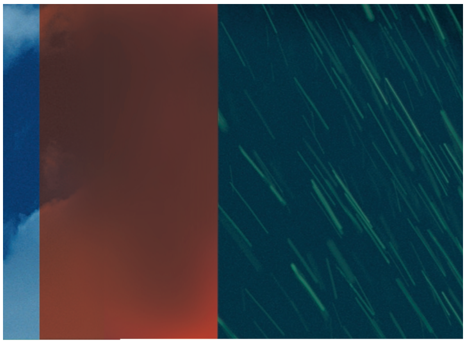

THE SUGARCANE PLANT

Terry Bull

THIS chapter outlines the evolution of sugarcane and describes the sugarcane plant in general terms in order to highlight the important physiological processes involved in growth, ripening and flowering. Growers and millers are fully aware of the need to balance growth and ripening to maximise the production of sugar. However, they are frequently less appreciative of the vital role played by flowering in the ongoing production of improved varieties.

EVOLUTION OF MODERN CANES

Sugarcane belongs to the genus Saccharum and is a grass, like most of the world's grain crops. However, instead of storing starch in seed heads like the grain crops, sugarcane has evolved to store sugar (sucrose) in its stalk. The archetypal soft, sweet chewing 'noble canes' belong to the species *Saccharum officinarum*, which appears to have evolved from its wild relatives in Papua-New Guinea (PNG).

Three of sugarcane's closest relatives are also found in PNG and are still used as building materials and food by the local people. These include the very vigorous but low-sugar species *S. spontaneum* that is found around streams and rivers throughout PNG and Southeast Asia. The heavier stalked, but still low sugar and high-fibred species, *S. robustum*, is found only in Papua-New Guinea. A third species, *S. edule*, is also not very sweet but produces an edible flower, like an elongated cauliflower, which is a delicacy throughout Melanesia and Polynesia.

Outside PNG, two other species, *S. sinense* and *S. barberi*, were widely used as sugarcanes in China and India. They probably evolved from natural hybrids between *S. spontaneum* and *S. officinarum* and many Indian varieties have these two species in their pedigrees. Figure 1 shows the general evolutionary trend from the high-fibre/low-sugar wild species towards the low-fibre/high-sugar noble canes and indicates the relative position of commercial varieties.

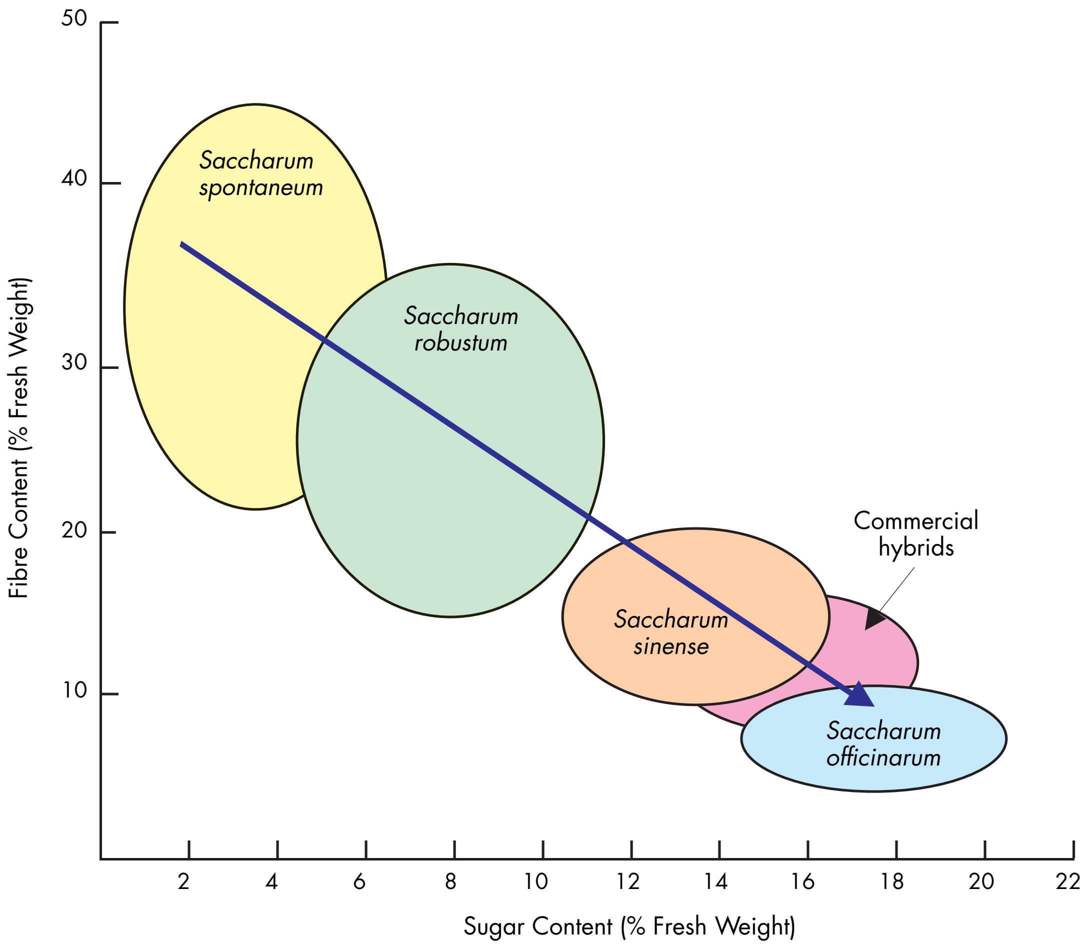

Figure 1. *Progressive change in fibre and sugar levels from wild to noble canes.*

The noble canes were used to establish most sugar industries around the world but they eventually succumbed to some serious diseases that threatened the viability of the industry worldwide. A fortuitous natural cross between *S. officinarum* and *S. spontaneum* in Indonesia produced a hybrid variety that was vigorous and resistant to the prevailing serah disease. This lucky event laid the basis for most sugarcane breeding programs and today's commercial varieties are complex hybrids between two or more *Saccharum* species. Consequently, modern varieties are more vigorous, heavier yielding and more disease and pest resistant than the old noble canes. The commercial varieties have higher fibre and a lower sugar content than the nobles but their greater vigour provides for increased sugar production. Nevertheless, achieving the full sugar content of noble canes in commercial varieties remains the target for most breeding programs.

MORPHOLOGY

The sugarcane plant is composed of stalks, leaves, roots and flowers. Each has an important role in crop growth, crop ripening and the production of new varieties.

Stalk (stem)

Sugarcane is propagated vegetatively by stem cuttings containing one or more buds (Figure 2). The bud produces a primary stalk on germination and each stalk is composed of nodes, with a bud, one or more rows of root buds (primordia) and a growth ring (intercalary meristem), separated by inter-nodal storage tissue.

