the root remains relatively constant, unless suitable external factors cause the concentration to change. In temperate regions, these usually increase toward harvest but are also reported to decrease in warmer locations (**Figure 4**).

The largest average sugar beet yields come from California and France (**Figure 2**). California's Mediterranean to semiarid

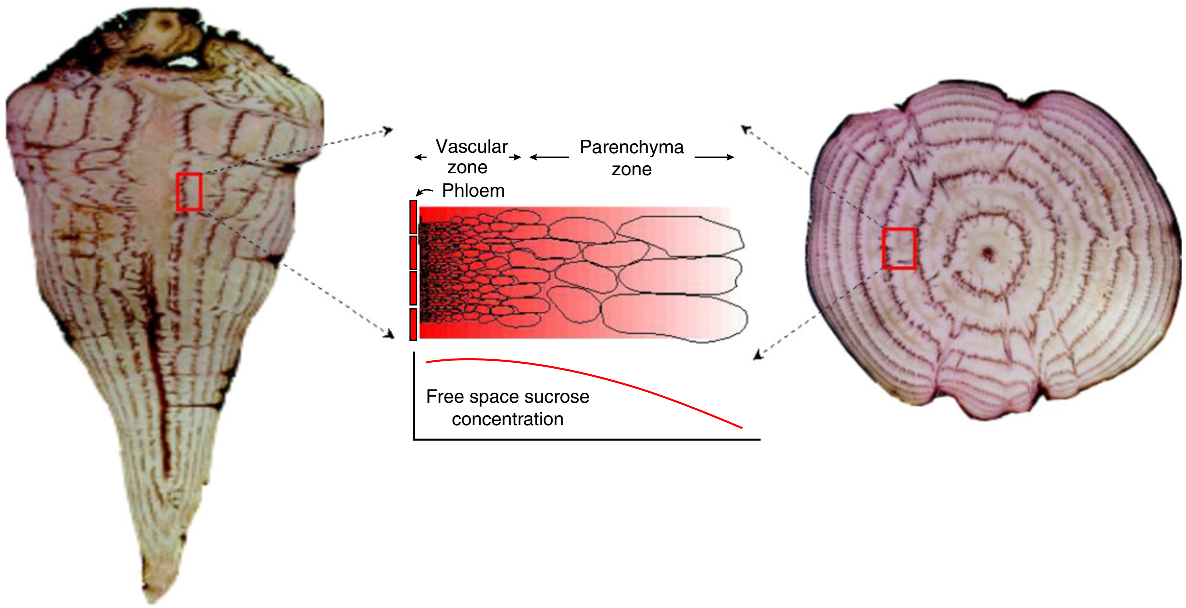

Figure 3 Longitudinal and transverse views of the secondary structure of sugar beet root. Sugar concentration is highest in cells in the vascular zones of the cambial rings visible in the root cross section on the right of the figure. Reproduced from Milford, G.F.J., 2006. Plant structure and physiology. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 30–49 (Chapter 3), with permission from John Wiley and Sons.

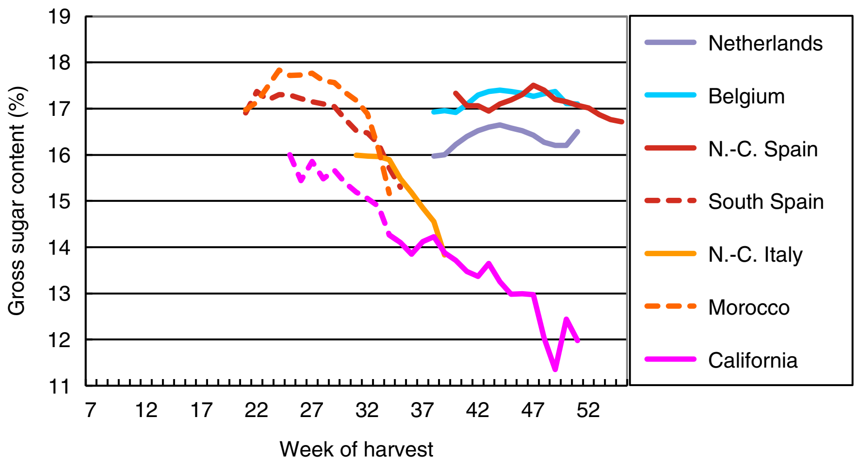

Figure 4 Root sucrose (gross sugar) concentration with time during harvest campaigns. In temperate countries or locations with cold autumn temperatures, sucrose concentrations are maintained during the harvest period, but in warmer Mediterranean locations, they tend to decline during the harvest period. Reproduced from Barbanti, L., Zavanella, M., Venturi, G., 2007. Losses in sugar content along the harvest campaign and means to contrast them. In: Proceedings International Institute for Beet Research Summer Congress, Marrakech, Morocco. pp. 165–175. Brussels, Belgium: International Institute for Beet Research.

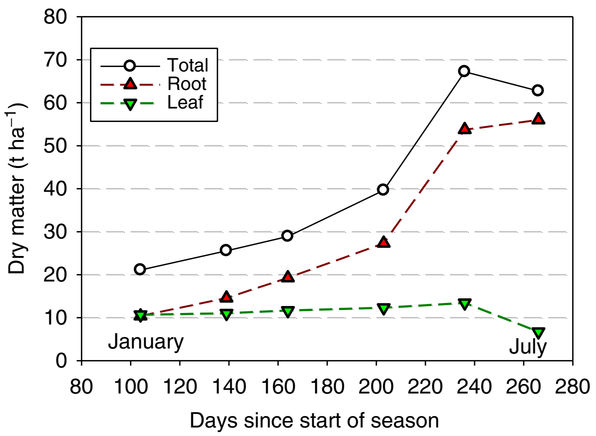

Figure 5 Dry matter accumulation (tons ha^{-1}) in a very high-yielding September-planted and July-harvested crop fertilized with 250 kg N per ha, from the Imperial Valley of California (Kaffka, 2007).

climate allows a long growing season, combined with high-quality soils and irrigation. The world's apparent commercial record yield has come from a field in the Imperial Valley in 2012 and equaled 28.0 Mg ha^{-1} of sucrose from a crop grown over a 300-day period from October to August (177 Mg ha^{-1} of roots at 15.89% sucrose; based on processor data). Average crops in this region reach 55% of the biomass and sugar yields of record crops. Over the total growing season, the record crop accumulated an estimated 147 kg total DM ha^{-1} day^{-1} (44.1 Mg total DM per 300 days) and 93.3 kg sucrose ha^{-1} day^{-1}. DM and sucrose accumulation is not uniform throughout the growing season. Initially it is relatively slow and then accelerates (Figure 5). Peak DM and sucrose accumulation rates can be double the average reported for the cropping season as a whole and most likely exceed rates of 200 kg sucrose ha^{-1} day^{-1}.

Sugar beet refining produces several products in addition to sucrose. These include molasses, dry root pulp, and monosodium glutamate, an amino acid salt used to enhance the flavor of foods. The sugar beet pulp left after sucrose extraction is used widely in the dairy and beef cattle industries as a feed supplement due to its highly digestible fiber and energy content. The tops of beets can be fed, grazed, or returned to soil as an organic matter and nutrient addition. Beet roots contain approximately 1% N, 0.1% P, and 1.1% K on a DM basis, although this varies (Cariolle and Duvall, 2006). An 80 Mg ha crop removes approximately 200 kg N, 20 kg P, and 200–250 kg K ha^{-1}, although actual amounts vary with yield and growing conditions. Because beets are efficient at accumulating photosynthate in a useful form, they are also efficient convertors of agricultural inputs, such as water and nitrogen. One of the reasons sugar beet requires relatively low use of fertilizer nitrogen is its efficiency in recovering residual soil nitrogen from previous crops or decomposed organic matter. Beets recover more of their N requirements from soils than other crops. The crop has been shown to require 25–50% less fertilizer nitrogen than maize (*Zea mays* L.) (Hills *et al.*, 1983).

Many interacting influences affect the balance between root growth and canopy growth. Sugar beets can redistribute N within the plant recovered from soils or take up additional N from soils. Redistribution buffers variations in soil N supply. As long as crops have the amount of N needed for optimum sugar yields, they are capable of sustaining fast rates of root growth and sugar production throughout the growing season without additional supply from the soil or fertilizer. A rapid increase in root sucrose content is correlated with cool night temperatures in the fall of the year coupled with a nitrogen deficiency. It has been repeatedly established that sugar beets require only modest levels of N to produce the highest sugar yields and that beets appear to recover more of their required N from soil reserves than other crops (Hills *et al.*, 1983). Ulrich and Hills (1990), working in California, established a method of plant testing to identify surplus or deficiency and suggested

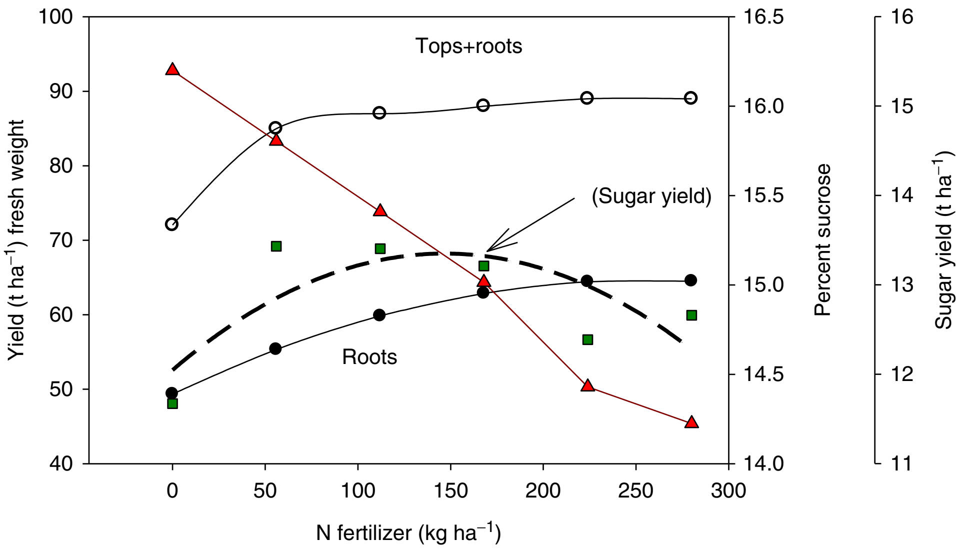

Figure 6 Root and sugar yields of a typical sugar beet crop. Reproduced from Hills, F.J., Sailsbery, R., Ulrich, A., 1982. 'Sugarbeet Fertilization,' Bulletin 1891. Oakland, CA: University of California, Division of Agriculture and Natural Resources.

that 1200 mg N per kg DM in mature leaf petioles was a reliable indicator for sufficiency of non-N limiting sugar beet growth. Generally, nitrogen fertilization is required for profitable sugar beet production. However, sugar yield is sensitive to the absolute amount and the timing of N availability, requiring sufficient amounts early for maximum vegetative growth, and also to a period of N deficiency before harvest for proper sugar accumulation in the storage roots. The highest sugar yields, a function of root yield and sucrose concentration, usually are achieved with a fertilizer rate lower than that which maximizes root yields (**Figure 6**; Hills *et al.*, 1982; Cariolle and Duvall, 2006). Excess N fertilizer results in larger total DM accumulation, but lower total gross and extractable sucrose yields, and could lead to losses of N to the environment. Milford *et al.* (1988), Armstrong and Milford (1983), and Hills *et al.* (1983) all reported that beets require lower levels of N than many other crops for maximum sugar yields and that sugar beet can serve as a nitrogen-scavenging crop to prevent possible nitrate pollution of groundwater. N fertilizer use has tended to decline with increasing yields. Milford (2006) and Milford *et al.* (1988) suggested that environmental or agronomic factors that affect the size and rate of development of the shoot influence sucrose accumulation in the root.

