Sugarcane - an old plantation crop that offers new environmentally friendly possibilities

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Abstract. Sugarcane is a tall, robust tropical C4 grass that has been grown in plantation systems for many centuries. Original commercial crops were largely produced from *Saccharum officinarum* lines collected from its centre of diversity. With the ability to breed hybrid varieties, incorporating other *Saccharum* species, came higher crop vigour and improved resistance to pests and diseases. This led to higher productivity; this was enhanced by better farming systems that utilised improved knowledge of plant nutrition, soil health and mechanisation. Plant breeding remains one of the most important research and development activities in sugarcane industries. The use of fibre from the milling process as a factory energy source enables many sugar factories to operate largely without resort to fossil fuels. The crop offers a number of environmental advantages at a time when climate change and increased levels of CO$_2$ are of increasing importance to a sustainable world. Improved factory efficiencies and other cropping developments may place the sugarcane industry at the forefront in sustainable energy production into the future. ‘Green electricity’ generation, the production of ethanol for fuel and the recycling of CO$_2$ may see the crop change from a source of sucrose to a source of energy. One of the challenges to face then may be whether crops are grown for food or energy – a dilemma to be solved as the environmental stakes become more profound.

Keywords: SugarSugarcane development, Cropping practice, Farming system, Product diversification.

1. Introduction
Sugarcane, a tall, robust, tropical C4 grass, has been a prized plantation crop for many centuries. Crop heights of between 2-4 metres generally leads to tonnages of 60-160 tonnes harvestable stalk material from each cropped hectare, depending on climate, soil health, fertility and farming system. Historically sugarcane plantations provided a valued and rich source of sugar in both the eastern and western hemispheres and are culturally and economically significant in countries such as the West Indies, India, Indonesia, United States (USA), Philippines, and Australia. The close and essential relationship between the crop and the sugarcane processing factory has necessitated large cropping areas not too distant from the factory; moving the bulky crop long distances is generally unprofitable. Economics provides incentive for large plantations to be established (in many cases owned by the milling company) near the sugarcane factory.

In this paper, a brief history of the origin of sugarcane is provided along with a description of current cropping practices and possibilities for further exploitation of this environmentally-friendly giant grass.
2. Original sugarcanes
Sugarcane belongs to the family Poaceae and the genus Saccharum, of which there are several different species, a few of which are characterised by the accumulation of sucrose in the stalk (culm).

2.1. Sweet sugarcane
There are three Saccharum species which accumulate significant quantities of sucrose; these are Saccharum officinarum, S. sinense and S. barberi. S. sinense has a centre of diversity in China and Taiwan, while S. barberi originated in northern India (2). Both species accumulate less sucrose than S. officinarum but were grown traditionally in their local region as a sucrose source.

S. officinarum is a domesticated garden cane with a centre of diversity in Papua New Guinea (PNG, 1, 5). PNG nationals cultivated the species as individual plants (stools) in their gardens for a source of sweetness, chewing on the relatively soft stalk material. In PNG, cane is grown from near sea-level to high mountainous areas (5). The species is thought to have originated around 6,000 years BC.

Over a period of several thousand years, S. officinarum was moved both westward toward SE Asia and Europe and east into the Pacific Islands. This led to S. officinarum becoming a traditional garden cane in Western Pacific nations, including such countries as Fiji, Solomon Islands, Tonga, Samoa and Hawaii (USA). These canes are also found in the Torres Strait Islands (Australian territory, 3), the Eastern Indonesian archipelago (4) and further afield in many Asian nations. With higher sucrose contents, S. officinarum became the favoured source of sucrose around the world.

2.2. Other PNG Saccharum species
Two other species have a centre of diversity in PNG; these include S. robustum (5), a wild cane that thrives along PNG riverbanks and other open areas, and S. edule - a domesticated species in which the aborted flower is used as a cooking vegetable (5). S. spontaneum, a shorter, thin-stalked, more vigorous, ‘grass-like’ species, is found in open fields in PNG (5) but has a broader centre of diversity in Asia. Its range extends through SE Asia, South Asia and into northern Africa. The stalks of S. edule, S. robustum and S. spontaneum do not accumulate sucrose; stalks of the latter two are often used as a source of fibre for building materials and other domestic applications.