The growth ring is the site of active cell elongation and, in young internodes, it is soft and 'cheesy' as cells elongate rapidly with

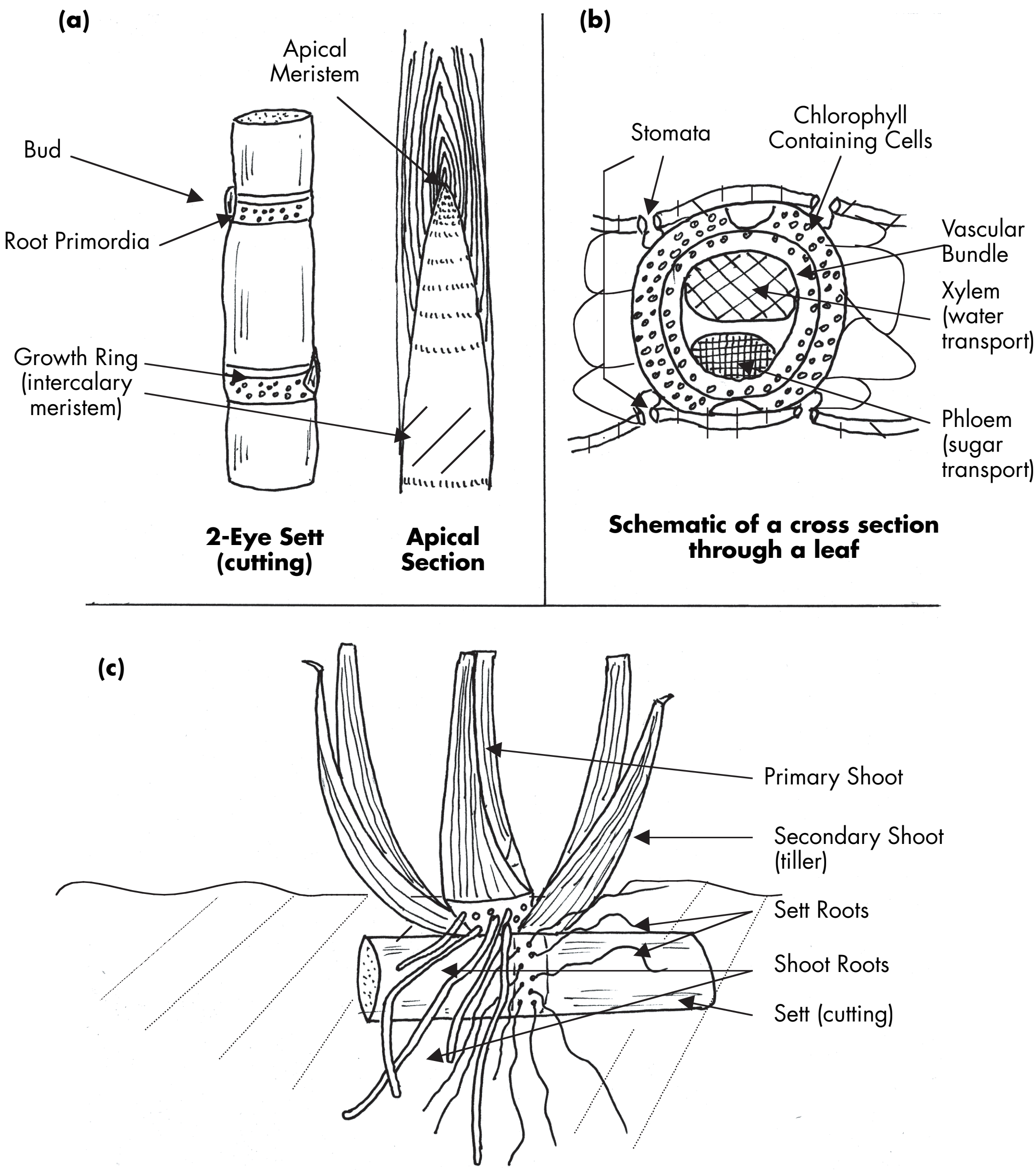

Figure 2. *Morphology of sugarcane **(a)** 2-eye sett (cutting) and section through stalk apex **(b)** schematic of a section through a leaf **(c)** germinating sett.*

very little cell wall thickening. In old internodes, cell elongation has ceased, cell-wall thickening is complete and the ring is hard and often difficult to see.

Internodes are the sugar-storage organs of the plant and vary in length from less than 10 mm to over 300 mm according to age and the growing conditions experienced. Sugar-cane stalks normally reach some 2–3 m in height in the normal growing season.

Leaf

Leaves are the photosynthetic 'engines' of the plant, producing the sugar that is stored in the stalks. Leaves are attached to the nodes and form two alternate ranks on either side of the stalk. They consist of two parts, a blade and a sheath, separated by a blade joint. Leaf size and number increase from germination and there are about 10 per stalk at maturity.

The leaves become both longer and wider as the plant develops, until a stable leaf size is established. Leaf width is correlated strongly with stalk diameter and varies from about 20 mm to 60 mm in commercial varieties. Leaf length depends upon variety and growing conditions but is usually between 0.9 m to 2.0 m in mature leaves.

Canopy structure varies with variety, but the two youngest leaves are usually vertical, with the older leaves becoming progressively more horizontal.

Root

Roots are the organs responsible for taking up the water and nutrients from the soil needed for plant growth. They also provide structural support for the plant. There are two main root types in sugarcane.

Germinating stalk cuttings produce sett roots from the primordia at the node. These roots maintain the cutting during germination but do not directly support the growing shoot.

Shoot roots are produced from the root primordia of young nodes on the new shoot (Figure 2). They are directly connected to the vascular system of the shoot and support the growth of the new plant, rendering it independent of the original cutting.

Some sugarcane roots can extend to over 2 m deep in a favourable soil profile and help to anchor the plant, but commonly the most active roots are found at less than 0.5 m from the soil surface.

Flower

Although sugarcane is propagated asexually for commercial purposes, many varieties flower and set seed. The flowers are borne in an open-branched panicle, commonly called an arrow. Each flower contains anthers, which carry the male pollen, and the female embryo cell with its stigma, down which pollen grows to fertilise the egg.

Anther emergence occurs as a wave down the flower, lasting up to 12 days and usually preceding stigma emergence by 1–2 days. Cross-pollinating flowers from different high-performing varieties or varieties with specific desirable characteristics produces new varieties for the industry.

GROWTH AND SUGAR STORAGE

Sugarcane is a unique plant capable of storing appreciable amounts of sugar (sucrose) in large above-ground stalks. This simple statement reflects the result of a complex series of physiological processes involved in crop growth and sugar storage. An understanding of these processes assists in not only understanding how sugar is produced but also how production can be increased. The source of all plant growth lies in the process of photosynthesis.

Photosynthesis

The leaves of the plant are the powerhouses for sugar production. Leaves contain cells with chlorophyll which catalyse photo-synthetic reactions whereby light energy is used to combine water and carbon dioxide into carbohydrates (sugars).