When N becomes deficient before harvest, leaf initiation and expansion is slowed relative to photosynthesis, and photosynthetically produced sucrose accumulates in roots as storage rather than as new vegetative growth. This is illustrated by results from California, where production occurred over a diverse set of climate conditions, allowing comparison of crops in different locations at the same time of year. Kaffka *et al.* (2001) found that very high sucrose concentrations occurred in sugar beet roots harvested in October from a high elevation growing region with a continental climate, where aridity results in very high levels of photosynthetically active radiation, but where higher elevations (1200 m) also correlated with night time temperatures at or near freezing in autumn. Naturally high organic matter soils provided large amounts of N mineralized from soil organic N. They suggested that leaf initiation and expansion (favored by excess N) was suppressed by cold temperatures at the end of the growing season to a greater degree than photosynthesis, favoring sucrose accumulation. Root storage tissues continue to develop in sugar beet as long as assimilate is available. Similarly, in California's milder central valley at the same time of year, sucrose concentrations in sugar beet roots typically declined in October under conditions with milder average temperatures, as deep-rooted crops recovered residual soil N supplies under conditions of declining water stress (**Figure 4**). Similar behavior with respect to beet sucrose concentration in autumn is widely reported from other temperate (Cariolle and Duvall, 2006) and Mediterranean regions with mild temperature conditions in late autumn that encourage additional crop growth (Barbanti *et al.*, 2007).

Improvements in plant breeding and seed technology have led to increasing levels of seed emergence and establishment, with the result that hand labor long associated with sugar beet production, especially around stand establishment, has been eliminated where modern agricultural technology is available. Over time, monogerm seed, improved weed control, improved planters, and seed treatments that reduce losses to pathogens and insect pests during the vulnerable period of crop emergence and establishment have reduced the need for large seed populations and hand thinning of seedlings. Planting to a stand and 70–80% emergence and establishment have become common in growing areas with advanced agricultural practices. Ideal plant populations are 75 000–80 000 plants per ha on 50–76 cm rows (Jaggard and Qi, 2006).

Most sugar beet production in temperate regions is based on rainfall and stored soil moisture. Variable weather at times results in water stress and yield limitations when rainfall is inadequate or poorly timed with crop demand. In arid and Mediterranean areas, careful and timely irrigation is essential for economic yields. Furrow or sprinkler irrigation is possible, and some drip irrigation systems are being used. Irrigation water requirements in locations where irrigation supplements growing season rainfall are small (100–200 mm per year), but in climates where irrigation is necessary, they commonly range from 600 mm of water per ha per season in a cool climate where the soil is filled with plentiful winter rain to as much as 1200 mm per ha in an arid location with a long growing season like the Imperial Valley of California (Dunham, 1993; Hills *et al.*, 1990). DM accumulation and sugar yield are a linear function of transpiration, although both are more easily and commonly correlated with evapotranspiration (ET) (Dunham, 2003). Actual irrigation amounts depend on the depth of the rooted profile, soil water-holding capacity and available water at the start of irrigation, planting and harvest dates, the length of the growing season, and climate during the growing season. Diverse estimates of water-use efficiency have been measured reflecting this varying set of influences.

Water-use efficiency for both total DM yield and sugar yield tends to decrease in warmer climates with higher temperatures and light intensities, where season-long irrigation is required, compared with locations with supplemental irrigation. Empirically determined water-use efficiency values for total DM production (q_{et}) and for sugar production (s_{et}) are summarized by Dunham (2003) and modified with additional data by Langner (1996). For total DM these ranged from 0.0068 Mg cm^{-1} ha^{-1} in Great Britain for a spring-planted crop to 0.0023 Mg cm^{-1} ha^{-1} in California's arid summer for the same. For sugar yield, at the same locations, values ranged from 0.004 to 0.0013 Mg cm^{-1} ha^{-1}. Intermediate values were also reported from environments with growing conditions less mild or extreme (**Table 3**). Beets are deep rooted, with many reports of soil water depletion to 2 m and some to 3 m (Kaffka *et al.*, 1999; Hills *et al.*, 1990). When grown on soils that have been preirrigated or that have large amounts of available water in the soil profile, maximum yields can be achieved at levels less than 100% irrigation (**Figure 7**), (Morillo-Velarde and Ober, 2006; Langner, 1996). In irrigated regions, if beets can be produced during the winter period, very high levels of water-use efficiency can be achieved (**Table 3**).

Sugar beet is a halophytic species that requires Na (Draycott and Christiansen, 2003) and tolerates salinity. It is considered one of the most tolerant crops (Maas, 1990) and can be produced by using low-quality water resources, like saline tile drainage water, in part, and on salt-affected soils (Kaffka *et al.*, 2005, 1999; Moreno *et al.*, 2001). When using drainage or other wastewater, care must be taken to account for N present in the irrigation water, because that reduces sucrose yields, even if it does not affect total DM.

Controlling pests and diseases is important for profitable crop production. Sugar beet is slow to establish and is susceptible to weed competition in its early stages. Moderate weed infestation is controlled by crop rotation and a combination of chemical and mechanical methods. In the United States, herbicide-tolerant sugar beet is now being grown but is not widely used elsewhere due to regulatory restrictions. Sugar beet is susceptible to preemergence and postemergence seedling rots known collectively as damping-off diseases. Other important diseases that must be controlled in areas where they occur are as follows: curly top, a virus disease transmitted by the sugar beet leafhopper; sugar beet yellows, a virus complex consisting of one or more different aphid-transmitted viruses; powdery mildew (*Erysiphe polygoni* DC) and Cercospora leafspot (*Cercospora beticola* Sacc.), diseases caused by leaf fungi; rhizomania caused by a virus (beet necrotic yellow vein)

Table 3 Diverse estimates of water-use efficiency for total dry matter (DM) and sugar production for irrigated sugar beets.

Location	*Year(s)*	*Soil type*	*Estimated* ET_c *(or range applied) (mm)*	*Water-use efficiency (Mg* cm^{-1} ha^{-1}*)*		*Reference*
				DM (Q_{et})	*Sucrose* (S_{et})	
Spring-planted trials						
Suffolk, UK	1979–84	Sandy loam	450	0.0068	0.004	Dunham (1989)
Jena, Germany	1984	Deep Loess	500	0.0061	nr	Roth *et al.* (1988)
Utah, USA	1980	Silt loam		0.0055	0.0022	Davidoff and Hanks (1989)
Nebraska, USA	1966	Very fine sandy loam	800 Cloudy sunny	0.0058 0.0027	nr	Brown and Rosenberg (1971)
Washington, USA	1976	Silt loam	640–730	nr	0.002–0.0016	Miller and Aarstad (1976)
California, USA	1980	Clay loam	900	0.0023	0.0013	Ghariani (1981)
California, USA	1987	Clay loam	980–1140	0.002	0.0009–0.0007	Howell *et al.* (1987)
Fall-planted trials						
California, USA	1972–73	Silty clay	900–1200	nr	0.002–0.0016	Ehlig and Lemert (1979)
California, USA	1996	Clay loam	430–600 (May) 440–870 (June) 560–1000 (July)	0.0055 0.0037 0.0036	0.0022–0.0017 0.0025–0.0014 0.0022–0.0014	Langner (1996)

Abbreviation: nr, Not recorded.
Source: Reproduced from Dunham, R.J., 2003. Water use and irrigation. In: Cooke, D.A., Scott, R.K. (Eds.), The Sugar Beet Crop, Science into Practice. London: Chapman and Hall (Chapter 8), pp. 279–309.

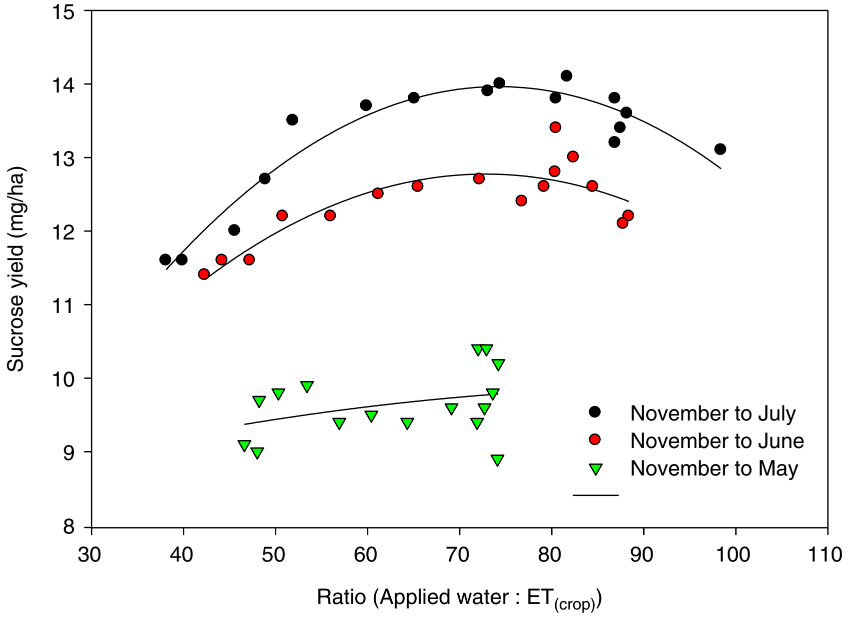

Figure 7 Sucrose yield in successive harvests from a fall-planted, summer-harvested trial in California's San Joaquin Valley, compared with the ratio of irrigation to measured crop evapotranspiration. There was little response to irrigation when the crop was harvested in May. In June and July, deficit irrigation resulted in the largest sucrose yields. Sugar beets were able to recover water from the soil profile in a way similar to their capacity to use residual soil N. Reproduced from Langner, P., 1996. Consumptive water use of fall planted sugarbeets in the San Joaquin Valley of California. MS Thesis, University of California, Davis.

transmitted by a soilborne fungus (*P. betae* Keskin); and sugar beet cyst nematode (*Heterodera schachtii* Schmidt) and root-knot nematodes (*Meloidogyne* sp.). Strategies for the control of these diseases involve development of resistant varieties, attention to time of planting, isolation of new plantings from old sugar beet fields that can serve as sources of virus inoculum in locations with year-round growing climates and practices, the selective use of fungicides, soil fumigation, and careful attention to crop rotation (Wisler and Duffus, 2000; Whitney and Duffus, 1986). Varietal resistance, including from transgenic sources, may become increasingly important (McGrath *et al.*, 2007). But currently there are limits. Foliar diseases, root rots, and insect predation are reasons why beets have not been widely grown in regions with humid, hot temperature conditions during the growing season.