2.3. Brief history
Sugarcane plantations were first established hundreds of years ago, using mainly S. officinarum lines. Under the plantation system, S. officinarum provided a semi-perennial cropping habit and was established vegetatively from pieces of stalk buried in the ground. The first harvest occurred after approximately 12 months. Following harvest, ‘ratoon’ crops grew from shoots that emerged from the remaining underground vegetative stool material. Successive 12-month old ratoon crops were grown until ‘ratoon’ shoots failed to emerge - due to stool damage or the influence of pests and diseases on root systems or underground buds.

S. officinarum lines tended to have short-lived cropping cycles due to disease or pest susceptibility and lack of crop vigour. Initially plantations provided a central basis for sugarcane cropping; in the early days slave labour was used in many countries to establish and harvest cane crops. In more recent times, mechanical cultivation has minimized labour inputs in countries where broader-scale cropping is practised. In such countries, the crop is now largely grown by individual farmers; however, the mix of plantations and farmers varies with country. In Australia, some of the largest producers remain milling companies who operate large estates, but there are also around 4,000 individual cane farmers, some of whom cultivate large areas.

The plantation system offered efficiency with minimal transport of the bulky harvest product. Light rail (tramways) provided the cheapest transport options; in some countries a large railway network leads to the relatively rapid and orderly transport of cane to the sugar factory. In modern harvesting systems, bacterial deterioration of the chopped cane stalks in association with transport delays may lead to the rapid breakdown of sucrose. For this reason, ‘cut-to-crush’ time targets have been defined - to maintain
sugar quality and to maximise sucrose recovery. In recently developed industries, the exorbitant cost of building railway lines rules out a comprehensive tramway system; road transport thus predominates.

3. Hybrid varieties

3.1 Natural occurrence
Two major breakthroughs led to greatly improved sugarcane productivity in the early 1900s. These were the discovery of sexual reproduction (by Parris in Barbados (1858) and Soltwedel in Java (1885)) and the realisation that true seedlings arising from parental crosses provided the opportunity to select for specific traits (1). Dutch breeders in Java used what turned out to be a natural hybrid between *S. officinarum* and *S. spontaneum* (the variety Kassoer) to backcross with *S. officinarum* to combine qualities of improved vigour and resistance to the disease ‘sereh’ with the high sugar content of the domesticated cane. The hybrids obtained provided the genetic base for many breeding programs today; hybrid canes were more vigorous, possessed greater resistance to pests and diseases and persisted for longer before replanting was needed (enabling more ‘ratoon’ crops). This hybridisation process led to the release of the ‘Java wonder cane’ (POI2878) in 1921 (1) - bred by the Indonesian Sugar Research Institute (ISRI / P3GI). This variety had a valuable influence on productivity around the world.

4. Crop development
The typical sugarcane phenotype has changed markedly over the years. Crops of *S. officinarum* had shorter, thicker stalks supporting broad leaves. Later, with a concerted breeding effort, both the phenotype (growth habit) and vigour of the crop changed; hybrid canes tend to have more, thinner, taller stalks with narrower leaves – a result of incorporating the genome of other *Saccharum* species.

4.1 Germplasm collections
In the traditional plantation system, ‘new’ commercial varieties consisted of fresh collections of *S. officinarum* lines from PNG and other such places. There were many germplasm collection expeditions, especially in the late 19th and early 20th centuries (1). One of Australia’s most important early varieties, Badila, came from a local village at the eastern end of the PNG mainland. The cane was introduced into Australia in 1896 and went on to dominate commercial crops for almost 40 years. This variety is now grown widely through SE Asia in small plot holdings, but no longer on a commercial basis in Australia.

Many other *S. officinarum* lines were collected by germplasm expeditions (1); these have been deposited in international germplasm collections and are available to plant breeders for use in introgression programs. Some of these lines were also widely cropped commercially.

A range of other *Saccharum* accessions were collected during such expeditions, including *S. robustum* and *S. spontaneum* lines. These species offered other desirable qualities to plant breeders, even though no sucrose accumulates in their stalks.

4.2 Breeding programs
With the observation of a natural hybrid in Indonesia, plus the possibility of strategic hybridisation demonstrated there, plant breeding suddenly offered huge scope for productivity improvements. Another necessity for plant breeding arises from a characteristic of the sugarcane cropping system, where commercial varieties only have a limited productive life. After 10-12 years of continuous cultivation, the productivity of individual varieties tends to decline; farmers discard older varieties in favour of higher-yielding, more vigorous newly-bred canes. Breeding programs are now the most important activity of R&D institutions. If new more vigorous varieties were not released, industry viability would be severely threatened.