The cells containing chlorophyll are near to pores (stomata) in the leaf surface. The stomata allow carbon dioxide from the air to enter the plant and water from the plant to evaporate into the atmosphere (Figure 2). The opening of the stomata is controlled by the turgidity of the plant.

If evaporation from the leaf exceeds the rate at which the plant can bring water from the soil to the leaves, the stomata close until equilibrium can be re-established. They also close at night to reduce water loss at a time when photosynthesis cannot occur.

The cells containing chlorophyll are also adjacent to the vascular bundles of the leaf. These bundles contain the plumbing for both water movement and sugar transport. Water and nutrients from the soil enter the vascular bundles in the root and flow through the plant to the leaves. Here the water is used in photosynthesis and to maintain the turgidity of the plant.

Sugars produced by photosynthesis are loaded into phloem cells, a part of the vascular bundle specifically concerned with sugar transport, and transported to support the production and expansion of new leaves, sheaths and stalk being produced in the growing zone at the apex of the stalk. They are also transported down the plant to support the production and growth of roots below ground.

Sugars are the building blocks for growth and storage and they provide the energy (respiration) required to drive these processes. However, not all the sugars are required immediately and any excess is stored in the internodes. Here it can be remobilised to support growth when conditions do not favor active photosynthesis. Over time, the residual excess sugar remains in the internode cells and contributes to the ripening process.

The final yield of sugar is a function of stalk growth to provide a large storage volume, and ripening to fill this volume with sugar. Five phases occur in the growth of sugarcane:

(1) Germination — where the plant is established and tillers are initiated;

(2) Early growth — where the leaf canopy is established and maximum growth or elongation of the storage organ (the stalk) occurs;

(3) Maturation — where stalk elongation slows down and sugar storage or ripening dominates;

(4) Flowering — where vegetative growth ceases and an arrow (flower) is produced;

(5) Ratooning — where stalks are harvested and crop re-growth occurs from underground buds on the severed stalks.

While convenient for discussion, some of these phases overlap considerably and basal internodes of the stalk can fill with sugar while the top of the stalk is still actively growing. Sugar is a stored fuel for the cane plant, so that both storage and mobilisation of sucrose occur continually as the plant responds to periods of growth constraint or periods of active growth.

Germination and stool establishment

Sugarcane is a vegetatively propagated plant. Cane setts or billets with one or more buds or eyes and numerous root primordia are planted into moist soil to establish the next crop. Although the cane sett contains all the food and water required for buds to germinate, the germination process itself is sensitive to temperature.

Varieties differ in their degree of temperature sensitivity, just as humans do, but in general terms germination will be very slow when soil temperatures drop below about 17°C to 18°C and will be increasingly faster as temperatures approach 35°C (Figure 3). Germination rarely occurs at temperatures below about 11°C and, even between 11°C and 18°C, the rate may be too slow to avoid death of setts due to attack by soil rots or other pathogens.

During the initial stages of germination, the root primordia around the nodes produce a flush of sett roots (Figure 3). These roots are transitory in terms of plant growth. They are not directly connected to the primary shoot,

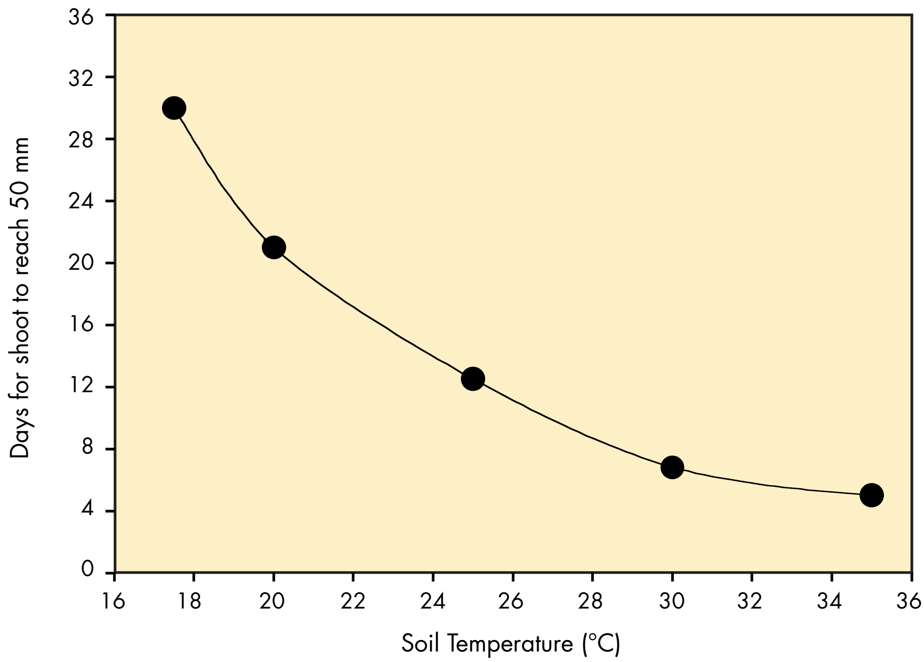

Figure 3. *Effect of temperature on germination.*

but they are important in maintaining the moisture level in the sett while the shoot elongates through the soil into the sunlight. Although the sett contains the food and water required for germination of the primary shoot, the levels are totally inadequate to support ongoing shoot and root growth. The emerging shoot must quickly become independent of the sett by producing leaves that can photosynthesise and produce the sugars needed to support its growth and development.

Once through the soil and in the light, the shoot grows rapidly, produces leaves and develops a series of short internodes under the ground as the stalk begins to elongate. Each node carries a new bud and new root primordia, and these are the basis for stool establishment and growth. The root primordia germinate and produce the shoot roots that will support the plant for the rest of the plant crop cycle.

These roots are an integral part of the vascular plumbing of the new plant and will harvest water and nutrients from the soil solution to support growth. The shoot is now independent of the original sett. At the same time, the new buds below ground produce the first flush of tillers or secondary shoots and the new stool is well on the way to being established.

Early growth

Rapid and sustained early growth of the stool is important for laying down the maximum volume of stalk for subsequent sugar storage or ripening. During this phase, the plant initiates a number of tillers, and the leaf canopy expands to capture the available light. Production of each new tiller requires a diversion of photosynthate from the primary stalk and older tillers. Growth of existing stalks slows or ceases for a short period until the new surge of tillers has produced leaves and is able to exist on its own photosynthate. Many of the younger tillers are subsequently lost when the canopy closes in and robs them of light. The number of tillers that die may be quite large, i.e. up to about 50 000/ha, but they are small in size and usually represent a loss of less than about 5% in overall crop yield.

Stalk elongation during this phase is very sensitive to both temperature and soil moisture. Under field conditions, too much water after heavy rain or irrigation will slow or stop elongation due to waterlogging in the root zone. After soil drainage has occurred, the elongation rates will recover but then progressively decline until the next rainfall or irrigation. Figure 4 shows that during early growth the rate of stalk elongation responds rapidly to rainfall events when temperatures are relatively high. In fact, high growth at high temperatures is dependent upon adequate soil moisture. However, as the average temperature declines, growth also declines, even after significant rainfall.