Although diverse production conditions result in differing planting and harvesting practices, sugar extraction and processing is remarkably similar in most beet factories throughout the world. Because sugar factories are expensive industrial facilities, it is prudent to operate them for as many days as possible. In northern temperate growing regions, beets are harvested in early to late autumn as day length and particularly temperature decline. Severe frost damages roots and causes rotting, so freezing weather with temperatures sufficient to freeze soil marks the end of the harvest period. Consequently, factories are designed to maximize the amount of beets that can be washed, sliced into cossettes, and diffused each day. Still, many more tons of beets are needed to support a modern sugar factory than can be processed only during sometimes short harvest periods in autumn. The problem of extending beet supplies to factories is solved variably, depending on interacting local circumstances. In most of Northern Europe, some sugar beet roots are stored along field margins under cover and delivered in late autumn as factory capacity allows. In the northern tier of US states (Idaho, Montana, Wyoming, and Michigan) cold weather beginning in early autumn allows recently harvested roots to be stored outside in piles with ventilation to maintain cool but not frozen conditions. In the Red River Valley region of Minnesota and North Dakota (USA), exceptionally cold weather beginning early in autumn allows massive piles of recently harvested roots to be maintained throughout winter. Frozen beets are then processed during the winter months before temperatures warm sufficiently in the spring to thaw the piles. Processing campaigns can last 200 or more days.

In Mediterranean or warmer regions, beets cannot be stored without significant losses of sucrose to respiration, changes in sucrose to other hexose sugars that cannot be used to make commercial sugar, and losses to pathogens in storage piles. Consequently, daily harvesting and processing is normal. In many locations, this limits the length of time that a factory can operate. For example, in the Imperial Valley of California (mentioned previously), harvest begins in April following planting the previous September and October and lasts until late July or early August, when desert temperatures become too hot to maintain beets in fields without significant loss to root rots or other pests and diseases. In less extreme semiarid or Mediterranean locations, to allow factories to operate for longer periods, complementary planting and harvesting districts can be combined to allow daily harvest over a multi-month period. This occurred in California in the San Joaquin Valley, where both summer and winter temperatures allowed crops to grow year round. In that case, harvest began in April after winter rains using beets sown the previous May and continued until late October or early November, harvesting

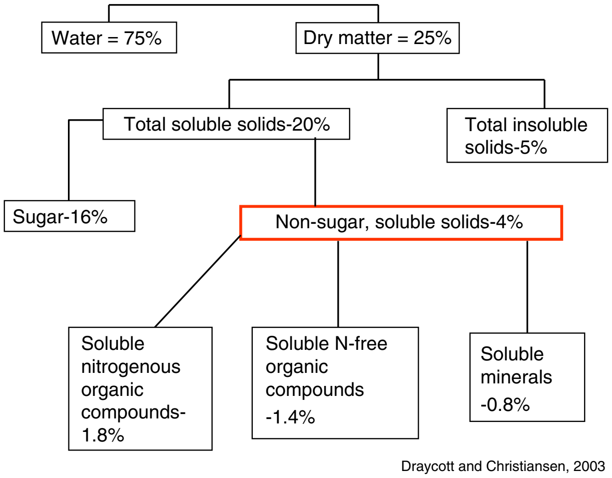

Figure 8 Composition of a typical sugar beet root at harvest. Total insoluble solids fraction is used as livestock feed (beet pulp). Adapted from Draycott, A.P., Christiansen, D.R., 2003. Nutrients for Sugar Beet Production. Cambridge: CABI Publishing, pp. 242.

beets from different regions with planting dates matched to expected harvest periods.

Creating a uniform, pure product (commercial sugar is 99.9% sucrose) from a variable feedstock is a challenging task on an industrial scale. Typical sugar beet composition is depicted in Figure 8, although all of these percentages can vary locally and seasonally. Sugar beets vary in quality as a function of many interacting factors, including agronomic practices, harvest conditions, location, and time of year. The goal of the sugar beet industry, both farmers and sugar manufacturers, is to maximize the recovery of sugar from beet roots. Sugar recovery is inhibited by the presence of large amounts of N compounds, like amino acids and by minerals like K and Na that are part of the ash content (Harvey and Dutton, 1993). Conversion of sucrose into its constituent sugars (fructose and glucose–referred to as inversion) during the diffusion process reduces commercial sugar yields and may lead to creation of other sugars that interfere with crystallization. The larger the molasses fraction, the less sucrose that can be recovered from the gross sugar stored in roots at harvest.

There is a long history in the sugar beet industry of trying to correlate crop production practices with decreased loss to molasses. Particular attention has been paid to the relationship between N fertility and fertilizer management with impurities in roots. There are a large number of regression-based formulas relating sugar recovery to amino N, Na, and K constituents in roots at harvest. These have been used to test beets at harvest and to encourage growers to produce higher quality beets through incentive payments. Formulas have varied over time and by region, with no particular formula proving to be universally applicable. The general consensus is that root quality remains elusively complex and a subject for ongoing research and empirical experimentation (Dutton and Hiuijbregts, 2006; Draycott and Christiansen, 2003).

On delivery to a factory, beets are first washed to make them free of soil and stones. Those processed immediately are then sliced into cossets and conveyed to large diffusers that dissolve sucrose and other soluble constituents from the plant. Dissolved sugar and other constituents are then passed through a series of steps that result in a purified sucrose syrup and byproducts, primarily molasses, monosodium glutamate, and proteins and amino acids (McGinnis, 1982). Residual fiber (called Marc or beet pulp) is a valuable livestock feed, not only for dairy cattle, but also for other livestock species, and even for human nutrition, and is dried for feeding purposes. Sugar beets have very little lignin, and the fiber is composed primarily of cellulose, hemicellulose, and pectin, in roughly equal amounts. Molasses may be added back to pulp if desired to further increase its energy and protein content.

The Sugarcane Crop

Sugarcane Breeding and Genetics

Sugarcane is a member of the *Saccharum* complex (Sreenivasan *et al.*, 1987). These tall, perennial, and tropical grasses include the originally domesticated sugarcane, *S. officinarum*; congeneric species, such as *Saccharum robustum*, *Saccharum sinensis*, *Saccharum barberi*, and *Saccharum spontaneum*; and various interspecific hybrids as well as related genera, such as *Erianthus*, *Ripidium*, and *Miscanthus*. *Saccharum officinarum* appears to have derived from selection and domestication of *S. robustum*. The early domesticated clones represented selection for multicolored stalks, high sap sucrose concentration, relatively low fiber, large diameter stalks, and limited tillering and flowering. The resulting 'noble canes' were those grown in household gardens in Papua New Guinea, were carried by Polynesians to the Hawaiian Islands, and formed the basis of early commercial production and crop improvement efforts.

Sugarcane improvement, as with sugar beet and other crops, is a constant requirement for the continued viability of the industry. Modern sugarcane improvement began with selection of high yielding *S. officinarum* clones in Java in the nineteenth century CE. These noble canes from the Javanese breeding collection initially dominated global commercial production. These were subsequently crossed with the wild species, *S. spontaneum*, to begin production of the modern hybrid, 'nobilized' cultivars in the early twentieth century. The noble canes were supplanted by the resulting interspecific hybrids, which exhibited improved disease resistance, broader environmental adaptation, and increased yield.

Wild *Saccharum* occurs across a surprisingly large range of rainfall and altitude (Irvine, 1983), frequently along nonsaline waterways where open vegetation allows high light penetration and where plant water deficit may be avoided. The broad adaptation is reflected in wide phenotypic diversity among *Saccharum* genotypes. For example, stalk diameter ranges from a few mm in some *S. spontaneum* genotypes to more than 10 cm in some *S. officinarum* chewing canes. Similar diversity is observed in genome structure (Hogarth, 1987; D'Hont *et al.*, 1996).

Saccharum spontaneum exhibits much greater diversity than *S. officinarum*, which does not exist outside of cultivation. *Saccharum spontaneum* is found in wild populations across Asia, North Africa, and the Middle East (Tew and Cobill, 2008). This diversity is reflected in observed variation in stress resistance (Moore, 1987) and genomic diversity (Zhang *et al.*, 2012). This diversity has contributed considerably to sugarcane improvement for the past century or more. *Saccharum spontaneum* exhibits lower stalk sucrose than the noble canes, higher fiber, thinner stalks, and sufficiently common flowering and tillering to make it a potentially invasive species. In commercial canes, sucrose accumulation and robust growth of thick stalks are derived mostly from *S. officinarum*, whereas genes for vigor, broad environmental tolerance, high fiber, and abundant tillering are derived mostly from *S. spontaneum*.

The sugarcane genome is a subject of considerable current investigation using modern genetic techniques. The *Saccharum* species are autopolyploids, with copy numbers (ploidy level) ranging from $5x$ to $16x$. The genome of *S. officinarum* is relatively uniform among genotypes, being autooctaploid ($x=10$; $2n=8x=80$ chromosomes), with only a few possible exceptions (Zhang *et al.*, 2012). In contrast, *S. spontaneum* is more variable ($x=8$; $2n=36$–128), although approximately three-quarters of genotypes contain some multiple of $8x$ (Ming *et al.*, 2001). *Saccharum officinarum* and *S. spontaneum* appear to have diverged approximately 1.5–2.0 million years ago (Jannoo *et al.*, 2007).

The genome size differs between species, with ploidy level and with monoploid chromosome number. The monoploid genome size of *S. officinarum* is estimated to be approximately 985 Mb (million base pairs) and of *S. spontaneum* approximately 843 Mb, with much greater variation in *S. spontaneum* (Zhang *et al.*, 2012). The full polyploidy genome within the *Saccharum* complex ranges from 2–12 Gb/C (billion base pairs per diploid cell; Zhang *et al.*, 2012). Genome size is a useful surrogate for chromosome number (Zhang *et al.*, 2012).

Commercial sugarcane germplasm is largely derived from crosses of *S. officinarum* x *S. spontaneum*, with repeated backcrossing to *S. officinarum*. Current sugarcane clones contain approximately 90% *S. officinarum* and 10% *S. spontaneum* germplasm (Ming *et al.*, 2001; D'Hont *et al.*, 1996). In crosses of female *S. oficinarum* x male *S. spontaneum*, an unusual chromosomal transmission is often observed in which the diploid, somatic complement ($2n$) of the female is retained along with the haploid, gametic ($1n$) complement of the male. This so-called $2n+n$ transmission and the unpredictable pairing of the variable number of homologous chromosomes in such crosses (Ming *et al.*, 2013) result in considerable complexity in the genomes of commercial clones. Similar to other vegetatively propagated species, sugarcane is heterozygous at most loci, with no existing inbred lines that would be useful for crop improvement.