At the end of this phase of growth, the crop is almost fully grown in terms of cane yield but the CCS or sugar level of the crop is still quite low, usually around 5 to 7 units. Modern cane varieties are very vigorous and have been bred to give high cane yields. If climatic and soil conditions have remained warm, wet and windy during this phase, the crop may have already lodged under its own weight and the top section of the fallen stalks will have curved upright to re-establish a full leaf canopy. In the wetter and warmer areas, some stalk death will have occurred due to damage and pathogen attack leading to some loss of yield. In the drier, cooler areas, stalk death and damage in lodged crops are usually minimal and yield loss will be minor.

Maturation and ripening

Ripening is a continuous and reversible process. During stalk growth, each internode tends to function as a single unit. While it has a leaf attached, the internode completes cell elongation and cell-wall thickening and tends to complete filling its storage volume with sugars. Hence, the internodes have generally completed their cycle by the time that the attached leaf dies, and the lower ones are essentially ripe while the upper part of the stalk is still growing. However, the stored sugar is still available for relocation to support tillering and/or support growth

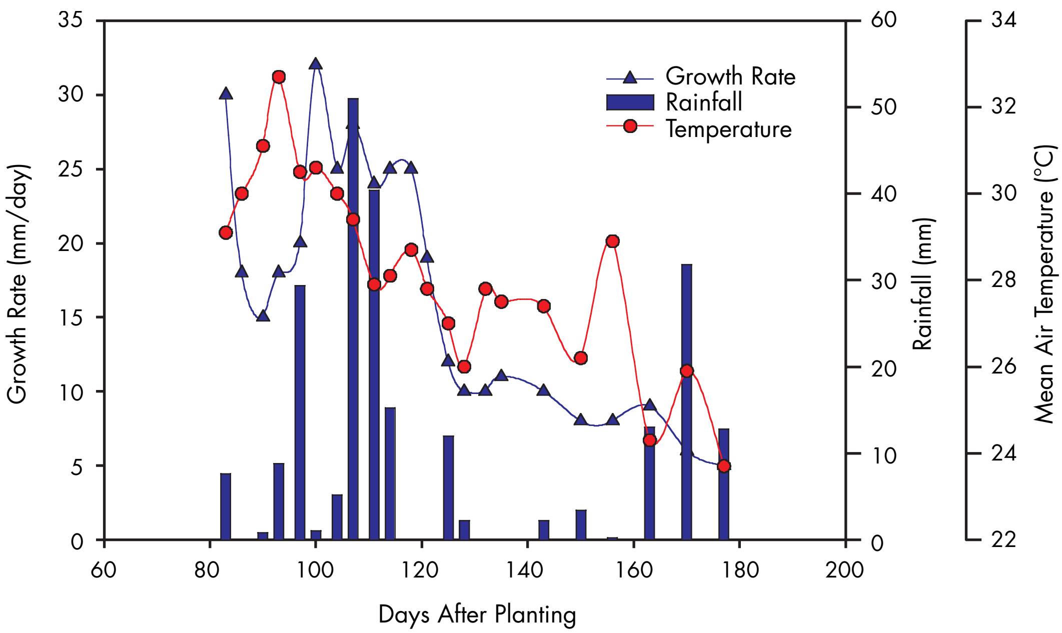

Figure 4. *Effect of temperature and rainfall on stalk elongation.*

when conditions are not favourable for photosynthesis. With stalk maturation, more and more internodes reach the same condition and a progressive increase in crop CCS is observed. The laying down of fibre and sugars displaces some water from the internode volume, so that the observed moisture content in the crop begins to drop.

Generally, the ripening phase corresponds to the cooler and drier time of year (Figure 5). Stalk elongation is more sensitive to these conditions than is photosynthesis (Figure 6), so stalk elongation becomes strongly restricted, but photosynthesis can continue until conditions become too cool and/or too dry when it too is inhibited. During this interim period, the most recently expanded internodes near the top of the stalk stop elongating and photosynthate previously used for growth is channeled into sugar storage. The net result is an overall increase in the sugar levels in the upper portion of the stalk.

Hence, ripening is an ongoing process that becomes particularly evident in the period when environmental conditions constrain stalk elongation and reduce losses from respiration, but do not greatly restrict photosynthesis.

Flowering

Flowering tends not to be a very important process in commercial cane production. The occurrence of flowering under field conditions is usually quite variable and strongly influenced by the variety.

When daylength, temperature and stage of plant growth are favourable, the stalk undergoes a physiological change and initiates flowering. Flower initiation causes the apical meristem of the stalk to switch from vegetative growth to flower production. This switch-over causes stalk elongation to cease and can lead to some incremental ripening, since, for a short period after the needs of producing the flowers have been met, there is an increase in available photosynthate for channeling into sugar storage. However, the advantage is usually transitory and, since stalk growth has ceased, the potential for maintaining a continued increase in sugar yield is limited.

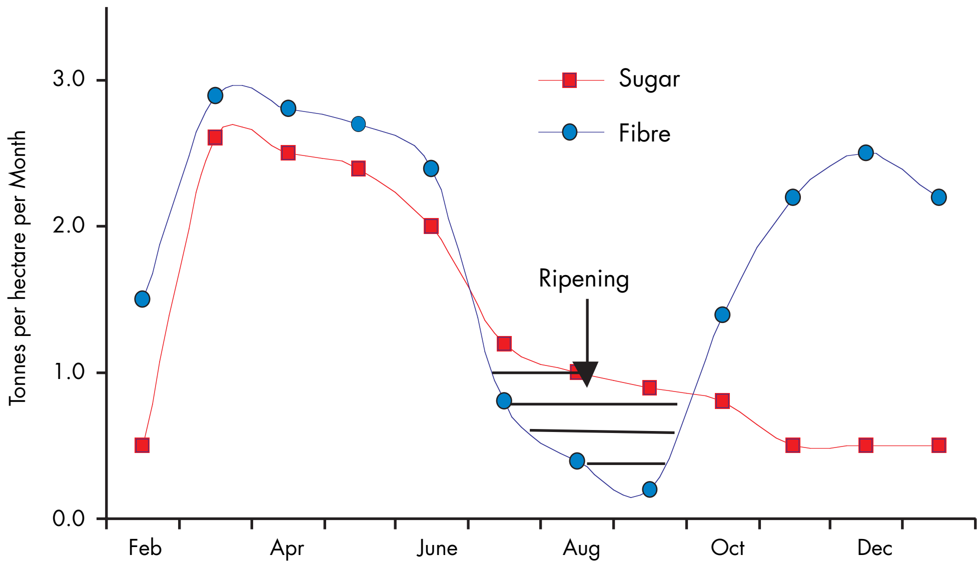

Figure 5. *Production rates of sugar and fibre during the year. Showing similar production rates until the onset of winter conditions when sugar production is greater and then the upsurge in fibre production during spring.*

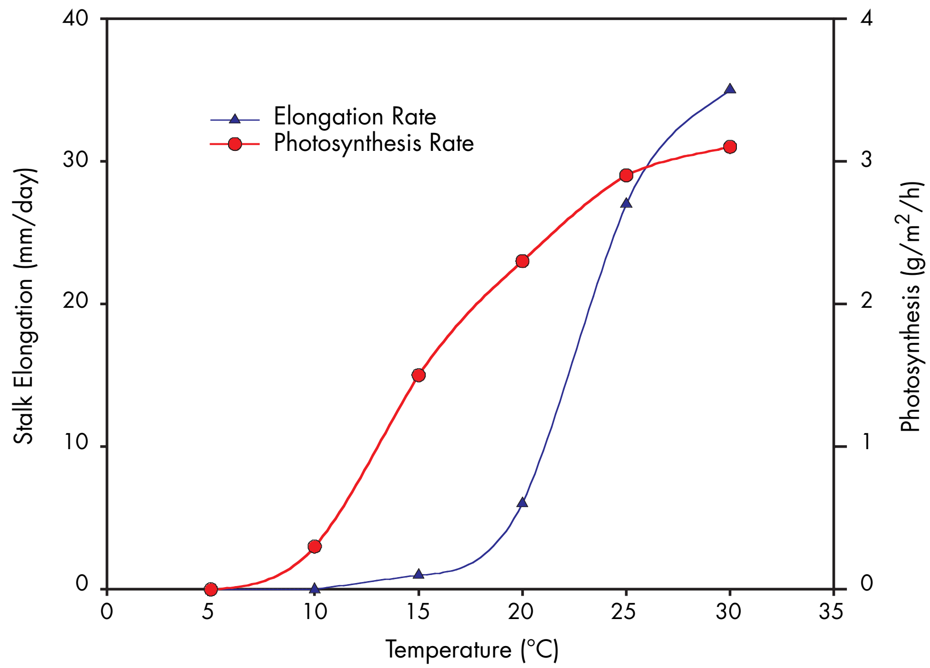

Figure 6. *Effect of temperature on rates of photosynthesis and stalk elongation. This figure shows that photosynthesis is less inhibited than stalk elongation by temperatures below about 22°C.*

On the other hand, flowering is of crucial importance for the continued production of improved varieties. Sugarcane flowers are bisexual, but pollen viability often varies between varieties and under different environmental conditions so that flowers may be essentially male (high pollen viability) or female (low pollen viability). Past breeding programs have relied on only those crosses that could be made when particular varieties flowered under field conditions. This tended to be an opportunistic process and breeders were frequently unable to make preferred crosses because the specific varieties did not flower. More recently, breeders have used controlled environments to simulate daylength and temperature conditions favourable to flowering in order to obtain flowers from most varieties. This has enabled them to embark on a much more controlled breeding program and achieve much better rates of genetic improvement in new varieties.

Ratooning

Sugarcane is a perennial crop and will continue through cycles of growth and maturation until it is finally harvested. However, the crop is normally harvested 12–18 months after planting and the next or first-ratoon crop is produced from the buds remaining on the underground portions of the stalk. Germination of the buds is inhibited prior to harvest by a hormone continually produced by the apical meristem in each stalk. Harvest of the above-ground stalks removes the source of the hormone and allows the buds to germinate when soil temperature and moisture conditions are favourable.

Ratooning is very similar to germination, but each stalk in the stool produces a ratoon stalk at the same time. Hence, the ratoon crop grows faster than the plant crop and the leaf canopy covers in much earlier. Ratoon crops tend to produce more stalks per hectare than plant crops, but the stalks are usually not as thick. Sugarcane can be repeatedly ratooned for many years and up to 20 ratoons have been grown commercially. However, any stool damage incurred during cultivation and harvesting operations or caused by pests and diseases is cumulative and causes successive ratoon-crop yields to decline until they reach a point at which further ratoons are no longer economic. With today's production methods, it is rare to grow more than four ratoons before ploughing out the crop and replanting.

MAXIMISING YIELDS AND PRECISION FARMING SYSTEMS

It is difficult to plan research and development to maximise yields without knowing the yield potential for a given location and production system. Estimation of the theoretical maximum yield under non-limiting conditions is an important consideration for any crop. It provides breeders, agronomists and growers with a real target to assess their progress towards optimising production levels. In effect, the estimation of maximum yield allows assessment of the remaining potential to increase commercial yields and helps in selecting the most practical or economic way of achieving this increase.

Calculations of maximum yield potential are based on the efficiency of photosynthesis in converting light to biomass and the daily light and temperatures received at a given location. The calculations assume that water and nutrients are fully supplied and that weeds, pests and diseases do not pose any problems. All of these factors can be more or less overcome by suitable production methodologies. The calculations also make basic assumptions about crop geometry and row spacing, commonly working with current plant spacings within and between rows. For sugarcane, we can expect that estimations of maximum yield will vary with latitude because of the associated differences in light and temperature regimes.

The following Table shows calculated maximum cane yields for four locations, based on available meteorological records of light radiation and temperature, a spring (1 August) planting date, a 1.5 m row spacing and a 14-month crop production period.

Location	Latitude	Cane yield (tonnes/ha)	
		Calculated maximum*	Commercial average**
Tully	17° 56′	196	99
Ayr	19° 34′	213	147
Bundaberg	25° 00′	194	102
Harwood	29° 26′	164	133

* Maximum yield calculated using average daily climatic data at each site from 1957 to 1997.

** Average commercial plant crop production from 1993 to 1998 (mill records).

Calculated average maximum yields show the expected variation when moving to lower latitudes from a cool zone (Harwood) through a warmer zone (Bundaberg) and a hot zone (Ayr) to a cloudy, wet tropical location (Tully). Maximum yields vary annually within locations according to actual daily light and temperature regimes. There is considerable overlap in the maximum yields between regions. In other words, while there is no single value for maximum yield for all latitudes and climatic conditions, 200 tonnes/ha is a reasonable target for a 14-month old, spring planted crop in most locations.

Comparison of the calculated maximum and actual commercial yields shows a 30–100 tonne/ha difference, which suggests that there is still appreciable scope to improve field production through breeding and agronomic procedures. However, reality is not so simple.

The commercial yields represent average production figures from a wide range of production conditions, management skills and levels of inputs. There is anecdotal evidence, supported by results from field trials, that the better growers can already achieve yields appreciably closer to the maximum yield for their area. This means that the current suite of varieties and best farming practices might already be fairly close to optimum for maximising yield. This approach also suggests that we should recognise that the gains from further breeding and agronomic research might be of diminishing benefit and we should focus on extending the adoption of best farming practices. Certainly, appreciable gains in industry production could be achieved if all growers optimised current operations.