Autopolyploidy is observed in several important crop species, including sugarcane and sugar beet (Ming *et al.*, 2013; Zeven, 1979). Despite the common occurrence of this genomic replication, it presents challenges for modern genetic analysis and the search for useable markers for selection. Identification of quantitative trait loci (QTL; a genomic marker) for phenotypic traits of interest is complex, as several alleles may segregate in various combinations, and individual genes may contribute only marginally to phenotypic traits of interest.

A study of QTLs for two independent traits – sugar content and plant height – found that multiple copies of favorable alleles, in unlinked regions of the genome, had less than additive effects (Ming *et al.*, 2013). This suggests that one copy, among the multiple potential locations in the polyploid genome, may be sufficient to provide physiologically relevant protein synthesis. Additional copies may potentially be manipulated in pursuit of other desirable traits with minimal negative consequences. This may simplify development of transgenic lines, as insertion of one copy of a novel allele may be sufficient to drive improved phenotype, despite the presence of other loci with less favorable alleles. However, multiple copies of important genes may confer environmental stability (Ming *et al.*, 2013) as observed in other species. In highly selected commercial clones, favorable alleles (Lam *et al.*, 2009) have been fixed at several loci, so that identification of QTLs is more difficult than in less selected genotypes.

The recently sequenced genome of *Sorghum bicolor* (Paterson *et al.*, 2009) has proven useful as a template to understand the sugarcane genome (Ming *et al.*, 1998, 2013; Dufour *et al.*, 1997). The sugarcane monoploid size is similar to that of the haploid *Sorghum* genome (Zhang *et al.*, 2012). Sugarcane diverged from *Sorghum* less than 10 million years ago (Jannoo *et al.*, 2007; Lam *et al.*, 2009). QTLs in an *S. spontaneum* x *S. officinarum* segregating population, for both high and low sugar content (Ming *et al.*, 2013), all mapped to one of eight distinct regions of the *Sorghum* genome. Loci of interest in the larger sugarcane genome may reflect a small number of ancestral genes, simplifying manipulation during crop improvement.

Sugarcane Industry Organization

Sugarcane production took place in nearly one hundred countries (FAOSTAT, 2013) during 2001–12. Another 10 countries, mostly small producers, ceased commercial production during or before this period. Annual global sugar production from sugarcane over this period was approximately 1.7 billion tons (**Table 1**). More than 90% was produced in the top 20 producing countries (**Table 2**), concentrated in tropical and subtropical areas. Central and South America produced 53.1% of global output with an additional 36.9% from Asia and 5.3% from Africa. The remainder was distributed with 2% or less from the Caribbean region, Oceania (including Australia), North America, and Europe (0.0003%).

The largest single producer during this period was Brazil (**Table 2**), with more than 500 million tons of cane production, reflecting vigorous government investment in an integrated sugar and biofuel economy based on sugarcane. India and China produced approximately 300 million and 100 million tons, respectively. Total production is closely related to area harvested, although differences in yield per land area are observed.

Average yields were largest in Central and South America and Oceania (**Table 1**). Of the top 20 producers (**Table 2**), only three have yields at or above 100 tons ha^{-1} $year^{-1}$ – Peru (122 tons ha^{-1} $year^{-1}$), Egypt (119 tons ha^{-1} $year^{-1}$), and Colombia (100 tons ha^{-1} $year^{-1}$). Only 10 countries achieved long-term average yields of 99 tons ha^{-1} or above, mostly characterized by prolonged dry periods and long growing seasons (Waclawovsky *et al.*, 2010). Many major producers, such as Australia (82 tons ha^{-1} $year^{-1}$), the United States (78 tons ha^{-1} $year^{-1}$), and Brazil (75 tons ha^{-1} $year^{-1}$), exhibited lower average yields. Production areas, such as the

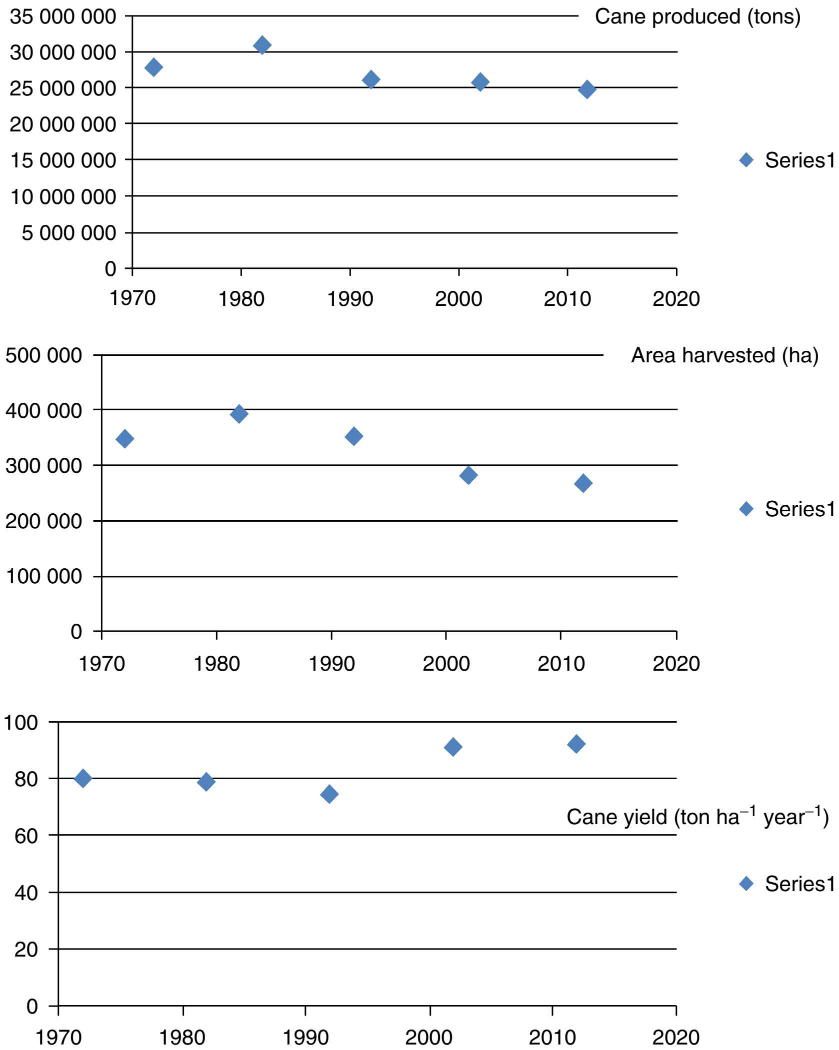

Figure 9 Fifty year trends in sugarcane production in the United States. Data obtained from the USDA National Agricultural Statistics Service (www.nass.usda.gov).

northern coastal deserts of Peru and the inland desert valleys of Southern California, arid and high irradiance environments, may provide substantial opportunities for very high yields and efficient use of limiting resources, such as land, water, and nitrogen.

Sugarcane production in the United States increased over the past 50 years (Figure 9) by 12%, although land area devoted to sugarcane increased by 28.7% (1972–2012). By 2011, the US industry had 45–47% of planted area in Florida and Louisiana, cool short season production environments, and 5.6% in southern Texas. Sugar production was 51% in Florida and only 38% in Louisiana and 5.6% in Texas. During this period the exceptionally productive Hawaiian industry declined by 87.3%. By 2011, Hawaii had 1.9% of US sugarcane plantings but 4.5% of US production. Hawaiian yields peaked at 220.0 tons ha^{-1} $year^{-1}$ shortly before the collapse of the industry on all but one of the sugar-producing islands. By 2013, only one sugar enterprise remained, on the island of Maui. These observations suggest that agronomic factors are not always decisive in determining the viability of a production system.

The sugarcane industry exists in a diverse matrix of countries, cultures, and economic systems. The organization of production reflects this diversity. In some areas, mills and production fields are owned by a single entity, commonly called a plantation system. This may represent large private enterprises or cooperative associations. A significant benefit of such organization is that improvements in both field operations (yield, production costs, sugar content) and mill operations (prevention of cane deterioration, recovery percentage, factory costs, and marketing) accrue to the benefit of both grower and refiner, and there are inherent incentives for improvement and investment in both operations. However, in much of the world, the industry is based on a large number of independent producers providing cane to mills that are operated by an unrelated entity. The result is an unavoidable conflict of interest in which incentives to increase cane quality and sugar recovery may not accrue to both parties, and distortions of industry expansion and investment are common (Todd *et al.*, 2004).

These conflicts have been addressed through a variety of payment schemes (Todd *et al.*, 2004), each with advantages and disadvantages with respect to the economic viability of the national sugarcane industry. Payments for cane delivery may be based on the average quality of cane delivered to the mill, which removes individual grower's incentives to improve quality. They may be based on the quality of an individual grower's cane, which incentivizes the individual. This results in competition, either between the growers for a fixed share of revenues in fixed revenue-sharing systems, or between individual growers and with the mill operator for a share of total revenues in variable revenue-sharing systems. This latter option may spread risk and reward most equitably but is complex to administer and requires quality testing at multiple points in the production pathway.

An example of a management decision that may depend wholly on industry organization and payment scheme is length of the harvest and milling season. A longer season makes most efficient use of high cost-fixed equipment at the mill but inevitably reduces cane quality and sugar recovery by extending the harvest season to nonoptimal periods. Depending on grower incentives and ownership of fields and mills, this improves profitability for all participants, or only for the mill owners. In some production areas, a blended system provides individual incentives that are calculated on the basis the average quality of cane delivered during each phase of the harvest (Todd *et al.*, 2004), rather than over the entire harvest season.

Sugarcane Growth and Management

Sugarcane production methods depend on soil type, rainfall, drainage, and availability of labor and mechanized equipment. Adapted genotypes exhibit high productivity, whereas the perennial life cycle allows economically efficient production, with one or more ratoon (stubble) crops. Replanting from vegetative stalk segments is required only after several generations when yields decline due to soil compaction, disease or pest pressure, reduced plant population, or cumulative harvest damage.

Ratoon production varies with environment, cultivar, harvesting techniques, and management, ranging from no ratoon crop to four or more. From two to five appears to be a common range among current sugar production areas. Sugar yield eventually declines, necessitating a fallow period and replanting with vegetative stalk pieces. The length of the ratoon period is ultimately an economic decision, balancing replanting costs with foregone sugar yields but may be skewed by considerations of labor supply, availability of new and improved cultivars, and international sugar market conditions (Ellis and Merry, 2004).

Planting costs are substantial in sugarcane, due to its vegetative mode of reproduction. Before replanting, the seed bed is usually worked to remove the previous crop and any weeds and to optimize soil tilth. Sugarcane is planted from vegetative stalk segments. These may be long sections with only the tops removed, or they may be shorter sections, with one to three buds per section. Both types of planting material may be hand cut or delivered by mechanized harvesters from nearby fields that are dedicated to seed production. This set aside from production is a significant cost of sugarcane establishment.

Stalk segments are planted in furrows that may be subsequently filled to result in flat planting. This may provide more even water availability and is suitable for many mechanized operations. However, erosion due to water runoff and pressure from some soilborne pests may be exacerbated, and crop waterlogging in poorly drained fields may be increased. For these reasons, i.e., to channel runoff, to elevate cane above moisture and moisture-attracted pests, and to raise soil temperatures, cane is often planted in ridges separated by well-maintained furrows. Irrigation may then be provided through the furrows if available and as required. If moisture availability on the ridges is inadequate, the cane may be planted in the furrows and ridges later constructed along the plant line, although this disruptive activity may slow growth.

Row spacing reflects a balance between increased costs to produced seed cane (planting stalks) and the time required for the crop canopy to fully cover the ground for maximal interception of sunlight. Productivity is closely related to seasonal intercepted solar radiation. In practice, row separation is usually between 1 and 2 m, with narrower spacing under poorer growing conditions or where erosion is a threat (e.g., hillsides) and wider spacing where rapid growth and canopy closure is expected. In some cases, available equipment dictates row configuration.

In irrigated and highly favorable production environments, cane is harvested at approximately 12 months of age, although this may vary from 9 months in temperate climates with unsuitable winter temperatures to 24–36 months in cooler but nonchilling environments or dryland situations with water-limited growth. Sugarcane exhibits a sigmoidal growth curve, as observed in sugar beet and other crops (**Figure 10**). The sheer magnitude of the developing canopy has led to this exponential middle portion of the growth curve to be called the period of Grand Growth.

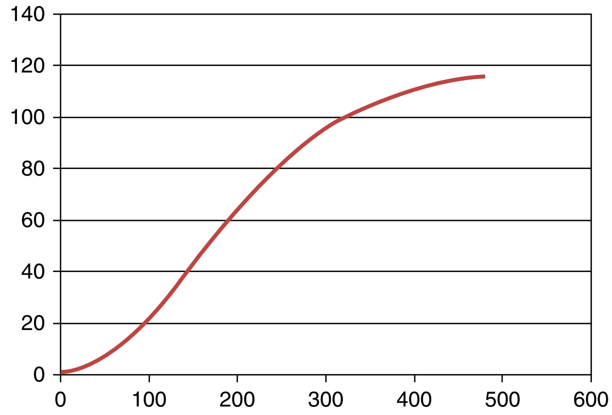

Figure 10 Biomass production in sugarcane during regrowth following harvest. This model from Simoes *et al.* (2005) describes the 4th and 5th rattoon of an early variety with vigorous regrowth in Brazil. Vertical axis is above-ground biomass (tons ha^{-1}); horizontal axis is days after cutting. The curve is generated from the equation given by Simoes *et al.* out to 480 days. $BM = 120 \times \exp(-(4.6981)) \times \exp(-(0.010098)) \times \text{Days}$.

In many production areas, sugarcane is harvested by hand, with cane knives or machetes and carried in bundles of 10–20 kg by individuals to collection points at the side of the field. Increasingly, harvest is mechanized, using machines that trim the tops and then sever the stalk near the base, leaving neatly aligned piles of intact stalks laid across the row. This type of whole-stalk or 'soldier' harvester imposes fewer cut surfaces and reduces risks of quality deterioration but requires burning in the piles and some additional logistical challenges. It is used to prepare seed cane for whole-stalk planting in some areas.

The alternative is a billet-cutting, or combine, harvester. This approach does not require burning of the trash, which is blown off during harvest by fans on the harvester. However, efficiency is improved by burning in the field. The cane is cut at the top to remove green portions, severed near the ground as above, and then chopped into convenient lengths before ejection into a receiving wagon pulled alongside. A highly mechanized system was in use throughout Hawaii until the recent decline of that industry. Fields were burned in place, then push-raked with large tracked vehicles into piles, which were loaded by infield cranes into trucks that were driven on private cane haul roads to the factory. Productivity and lodging in this system exceeded the capacity of available harvest equipment.

Burning of the cane requires that irrigation be terminated in a timely fashion and that rainfall does not occur during the critical period. The primary benefit of burning is to remove leafy field trash, both reducing the volume and weight of material to be hauled to the mill and increasing the efficiency of mill operations. Infield burning has the additional benefit of driving off or destroying pests and potentially dangerous wildlife, before entry of harvest crews. Disadvantages are the requirement for suitable weather and increasing concerns by neighboring populations regarding the hazards and nuisance of smoke inhalation.

Harvest method and the amount of soil and leafy trash carried to the mill have a large influence on sugar recovery. Growth conditions and management, particularly harvest date, may result in a wide range of juice content and soluble solids (Brix, %). High-quality sugarcane stalks typically have a Brix of approximately 18%, of which approximately 90% is sucrose. Additional factors within the mill associated with crushing and extraction, removal of impurities, and crystallization also have a large effect on sugar recovery. In general approximately 10% of fresh cane weight is recovered as sugar.

Sugarcane water requirements are substantial and highly dependent on environment and crop growth stage. Sugarcane is traditionally grown in the humid tropics, where ET is reduced by high relative humidity and where water is available for extended periods of the growing season. As cultivation has moved to higher radiation but drier environments, the risk of crop water deficit increased, and in many areas supplemental or full irrigation has been applied. Although sugarcane is considered a heavy user of water, the water requirements depend on the environment. It is most useful to consider water requirements relative to alternative crop choices. For example, in the hot, inland Imperial Valley of California, water requirements calculated from the crop coefficients provided by the UN FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998) indicated that approximately 1.8 m of water was required, about the same as the existing dominant crop in the area, alfalfa (*Medicago*).

Sugarcane is sensitive to soil water depletion, with shoot extension growth declining as available soil moisture declines by less than 10%. Stomatal closure is slightly less sensitive, beginning to decline approximately 15% depletion (Nable *et al.*, 1999). In parallel experiments in large pots, the more drought tolerant, but closely related plant, *Sorghum* maintained both shoot growth and stomatal conductance until approximately 50% depletion.

Successful cultivation of sugarcane has been achieved with many types of irrigation systems, from furrow to sprinkler and drip. Under some conditions, flood irrigation of flat-planted cane may be appropriate. With the large inputs of water required by sugarcane, sufficient attention must be paid to drainage. This must provide for an unsaturated root zone to 60 cm or more (Ellis and Merry, 2004). Drainage must not lead to excessive losses of irrigation water, particularly as may occur with furrow systems in sandy fields, but must allow enough drainage through the profile to avoid buildup of salts. Available commercial sugarcane clones are not tolerant of saline conditions. Under conditions of poorly drained soils with flat gradients, it may be necessary to provide drainage aids. These may be closely spaced drainage ditches or even buried drain tile, which carry percolated soil solution to nearby ditches and away from the field.

In many production areas, runoff from sugarcane fields, with its burden of nitrates, phosphates, dissolved carbon, and pesticides, is an environmental threat to adjacent ecosystems and is highly regulated. These relatively recent pressures, as well as the long-standing imperative to control soil erosion losses, make control of water inputs and drainage an important component of management.

Fertilizer requirements depend on the environment, previous crop, and residual soil fertility. In heavier, nonpeat soils, substantial N fertilization is required for sustained yields. As in most cropping systems, nitrogen is the nutrient that is most likely to become limiting in sugarcane production (Irvine, 2004). In general, approximately 100 kg N ha^{-1} is required for the plant crop and approximately 150 kg ha^{-1} for each successive ratoon crop. Nitrogen applications must be accompanied by sufficient irrigation or rainfall to facilitate uptake. Because of the potential for losses due to deep drainage, runoff, and volatilization, application of nitrogen is typically delayed until rapid crop growth has begun and immediate uptake and utilization are most likely to occur. In production for sugar, nitrogen is applied early and the plant is allowed to deplete soil reserves. This along with dry, cool weather leads to ripening, or accumulation of sugar rather than fiber in the stalk. For bioenergy, later application of nitrogen will sustain the maximum period of biomass accumulation.

Sugarcane is understood to be less N efficient than many crop species, suggesting that alternative practices might be considered. There is recent evidence that *Saccharum* may differ from even closely related cereal crops, in preferentially utilizing ammonium rather than nitrate from the soil N pool (Robinson *et al.*, 2011). As nitrate fertilizers are labile in the environment, increased use of other, particularly more reduced, forms of N may reduce the environmental impact of sugarcane and energy cane cultivation and reduce the net greenhouse gas balance of associated biofuels.

Under some conditions, deficiencies of potassium, calcium, and phosphorous will have to be addressed, based on soil test. Other nutrients are essential but at much lower levels and are not commonly limiting, including magnesium, sulfur, iron, boron, manganese, zinc, copper, nickel, molybdenum, and chloride. Calcium is typically applied as lime before planting, usually with the intent to raise soil pH, as levels in most soils are sufficient. Addition of lime may increase the availability of phosphorous and reduce the availability of aluminum. Potassium is not often deficient, and oversupply of this element will carry over into the mill, passing through clarification to accumulate in the molasses where it impedes crystallization of sugar and reduces recovery (Irvine, 2004).

Pest management in sugarcane reflects the fact that sugarcane is typically grown in a monoculture. This accentuates the risk of epiphytotics, although sugarcane is not an extremely vulnerable crop. On a global basis, sugarcane is susceptible to a number of bacterial diseases, leading to stunted growth, occluded xylem, and foliar symptoms and a variety of fungal diseases from rusts, mildews, and smuts to rots that consume the sugar storage tissues in the stalk. Effective production requires vigilance, as unexpected diseases may appear suddenly. Although seed pieces (setts) may be treated with fungicide, the principal defense against known diseases is through genetic resistance acquired in sugarcane-breeding programs.

In some environments, insect pressure may be severe and may require treatment. Sugarcane is subject to attack by stalk-boring insects, and buried seed pieces are vulnerable to a wide variety of pests that may destroy the viable buds. Nematodes may be a problem in sandy soils. Leaf feeders are typically not a major challenge to sugarcane culture except that some, such as leafhoppers, may vector serious viral diseases. Where available, the use of biological control has often proven effective. As with pathogens, the most effective defense is genetic resistance derived in the breeding programs.

Weeds are a serious challenge in sugarcane culture because of the relatively slow canopy closure. This provides weeds a prolonged period of full sunlight and minimal competition from the developing crop. In particular, a wide variety of grasses are difficult to remove once the cane crop becomes established. If weeds can be suppressed in the early season, eventually the dense sugarcane canopy, with LAI up to seven, will provide effective suppression of most weeds. Tillage and preemergent herbicides are the most successful control strategies.

Sugarcane is grown in a large number of countries under a very wide range of conditions. Although the ancestral chewing canes were strictly tropical, with introgression of highly diverse wild relatives, sugarcane has now spread, often under irrigation, to environments characterized by cool winters and very hot summers. Sugarcane remains a dominant source of natural sweetener in global markets.