However, this conclusion presupposes that the current commercial row geometry is the best for maximising yields. It is not. Mechanisation of the industry has meant that the progressive increase in size of machinery has dictated the row spacing adopted. This has led to a suboptimal row arrangement for the effective interception of available light, water and nutrient resources.

A reassessment of row spacing to improve the use of available light, water and nutrients should give a significant increase in the maximum potential yield. High-density planting is one way to enhance the use of light, water and nutrients during the early stages of crop growth. Simulation modeling suggests that the yield in 14-month-old plant crops can be raised by about 17 tonnes/ha in dual rows (two rows 0.5 m apart with row pairs at 1.8 m centres) and about 60 tonnes/ha in rows 0.5 m apart.

While adoption of high-density planting offers the opportunity to significantly extend the yield barrier, its realisation will require a large change in farming procedures and the development of specialised equipment. The net result will be a far more precise multi-row farming system that incorporates current best practices including controlled traffic and minimum tillage, accurate fertiliser and herbicide placement, and properly scheduled irrigation. In addition, new varieties that are better suited to close rows will be required.

Location	Calculated maximum yield of cane (tonnes/ha)*		
	1.5 m rows	Dual rows**	0.5 m rows
Bundaberg Ayr	194 213	212 230	256 273

* Maximum yield calculated using average daily climatic data (1957–1997).

** Two rows 0.5 m apart with 1.8 m between centres of adjacent pairs.

The sugarcane plant has the built-in capacity to increase industry cane yields by about 100 tonnes/ha through the adoption of existing better farming practices and by an additional 60 tonnes/ha through the adoption of more suitable row spacings and precision farming technologies. These gains would represent almost a doubling of current cane production by the industry.

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SUGAR ACCUMULATION

Michael O'Shea

SUGARCANE has enjoyed a rich historical background, having existed in New Guinea approximately 8000 years ago where it served as a garden plant. Subsequent spread through the Malay Archipelago occurred around 3000 years ago, and was followed by colonisation of Indochina and Bengal, and the probable hybridisation with the wild canes of India and China, laying the foundations for the future development of the sugarcane-based sugar industry of India.

Sufficient interest in the wild canes was probably taken by indigenous peoples to ensure that there was a crude selection process in place to maintain desirable characteristics, such as sweetness and the ease of growing and chewing.

Nowadays, nearly 60% of centrifugal sugar is obtained from sugarcane, with the remainder sourced from sugarbeet. In addition, the sugarcane plant provides benefits such as fibre, food and fodder. However, the principal product isolated and the primary reason for intensive plant improvement programs is sucrose.

Sucrose (α-D-glucopyranosyl-β-D-fructofuranoside) is a disaccharide containing fructose and glucose with both monosaccharides bound by their respective anomeric carbons, thereby rendering sucrose a non-reducing sugar. It is extremely soluble in water and chemically inert, although very sensitive towards acid-catalysed hydrolysis.

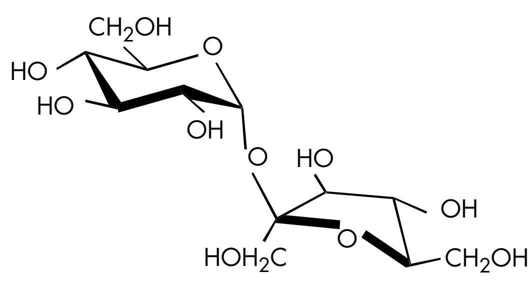


Figure 7. *Chemical structure of sucrose*

Transport of sugar in the form of a disaccharide conveys advantages to plants, since a disaccharide has a lower osmotic pressure than would the same concentration of monosaccharide sugars. As a storage carbohydrate, sucrose is accumulated from the photosynthetic process and constitutes a reservoir of potential energy. The reverse process, respiration, occurs in all living tissues and liberates energy.

SUCROSE ACCUMULATION

Sucrose is a readily reversible end product of carbohydrate metabolism. In sugarcane, the sucrose-starch light-dark cycles in leaf tissue are similar to those in other plants. However, in the stalk, starch formation and storage occupy a greatly reduced role, presumably due to breeding and selection for varieties with enhanced stored sucrose levels. Sucrose, therefore, dominates as an accumulating end product and is transported from the leaves to the stalk via the phloem.

It is not surprising to find that many aspects of sugarcane research (both breeding and biotechnology techniques) are directed towards increasing the quantity of sucrose accumulated in the sugarcane stalk. However, from a plant-breeding point of view, the increased direction of carbohydrate metabolism towards sucrose accumulation will not be viable unless it is not at the expense of growth vigour, increased susceptibility to pests and diseases, plant elasticity, biomass yield or the quality of the juice and/or sugar obtained. The highest possible sucrose accumulation is about 27% (current commercial varieties produce sugarcane stalks containing around 15% sucrose by weight), which allows for the lowest limit of fibre required for plant structure maintenance of 5% with the remainder being water.

During photosynthesis, carbon is fixed by the plant and can be used for plant growth, production of more leaves, roots or stem elongation, or alternatively can be stored as sucrose, predominantly in the stem. Sucrose accumulation is a combination of stalk elongation and expansion, which provides the necessary storage volume, and sucrose production and storage, which fills the available volume. During the early stages of plant growth, the production of sucrose and structural materials such as fibre are balanced (Figure 5).

Generally speaking, increased sucrose storage only occurs when external stresses develop and restrict stalk elongation (carbon consumption) more than photosynthesis (carbon storage). The excess fixed carbon can be redirected into sucrose production and storage. In some cases, these stresses can be too severe, and photosynthesis may also be restricted, with the effect that sucrose may not accumulate or may even be removed from storage and be consumed to meet demand.

One of the major problems competing with incremental advances in sucrose accumulation is the syndrome of yield decline. This is best explained as the inability of a commercial variety to maintain original yield levels after a few years.

Many contributing factors have been implicated in the development of this syndrome, including soil erosion and compaction, loss of soil nutrients such as trace elements and organic matter, pests and diseases.

In the Australian sugar industry, a broad research effort is directed at identifying causative factors, but perhaps the ultimate solution is the continual release of superior varieties.

Current practice in the improvement of sucrose accumulation can be summarised in the following areas.

(1) Breeding and selection procedures, which provide improved cultivars based on the favourable combination of genes from planned cross-pollination experiments.

(2) Agronomy and extension practices which provide growers with necessary information to achieve the potential of specific cultivars. This may take the form of fertiliser regimes, irrigation practices, pest and disease management, and the timing and application of ripeners.

(3) Crop physiology and modelling methods which provide information on the responses of sugarcane to various treatments. This also provides a valuable database of information and a starting point for the application of (2) or (4).

(4) Molecular modification resulting in transgenic sugarcane, which has the ultimate aim of relieving bottlenecks in the biosynthetic process or reducing wasteful reactions that prevent increased sucrose accumulation.