Future Prospects for Sugar Crops

Sugar Beet

With the use of sugar beets, the yield of sugar achieved in most of the principal beet-producing countries has increased substantially over the last several decades. Most of this yield progress is due to increasing root yields (**Figure 2**), although sugar content in beets has increased less or been largely stable (Jaggard *et al.*, 2012). Yield increases can be attributed to several interacting factors, including improvements in plant breeding techniques and information technology, improved seed quality and agronomic practices, and planting and harvesting machinery. Where adopted, all these practices have led to improved overall efficiency in the sugar beet industry, from crop production to factory operations (Parkin and De Bruijn, 2010). Increasing levels of atmospheric CO_2 have also contributed to increasing yields over time. Weigel and Manderschied (2012), Jaggard *et al.* (2007), Demmers-Derks *et al.* (1998), and others have correlated significant increases in root yield and total biomass under enriched CO_2 conditions when fertilization levels were sufficient to support increased crop growth. Part of the effect was attributed to warmer summer temperatures (Jaggard *et al.*, 2007). Crop nitrogen use efficiency was also improved in many industrialized production areas (**Figure 11**). Increasing levels of atmospheric CO_2 should support slowly increasing yield trends if other agronomic factors are adjusted appropriately for higher yield expectations. Donatelli *et al.* (2003) in a modeling study suggested that in regions where temperatures increase due to climate change, irrigation may be needed to sustain yield increases. Similarly, Jones *et al.* (2003) predicted significant yield increases but also increased yield variance due to more frequent occurrences of drought in parts of Europe.

Comparisons of yields and yield trends among developed and developing regions indicate that there is still substantial technical opportunity for improvement in beet crop yields in many areas of the world. For example, yields in California are two or more times greater than those in Egypt and Iran, with areas with similar climates. In recent years, there has been a significant investment made in molecular genetics and the use of transgenic traits for herbicide tolerance and pest and disease resistance has taken place. Currently, herbicide-tolerant sugar beets are grown in the United States and Canada but have not been accepted for use in other countries due to differing perceptions of risk and regulatory cultures. Nonetheless, the potential value of molecular breeding to improve crop productivity, reduce pesticide use, and increase overall efficiency is widely recognized within the industry and is expected to eventually become part of hybrid development programs (Lathouwers *et al.*, 2005).

Part of the value of molecular breeding techniques is their potential to improve environmental performance in sugar beet production systems, especially where intensive agricultural practices are carried out (McGrath *et al.*, 2007). Märländer *et al.* (2003) identified several additional new technologies for improving the environmental performance of beet production, including conservation tillage, and integrated production strategies to reduce inputs and use of pesticides and fertilizers per unit yield and off-farm emissions. Kaffka *et al.* (2005, 2001, 1999) had demonstrated the use of precision agricultural techniques and the capacity of sugar beets to use low-quality water for irrigation to improve salinity management in salt-affected areas and to recover nutrients where groundwater and surface water are affected by eutrophication. In general, there has been an improvement in the efficiency of sugar beet

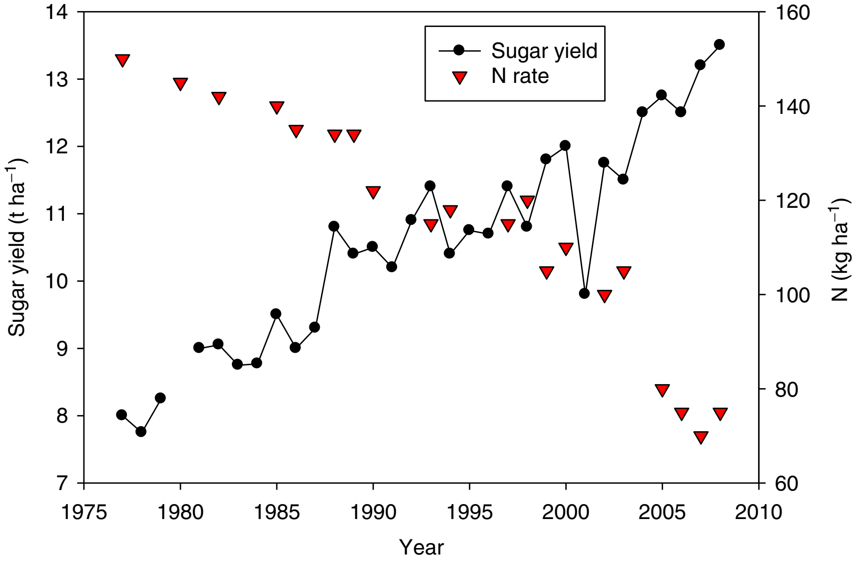

Figure 11 Yield and N fertilizer-use trends from France. Yields have increased, whereas N fertilizer use has declined. This phenomenon is common throughout the sugar beet industry in regions with developed, intensive agricultural systems. Reproduced from Cariolle, M., Duvall, R., 2006. Nutrition nitrogen. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 169–184 (Chapter 8), with permission from John Wiley and Sons.

production over time. The labor invested in producing a hectare of sugar beets has declined, whereas yields have increased.

Both sugarcane and sugar beet provide a readily fermentable source of carbohydrates for conversion to ethanol, other higher alcohols, and biochemical feedstocks. The efficiency attributed to sugarcane as a biofuel source is due in part to the use of bagasse for the production of electricity needed to power the sugar or ethanol refinery. In contrast, sugar beet residues are commonly fed to livestock because they are a highly digestible feed for ruminant livestock. Because the fiber portion of beet roots is digestible and low in lignin, they can also be converted to C_6 and C_5 sugars using enzymes (Santek, *et al.*, 2010). This increases the overall sugar yield from beets available for fermentation to alcohols and makes beets a promising bioenergy feedstock (Panella and Kaffka, 2011), which compares favorably to both sugarcane and strictly cellulosic feedstocks (**Figure 12**). In Europe, some of the sugar produced at refineries in excess of sugar market requirements is converted to ethanol (Klenk and Kunz, 2008). Beet roots also digest readily when used in anaerobic digesters and are used for this purpose on a wide scale in Germany and elsewhere in Europe (Demirel and Scherer, 2008).

Sugarcane

Well-adapted sugarcane clones are considerably closer than most crop species, including those with the same photosynthetic pathway, to achieving theoretical maximal yields of approximately 6% of the energy available in sunlight (Zhu *et al.*, 2008). The maximum reported efficiency in the field is only approximately 4.3%. Maximum theoretical potential productivity of sugarcane is approximately 280 tons ha^{-1} year^{-1}, and with reduction for radiation striking bare ground during incomplete canopy closure, approximately 220 tons ha^{-1} year^{-1} of above-ground biomass. With a harvest index of approximately 0.8 (leaving only roots, stubble, and some leafy trash in the field), potential above-ground dry biomass yield is 177 tons ha^{-1} year^{-1}, equivalent to 360–380 tons ha^{-1} year^{-1} of fresh millable stalk material (Waclawovsky *et al.*, 2010). This is substantial relative to other potential crops.

Yields of sugarcane have increased steadily in many production areas, by approximately 1% year^{-1}, reaching approximately 150 tons ha^{-1} year^{-1} of above-ground dry biomass under optimal experimental conditions in irrigated, high irradiance conditions in Brazil (Waclawovsky *et al.*, 2010). Record commercial yields were lower, approximately 120 tons ha^{-1} year^{-1}, and typical grower yields yet lower (**Table 1**), globally averaging approximately 35 tons ha^{-1} year^{-1} dry biomass or 72 tons ha^{-1} year^{-1} of millable cane over the first decade of the current millenium. In sugarcane, as in other crops, closing the gap between record and typical yields is an important goal for sugarcane production both for sugar and for bioenergy.

As producers around the world seek to expand production of sugarcane for sugar and bioethanol by expanding production into marginal areas, efforts will intensify to develop tolerance to drought, heat, and chilling. Efforts in Brazil to extend production to the south (higher latitudes), and in the United States to expand production northward and into the western inland valleys, have stimulated considerable efforts to enhance chilling tolerance in high-yielding clones. Genetic improvement of tolerance to heat and chilling appears feasible by selection among current germplasm, by further crossing with related wild species, particularly *S. spontaneum*, which exhibits considerable tolerance to abiotic stresses (Moore, 1987), and with the closely related genus, *Miscanthus*.

Sugarcane may represent a bridge crop for biofuel production from other sources. Current commercial clones provide sugar in high yields for direct fermentation. These clones

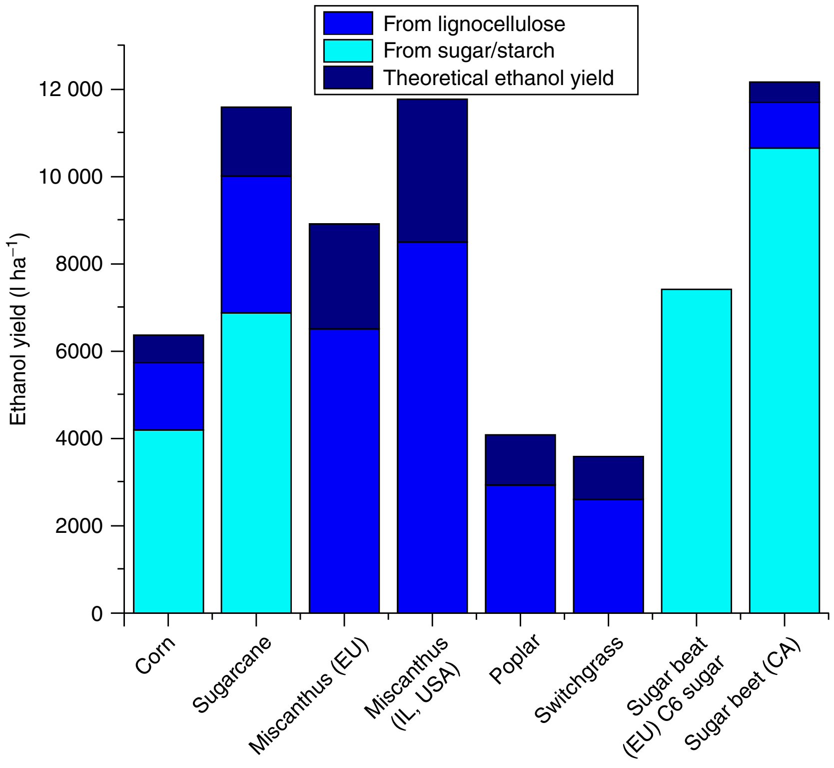

Figure 12 Potential ethanol yields from selected feedstocks. Crops like beets can be produced with high yields and efficiency using current or near-term technology. Light blue, current or simple technology, mid-blue (new or pilot-scale technology) and dark blue (no current technology available-the theoretical conversion limit). Reproduced from Kaffka, S.R., Zhang, T., Kendall, A.M., Yeo, B.-L., 2014. Advanced technology and modeling support biofuel production from beets in California. Proceedings of the 74th IIRB congress, Dresden. Available at: http://www.iirb.org/ (accessed 29.04.14).

also provide lignocellulose in bagasse and field trash (leaves) for current exploitation as a combustion fuel at the sugar mill and for future exploitation as a biofuel once required technologies mature. In many sugarcane systems, direct combustion of trash and bagasse provides much of the energy to evaporate sugarcane juice. In some areas, the material is used to cogenerate electricity, which may be produced in excess of mill requirements and sold into the local electricity grid. Current breeding programs are seeking to enhance stress tolerance and vigor, thereby reducing inputs and expanding production areas. This is done through selection and by increasing the percentage of other *Saccharum* species and related genera. Use of sugarcane to produce ethanol from sugar has the advantage of flexibility, as executed in Brazil. Here the sugar can be diverted between consumption and fermentation at short notice in response to market conditions.