FACTORS INFLUENCING SUCROSE ACCUMULATION

Sucrose accumulation can be increased by factors such as environmental stresses (water, nutrient and temperature), application of chemical ripeners and planting density or arrangement. The phenomenon of ripening occurs when growth or stalk elongation ceases or slows, along with the accumulation of sucrose in tissues developed during the growth phase. Therefore, conditions that promote growth are not conducive for sucrose accumulation.

Plant maturity also has a role in the relative rate of sucrose accumulation since, in the early stage of growth, plant tissues contain high levels of nitrogen, moisture, invert sugars and enzymes such as invertase and phosphatase, while operating with enhanced nitrogen metabolism and respiration rates. The process of ageing eventually produces conditions where there is a gradual exhaustion of nitrogen and water, lowered reducing sugars, and reduced activities of the enzymes, resulting in the accumulation of sucrose. Thus, cane maturity is a function of age, nitrogen and moisture status, but is unpredictably complicated by climatic parameters such as light, temperature, rainfall and humidity.

Adding to this complexity is the fact that different varieties of sugarcane possess different sensitivities to the stresses that alter the rates of photosynthesis, structural growth and sucrose accumulation.

Water stress

Sugarcane has a high water requirement, but it is also tolerant of drought. Reduced irrigation and the development of mild water stresses or deficits may not reduce the yield of sucrose from sugarcane, and can enhance sucrose accumulation. This is an important aspect of ripening in much of the heavily irrigated areas of Australia, where an increased yield of sucrose is often obtained by withholding water during a drying out period prior to harvesting. This has the additional benefit of ensuring more favourable conditions for mechanical harvesting operations.

The overall effect of increased sucrose accumulation is presumably due to the reduction of stalk elongation and growth processes, thereby increasing the relative proportion of plant activity devoted to the sucrose accumulation process.

Nutrient stress

A similar situation to water stress exists in nitrogen stress, where a lack of nitrogen late in the season, once maximum growth has been achieved, will reduce growth rates and favour sucrose accumulation.

However, other external factors can significantly influence nitrogen utilisation, including soil type, residual soil nitrogen, sources of nitrogen losses (e.g. rainfall), fertiliser application rates and general growth conditions.

Temperature

Sugarcane growing areas of Australia generally provide a climate which fosters ripening.

Cool sunny winters slow down growth rates and carbon consumption, while photosynthesis may continue, thereby enhancing sucrose accumulation.

Stalk elongation rates are more sensitive to lower temperatures than are photosynthetic rates (Figure 6). Hence, the accumulation of sucrose will not be favoured at high temperatures, since the growth rates increase more than the corresponding photosynthetic rates.

Artificial ripeners

In some sugarcane growing regions of the world, normal ripening does not occur, and there is widespread interest in developing chemical methods to induce and/or increase ripening or to enable its synchronisation with harvest. Most chemical ripeners are plant growth regulators or herbicides that are applied in sub-lethal doses, and induce ripening by chemically restricting growth, allowing the plant to accumulate sucrose.

Several sugarcane growing countries use ripeners to profitably increase sucrose levels at harvest. The responses of a particular crop to artificial ripeners depend on the nutritional condition of the crop, the age and overall health of the crop, the climate, juice quality, and the variety being treated.

Despite considerable research effort, the successful development of a universally satisfactory ripening compound has not yet occurred. The major reason is the complexity of sugarcane physiology with respect to variety, cultural treatments and environmental and ecological variables.

Within the Australian sugar industry, there is no widespread use of chemical additives to increase ripening, despite Ethrel (ethephon) being registered for such use. With the current interest in extending the harvesting season forward in Australia, the use of ripeners may become an important mode of increasing early season CCS at a time when the conditions are not as conducive for natural ripening.

DISTRIBUTION OF SUGARS AND IMPURITIES

The chemical composition of sugarcane varies between varieties and is also heavily influenced by growing conditions. Factors that affect the composition of sugarcane include climate, water supply (whether irrigated or rainfed), fertiliser treatment, weed control, pest and disease levels, soil type, environment and plant age. Varietal response to the above stimuli is not constant.

Prior to stem formation in young sugarcane, there is negligible sucrose present. Only when stem elongation occurs does sucrose become a stored commodity and this is only in small amounts until the onset of maturity. During the ripening process, stem elongation slows. However, sucrose continues to be produced and the sugarcane stalk ripens from the bottom upwards. The composition for a well-ripened intact sugarcane stalk grown in arid subtropical conditions is given in Figure 8.

The non-sugar organic component contains a multitude of minor compounds, including cellulose and hemicellulose, lignin, fats, wax, pectin, gums, dyes, resins, proteins and soluble nitrogen compounds including amino-acids. As well, there are many inorganic components, comprising the total ash fraction, which vary considerably with age, variety and nutrient supply.

The distribution of sucrose and subsequent juice purity of different sections of a sugarcane stalk have been the subject of some early research that was primarily directed towards determining the optimal height for the topping of stalks.

The mature section (d in Figure 9) of the stalk begins three nodes below the attachment point of the first partially green leaf and contains approximately 75–80% of the total sucrose in the stalk (Figure 9). Juice purity decreases and non-sucrose content and water content increase towards the tip of the stalk.

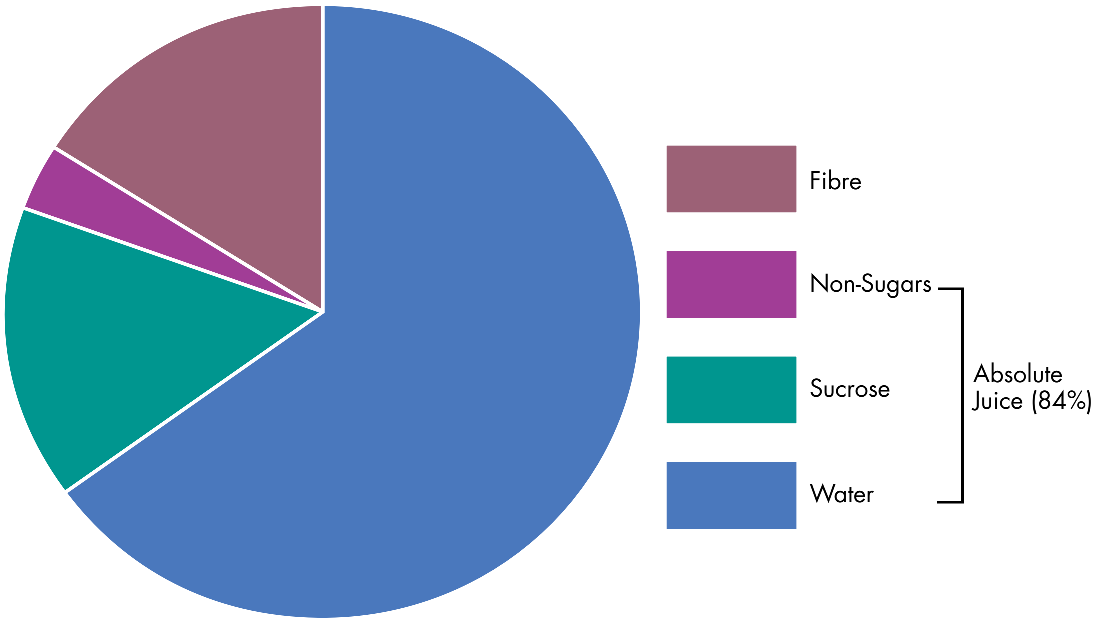
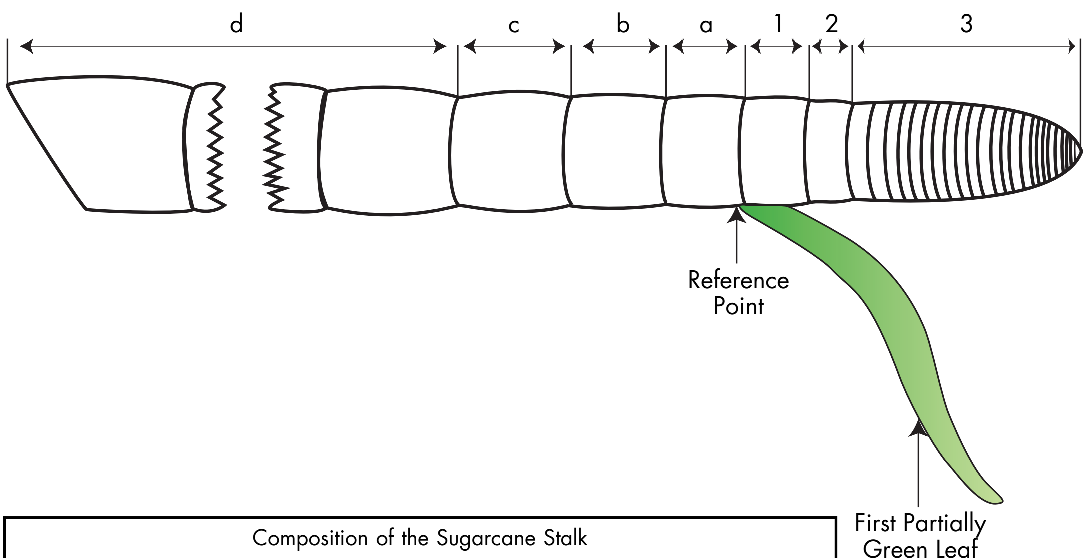


Figure 8. *Composition of well-ripened cane.*



Composition of the Sugarcane Stalk

Part	d	c	b	a	1	2	3
Brix of juice	20.75	17.77	15.87	13.64	11.69	10.00	7.54
Purity of juice	94.0	87.2	81.5	72.9	60.6	50.2	29.7
Weight per cent of total cane	78.58	2.25	1.99	1.74	1.48	1.27	12.69

Figure 9. *Sucrose content and juice purity along the sugarcane stalk.*

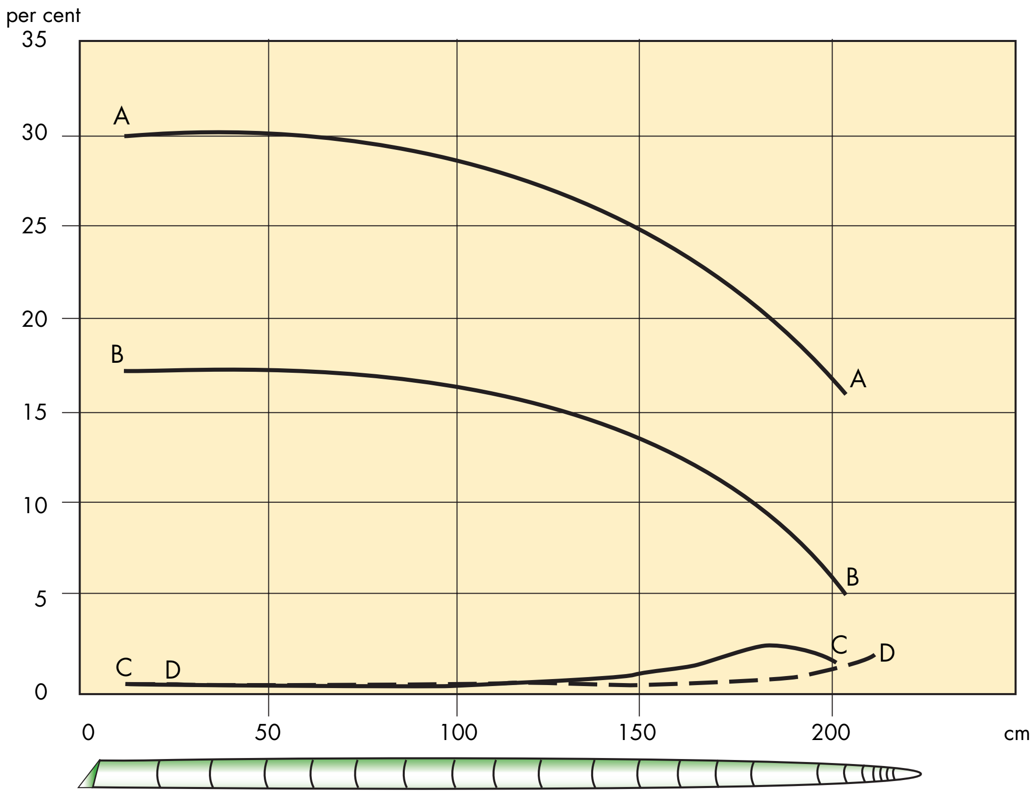


Figure 10. *The composition of ripening cane. (A) Dry matter; (B) Sucrose; (C) Reducing sugars; (D) Nitrogen. (A, B and C refer to per cent fresh weight, D refers to per cent dry weight).*

Figure 10 shows average results taken from many individual measurements of single variety stalks of similar size, length and growth habit. It clearly shows the declining sucrose content along the stalk towards the growing tip, as well as highlighting the increased levels of reducing sugars and nitrogen-containing material in the same direction.

The sugarcane plant is capable of absorbing more nitrogen from the soil than is necessary for its immediate growth requirements, in which case the excess nitrogen is stored in the form of readily transported amino acids, particularly asparagine. As the plant matures, the nitrogen content falls and reaches a minimum in properly matured cane.

The highest concentrations of inorganic nutrients are found in the most active tissues, which are the leaves, roots and growing tip of the stem. The concentrations in the older parts of the stalk tend to decrease as the plant matures.

The mineral composition of the stalk is a function of the developmental stage of the plant, whereas there are less marked variations of mineral composition within tops and leaves. The ash content of the upper section of the stem is up to 12.5%, expressed on dry matter, with the mineral content decreasing down the stem to a level of approximately 1% in the bottom portion.

Further work has shown that this trend of gradually declining concentration down the ripening stalk is mirrored in the analysis of individual mineral components, with the exception of silicon which remains at minimal levels throughout the plant.

FURTHER READING

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