Selection for high sugar has potentially created a genetic bottleneck that has narrowed the genetic resources from which high biomass and low- or high-lignin clones might be selected. This may have reduced maximum potential productivity in current commercial germplasm. This may be relieved as selection for total biomass in pursuit of efficient lignocellulosic bioenergy feedstocks is undertaken. Higher fiber clones that still contain relatively high sugar have been termed 'Type I Energy Canes' (Tew and Cobill, 2008). These were advocated some time ago by Alexander (1985). Selection within current breeding programs will most likely identify improved Type I cultivars, with somewhat higher fiber and lower sugar than conventional selections within these programs, but improved total biomass production Tew and Cobill, 2008). These may be a stop-gap solution toward maximum biofuel production.

In the long run, dedicated clones are more likely to outperform these compromise candidates in terms of biomass production, stress tolerance, and yields of lignocellulosic biofuel. These Type II clones are more likely to require separate crossing and selection programs. The emphasis will be on biomass production with stress tolerance. There appears to be considerable potential for enhanced productivity. Lignin and cellulose are coregulated at the level of gene expression (Ragauskas *et al.*, 2006) with studies in other species suggesting that repressing lignin may increase cellulose synthesis and digestibility. Further, stress tolerance has been linked to high fiber content (Ming *et al.*, 2001; Irvine, 1977), which will be more readily exploited for energy cane than it has been for sugarcane. As the lignocellulosic industry matures, selection for high- or low-lignin content may allow fine-tuning of cultivars for specific biofuel conversion processes. Improvement of tolerance to cold and heat will allow cultivation of the sugarcane feedstock in regions where the fuel markets are strongest, reducing transportation costs. In this case, market forces may reverse the decline in sugarcane and energy cane production observed in countries, such as the United States (**Figure 9**), as multiple product streams are developed.

Conclusions

A large amount of sugar from sugarcane production is diverted currently to ethanol. Brazil has demonstrated the feasibility of an integrated sugar/ethanol economy and many other countries are now developing this capacity. Ethanol from sugarcane sugar is at present one of the most efficient sources of biofuels that can be produced on a large scale. With future development of lignocellulosic processes, ethanol yields could increase by threefold, and the environmental benefits of sugarcane biofuel will be even greater (Oliverio *et al.*, 2010). However, once bagasse can be directly converted into other fuels, other cellulosic sources of biomass that produce little sugar but are inexpensive like crop residues and woody biomass will also become available. A distinct advantage of biofuel programs based on Type I or Type II energy cane clones is that the breeding, selection, management, and materials handling aspects of the production system are already well established for sugarcane. In a similar manner, this is also true for sugar beets that are used to a lesser extent as an ethanol source. These advantages of existing sugar crops will remain a factor in favoring their use compared with strictly cellulosic materials.

Some countries are more dependent on sugar production for their trade than others. Although sugar production is less important in nations that produce sugar beet, the crop has an important biological role in crop rotations and an important economic role in providing income to farmers and processing and refining jobs locally. Also, established industries representing significant capital investment have been developed to process beets into sugar. The cost of growing and processing sugar beet in the industrialized world is higher on an average than equivalent costs for sugarcane. This is due in part to differences in labor and other costs, the value of assets devoted to crop production in the industrialized and developing nations, and environmental regulations. It is unclear how trade issues affecting sugar beet production will be resolved in the future.

References

Alexander, A.G., 1985. The Energy Cane Alternative. Amsterdam: Elsevier Science Publishers B.V. pp. 509.

Allen, R.G., Pereira, L.S., Raes, D., Smith., M., 1998. Crop evapotranspiration-guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome: FAO.

Armstrong, M.J., Milford, G.f.J., 1983. The nitrogen nutrition of of sugar beet. British Sugar Beet Review 53 (4), 42–44.

Barbanti, L., Zavanella, M., Venturi, G., 2007. Losses in sugar content along the harvest campaign and means to contrast them. In: Proceedings International Institute for Beet Research Summer Congress, Marrakech, Morocco, pp. 165–175. Brussels, Belgium: International Institute for Beet Research.

Barnes, A.C., 1974. The Sugarcane. London: Leonard Hill Books.

Bosemark, N.O., 2006. Genetics and breeding. In: Draycott, A.P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 50–88 (Chapter 4).

Brown, K.W., Rosenberg, N.J., 1971. Energy and CO_2 balance of an irrigated sugar beet (*Beta vulgaris*) field in the Great Plains. Agronomy Journal 63, 207–213.

Cariolle, M., Duvall, R., 2006. Nutrition nitrogen. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 169–184 (Chapter 8).

Davidoff, B., hanks, R.J., 1989. Sugar beet production as influenced by limited irrigation. Irrigation Science 10, 1–17.

Demirel, B., Scherer, P., 2008. Production of methane from sugar beet silage without manure addition by a single-stage anaerobic digestion process. Biomass and Bioenergy 32, 203–209.

Demmers-Derks, H., Mitchell, R.A.G., Mitchell, V.J., Lawlor, D.W., 1998. Response of sugar beet (*Beta vulgaris* L.) yield and biochemical composition to elevated CO_2 and temperature at two nitrogen applications. Plant, Cell and Environment 21, 829–836.

D'Hont, A., Grivet, L., Feldmann, P., *et al.*, 1996. Characterisation of the double genome structure of modern sugarcane cultivars (*Saccharumn* spp.) by molecular cytogenetics. Molecular and General Genetics 250, 405–413.

Donatelli, M., Tubiello, F.N., Peruch, U., Rosenzweig, C., 2003. Impacts of climate change and elevated CO_2 on sugar beet production in northern and central Italy. Italian Journal of Agronomy 6, 133–142.

Draycott, A.P., Christiansen, D.R., 2003. Nutrients for Sugar Beet Production. Cambridge: CABI Publishing, pp. 242.

Dufour, P., Deu, M., Grivet, L., *et al.*, 1997. Construction of a composite sorghum genome map and comparison with sugarcane, a related complex polyploidy. Theoretical and Applied Genetics 94, 409–418.

Dunham, R.J., 1989. Irrigating sugar beet in the United Kingdom. In: Anon (Ed.), Proceedings of the 2nd Northwest European Irrigation Conference, Silsoe, 1987, pp. 109–129. UK: United Kingdom Irrigation Association and Cranfield Press.

Dunham, R.J., 2003. Water use and irrigation. In: Cooke, D.A., Scott, R.K. (Eds.), The Sugar Beet Crop, Science into Practice. London: Chapman and Hall, pp. 279–309 (Chapter 8).

Dutton, J., Hiuijbregts, T., 2006. Root quality and processing. In: Draycott, A.P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 409–442 (Chapter 16).

Ehlig, C.F., Lemert, R.D., 1979. Water use and yields of sugarbeets over a range from excessive to limited irrigation. Soil Science Society of America 43, 403–407.

Ellis, R.D., Merry, R.E., 2004. Sugarcane agriculture. In: James, G.L. (Ed.), Sugarcane, second ed. Oxford: Blackwell Sciences Ltd, pp. 181–194.

FAOSTAT, 2013. Food and Agriculture Organization of the United Nations. Available at: http://faostat.fao.org/default.aspx (accessed 18.02.14)

Galloway, J.H., 1989. The Sugar Cane Industry: An Historical Geography from its Origins to 1914. Cambridge: Cambridge University Press.

Ghariani S.A., 1981. Impact of variable irrigation water supply on yield determining parameters and seasonal water-use efficiency of sugar beets. PhD Thesis, University of California.

Grantz, D.A., 1989. Effect of cool temperatures on photosynthesis and stomatal conductance in field grown sugarcane in Hawaii. Field Crops Research 22, 143–155.

Grantz, D.A., 2014. Water, transpiration, and gas exchange. In: Moore, P.H., Botha, F.C. (Eds.), Sugarcane: Physiology, Biochemistry & Functional Biology. Ames, IA: Wiley Blackwell, pp. 221–254 (Chapter 10).

Harvey, C.W., Dutton, J.V., 1993. Root quality and processing. In: Cooke, D.A., Scott, R.K. (Eds.), The Sugar Beet Crop, Science Into Practice. London: Chapman and Hall, pp. 571–617 (Chapter 15).

Hills, F.J., Broadbent, F.E., Lorenz, O.A., 1983. Fertilizer nitrogen utilization by corn, tomato, and sugarbeet. Agronomy Journal 75, 423–426.

Hills, F.J., Sailsbery, R., Ulrich, A., 1982. 'Sugarbeet Fertilization,' Bulletin 1891. Oakland, CA: University of California, Division of Agriculture and Natural Resources.

Hills, F.J., Winter, S.R., Henderson, D.W., 1990. Sugarbeet. In: Stewart, B.A., Nielsen, D.R. (Eds.), Irrigation of Agricultural Crops. Madison, WI: American Society of Agronomy.

Hogarth, D.M., 1987. Genetics of sugarcane. In: Heinz, D.J. (Ed.), Sugarcane Improvement through Breeding. Amsterdam: Elsevier Science Publishers, pp. 503–542.

Howell, T.A., Ziska, L.H., McCormick, R.L., Burtch, L.M., Fischer, W.B., 1987. Response of sugarbeets to irrigation frequency and cutoff on a clay loam soil. Irrigation Science 8, 1–11.

Irvine, J.E., 1977. Identification of cold tolerance in *Saccharum* and related genera through refrigerated freezing screening. Proceedings of International Society of Sugar Cane Technologists 16, 147–156.

Irvine, J.E., 1983. Sugarcane. In: Symposium on Potential Productivity of Field Crops under Different Environments, pp. 361–381. Los Banos, Laguna: International Rice Research Institute.

Irvine, J.E., 2004. Sugarcane agronomy. In: James, G.L. (Ed.), Sugarcane, second ed. Oxford: Blackwell Sciences Ltd, pp. 143–159.

Jaggard, K., Koch, H.-J., Arroyo Sanz, J.M., *et al.*, 2012. The yield gap in some sugar beet producing countries. International Sugar Journal 114 (1363), 496–499.

Jaggard, K.W., Qi, A., 2006. Agronomy. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Pub. Ltd, pp. 134–168 (Chapter 7).

Jaggard, K.W., Qi, A., Semenov, M., 2007. The impact of climate change on sugar beet yields in the UK. Journal of Agricultural Science 145, 367–375.

James, N.I., 1980. Sugarcane. In: Fehr, W.R., Hodley, H.H. (Eds.), Hybridization of Crop Plants. Madison, WI: American Society of Agronomy-Crop Science Society of America, pp. 617–629.

James, G.L., 2004. An introduction to sugarcane. In: James, G.L. (Ed.), Sugarcane, second ed. Oxford: Blackwell Sciences Ltd, pp. 1–19.

Jannoo, N., Grivet, L., Chatret, N., *et al.*, 2007. Orthologous comparison in a gene-rich region among grasses reveals stability in the sugarcane polyploidy genome. Plant Journal 50, 574–585.

Jones, P.D., Lister, D.H., Jaggard, K.W., Pidgeon, J.D., 2003. Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. Climate Change 58, 93–108.

Kaffka, S., Daxue, D., Peterson, G., 1999. Saline water can be reused to irrigate sugarbeets, but sugar may be low. California Agriculture 53 (1), 11–15.

Kaffka, S.R., 2007. Fertilizer N management for high-yielding sugar beets in California. Proceedings of IIRB Summer Congress, Marrakech, Morocco. Brussels, Belgium: International Institute for Beet Research.

Kaffka, S.R., Kirby, D., Peterson, G.R., 2001. Reducing fertilizer in sugarbeets can protect water quality. California Agriculture 55 (3), 42–48.

Kaffka, S.R., Lesch, S.M., Bali, K.M., Corwin, D.L., 2005. Site-specific management in salt-affected sugar beet fields using electromagnetic induction. Computers and Electronics in Agriculture 46, 329–350.

Kaffka, S.R., Zhang, T., Kendall, A.M., Yeo, B.-L., 2014. Advanced technology and modeling support biofuel production from beets in California. Proceedings of the 74th IIRB congress, Dresden. Available at: http://www.iirb.org/ (accessed 29.04.14).

Klenk, I., Kunz, M., 2008. Europaiches bioethanol aus getreide und zuckerruben – eine okologische und okonomische analyse. Zuckerind 133 (10), 625–635.

Lam, E., Shine, Jr., J., da Silva, J., *et al.*, 2009.Improving sugarcane for biofuel: Engineering for an even better feedstock. Global Change Bioenergy 1, 251–255.

Langner, P., 1996. Consumptive water use of fall planted sugarbeets in the San Joaquin Valley of California. MS Thesis, University of California, Davis.

Lathouwers, J., Weyens, G., Lefebvre, M., 2005. Transgenic research in sugar beet. In: Pidgeon, J., Richard-Molard, M., Weevers, J.D.A., Beckers, R. (Eds), Advances in Sugar Beet Research, IIRB, vol. 6. Brussels, Belgium: International Institute for Sugarbeet Research, pp. 5–24.

Mangelsdorf, A.J., 1950. Sugar cane as seen from Hawaii. Economic Botany 4, 150–176.

Märländer, B., Hoffman, C., Koch, H.-J., *et al.*, 2003. Environmental situation and yield performance of the sugar beet crop in Germany: Heading for sustainable development. Journal of Agronomy and Crop Science 189, 201–226.

McGinnis, R.A. (Ed.), 1982. Sugarbeet Technology, third ed. Denver, CO: Sugarbeet Development Foundation.

McGrath, J.M., 2011. Beta. In: Kole, C. (Ed.), Wild Relatives: Genomic and Bredding Resources, Industrial Crops. Heidelberg: Springer-Verlag, pp. 1–28.

McGrath, J.M., Saccomani, M., Stevanato, P., Biancardi, E., 2007. Beet. In: Kole, C. (Ed.), Genome Mapping and Moelcular Breeding in Plants, vol. 5. Heidelberg: Springer-Verlag, pp. 135–150.

Milford, G.F.J., 2006. Plant structure and physiology. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 30–49 (Chapter 3).

Milford, G.F.J., Travis, K.Z., Pocock, T.O., Jaggard, K.W., Day, W., 1988. Growth and dry-matter partitioning in sugar beet. The Journal of Agricultural Science – Cambridge 100, 301–308.

Miller, D.E., Aarstad, J.S., 1976. Yields and sugar content of sugarbeets as affected by deficit high-frequency irrigation. Agronomy Journal 68, 231–234.

Ming, R., Liu, S.C., Lin, Y.R., *et al.*, 1998. Detailed alignment of saccharum and sorghum chromosomes: Comparative organization of closely related diploid and polyploid genomes. Genetics 150, 1663–1682.

Ming, R., Liu, S.-C., Moore, P.H., Irvine, J.E., Paterson, A.H., 2013. QTL analysis in a complex autopolyploid: Genetic control of sugar content in sugarcane. Genome Research 112, 2075–2084.

Ming, R., Moore, P.H., Wu, K.-K., *et al.*, 2001. Sugarcane improvement through breeding and biotechnology. Plant Breeding Reviews 11, 15–118.

Moore, P.H., 1987. Breeding for stress resistance. In: Heinz, D.J. (Ed.), *Sugarcane Improvement through Breeding*. Amsterdam: Elsevier Science Publishers, pp. 503–542.

Moreno, F., Cabrerra, F., Fernandez-Boy, E., *et al.*, 2001. Irrigation with saline water in the reclaimed marsh soils of south-west Spain: Impact on soil properties and cotton and sugar beet crops. Agricultural Water Management 48, 133–150.

Morillo-Velarde, R., Ober, E., 2006. Water use and irrigation. In: Draycott, P. (Ed.), Sugar Beet. Oxford: Blackwell Publication Ltd, pp. 221–255 (Chapter 10).

Nable, R.O., Robertson, M.J., Berthelsen, S., 1999. Response of shoot growth and transpiration to soil drying in sugarcane. Plant and Soil 207, 59–65.

Oliverio, J.L., Carmo, V.B., Gurgel, M.A., 2010. The DSM-Dedini sustainable mill: A new concept in designing complete sugarcane mills. Proceedings of International Society of Sugar Cane Technologists 27, 1–34.

Panella, L., Kaffka, S.R., 2011. Sugar beet (*Beta vulgaris* L) as a biofuel feedstock in the United States. In: Eggleston, G. (Ed.), Sustainability of the Sugar and Sugar-Ethanol industries. Washington, DC: American Chemical Society, pp. 164–175 (Chapter 10).

Panella, L., Kaffka, S.K., Lewellen, R.T., *et al.*, 2013. Yield gains in US sugarbeet, contributing factors and future prospects. In: Smith, S., Diers, B., Carver, B., Specht, J. (Eds.), Yield Gains in Major U.S. Field Crops. Madison, WI: CSSA.

Parkin, G., De Bruijn, J.M., 2010. Major challenges and changes in the European Sugar Sector. In: Eggleston, G. (Ed.), Sustainability of the Sugar and Sugar-Ethanol Industries. Washington, DC: American Chemical Society, pp. 39–52.

Paterson, A.H., Bowers, J.E., Bruggmann, R., *et al.*, 2009. The *Sorghum bicolor* genome and the diversification of grasses. Nature 457, 551–556.

Ragauskas, A.J., Williams, C.K., Davison, B.H., *et al.*, 2006. The path forward for biofuels and biomaterials. Science 311, 484–489.

Robinson, N., Brackin, R., Vinall, K., *et al.*, 2011. Nitrate paradigm does not hold up for sugarcane. PLoS ONE 6, e19045. doi:10.1371/journal.pone.0019045.

Sage, R.F., Kubien, D.S., 2007. The temperature response of C_3 and C_4 photosynthesis. Plant, Cell & Environment 30, 1086–1106.

Santek, B., Gwehenberger, G., Santek, M.I., Narodoslawsky, M., Horvat, P., 2010. Evaluation of energy demand and the sustainability of different bioethanol production processes from sugar beet. Resources, Conservation, and Recycling 54, 872–877.

Savitsky, V.F., 1952. Monogerm Sugar Beets in the United States. Proceedings of International Society of Sugar Cane Technologists 7, 156–159.

Simoes, M.D.S., Rocha, J.V., Lamparelli, R.A.C., 2005. Growth indices and productivity in sugarcane. Scientia Agricola 62, 23–30.

Sreenivasan, T.V., Ahloowalia, B.S., Heinz, D.J., 1987. Cytogenetics. In: Heinz, D.J. (Ed.), Sugarcane Improvement through Breeding. New York, NY: Elsevier, pp. 211–254.

Tew, T.L., Cobill, R.M., 2008. Genetic Improvement of Sugarcane (*Saccharum* spp.) as an Energy Crop. In: Vermerris, W. (Ed.), *Genetic Improvement of Bioenergy Crops*. New York, NY: Springer, pp. 249–272.

Todd, M., Forber, G., Digges, P., 2004. Cane payment systems. In: James, G.L. (Ed.), Sugarcane, second ed. Oxford: Blackwell Sciences Ltd, pp. 181–194.

Ulrich, A., Hills, F.J., 1990. Plant analysis as an aid in fertilizing sugarbeet. In: Westerman, R.L. (Ed.), Soil Testing and Plant Analysis, third ed. Madison, WI: Soil Science Society of America.

Waclawovsky, A.J., Sato, P.M., Lembke, C.G., Moore, P.H., Souza, G.M., 2010. Sugarcane for bioenergy production: An assessment of yield and regulation of sucrose content. Plant Biotechnology Journal 8, 1–14.

Weigel, H-J., Manderschied, R., 2012. Growth response to free air CO_2 enrichment and nitrogen fertilization: Rotating barley, ryegrass, sugar beet, and wheat. European Journal of Agronomy 43, 97–107.

Whitney, E.D., Duffus, J.E. (Eds.), 1986. Compendium of Beet Diseases and Insects. St. Paul, MN: The American Phytopathological Society.

Wisler, G.C., Duffus, J.E., 2000. A century of plant virus management in the Salinas Valley of California, 'East of Eden.' Virus Research 71, 161–169.

Zeven, A.C., 1979. Polyploidy and domestication: The origin and survival of polyploids in cytotype mixtures. In: Lewis, W.H. (Ed.), Polyploidy, Biological Relevance. New York: Plenum Press, pp. 385–408.

Zhang, J., Nagai, C., Yu, Q., *et al.*, 2012. Genome size variation in three Saccharum species. Euphytica 185, 511–519.

Zhu, X.G., Long, S.P., Ort, D.R., 2008. What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? Current Opinion in Biotechnology 19, 153–159.

Zimmerman, K., Zeddies, J., 2000. Evolution of Sugar Beet Breeding and Its Contribution to Value Added. Hohenheim: Hohenheim University, Department of Agricultural Economics.

Relevant Websites

http://www.bsdf-assbt.org/assbt/assbt.htm
American Society of Sugar Beet Technologists.

http://www.ifz-goettingen.de/site/en/38/home.html
Institute for Sugar Beet Research.
http://www.iirb.org/
International Institute of Sugar Beet Research.
http://smbsc.com/SugarProcess/video_MakingSugar.aspx
Southern Minnesota Beet Sugar Cooperative.
http://www.ers.usda.gov/topics/crops/sugar-sweeteners.aspx
United States Department of Agriculture/Economic Research Service.
www.nass.usda.gov
USDA National Agricultural Statistics Service.