4.2.1 Local programs: Hybrid varieties are now grown extensively around the world, with almost every country breeding their own locally-adapted varieties. Breeding programs vary enormously, with the size, type and success of the program defined by the funding directed to this activity and the breeding
strategy adopted. In Australia, a strong strategic approach to breeding has been implemented. The highest-yielding and latest hybrid clones (whether they are commercial or not) are quickly adopted as parents; pure lines of each of the *Saccharum* species are not used, except in specific introgression breeding.

4.2.2 *Germplasm introgression:* Different *Saccharum* species were initially crossed with *S. officinarum* parents to incorporate vigour, higher biomass accumulation plus pest and disease resistance. Back-crossing (repeated crossing of F1 hybrids with *S. officinarum*) maintained the desired sucrose accumulation and less of the undesirable wild cane traits. Only limited genetic material was introduced from the ‘wild canes’. *S. spontaneum* appears to provide better parental material than the other *Saccharum* species.

In more recent times, further introgression of the genome of wild canes has been attempted, with crosses between the closely-related *Erianthus* genus and *Saccharum* accessions. Qualities being pursued include drought tolerance, pest and disease resistance and crop vigour. Limited outcomes from this initiative have eventuated but some lines are showing significant promise.

4.2.3 *Variety selection:* In Australia, the parental crossing and selection program includes routine detailed analyses and on-going re-assessment. Parents are selected based on their history (success in producing new commercial varieties), disease resistance, propensity for flowering and fertility. Crosses are made in purpose-built facilities that ensure the longevity of the flowers and excellent seed viability. Over the last 30 years, photoperiod facilities have been used to stimulate flowering in ‘shy’ varieties and to synchronise flowering in parents with desirable qualities (7). The true seed (‘fuzz’) is collected, stored and then germinated to produce around 100,000 seedlings annually. These true seedlings are then subjected to around 10-14 years of selection, with only a handful of these performing well-enough to be considered for commercial release.

Initially, family selection is applied – all seedlings from each set of parents are assessed with only the best families selected (6). These families are promoted to the next selection stage where individual clones are assessed based on yield in individual plots; yields are measured via mechanical weighing devices. The same clones are tested for disease resistance, and those susceptible to the major diseases discarded; this eliminates the possibility of commercial losses associated with the most significant diseases. Commercial varieties generally possess adequate resistance to the major diseases. Selection is based on the performance of new clones compared to the yield of the current major commercial varieties; only those that yield the same or better are released to industry.

5. Farming systems

5.1 *Traditional farming systems*

Farming systems were initially similar around the world. Sugarcane crops were vegetatively propagated with short sections of stalk material buried in rows in previously cultivated ground. Fields were cultivated by hand or with horses and rudimentary equipment. Weed control was via mechanical means (hoes or other implements). Row spacing was relatively narrow (in cases <1 m); limited soil compaction was an advantage of this system. Small-scale fertiliser application occurred, with a poor understanding of both crop requirements and deficiencies. Harvesting was also undertaken using knives with manual handling of whole stalks onto railway wagons or horse-drawn drays for transport to the sugar factory. Farms initially were small, in part a result of the high labour requirement. In several SE Asian nations, it was (and is) not uncommon for sugarcane plots to be one hectare or less.

Factories, and the product they produced, varied considerably with country. The typical sugarcane factory produced sucrose crystals, but in some countries other products were also produced. This included jaggery – a boiled and concentrated form of sucrose. This is still produced in India and some other South / SE Asian nations.


5.2 Modern farming systems
The growth and profitability of the sugarcane industry in western countries depended on achieving economies of scale. During the 20th century, many mechanical developments led to reduced labour inputs, larger cropping areas and cheaper costs of production. The adoption of tractors facilitated more rapid field preparation and the possibility of the application of insecticides and herbicides on a broad scale. The introduction of whole stalk planters, which both cut and plant stalk pieces at the same time made broad-scale planting operations possible and viable. Further improvements in productivity came with the application of fertilisers to replenish depleted soils. Detailed soil analyses now indicate elemental deficiencies, so enabling optimised fertiliser applications. Quantification of organic matter and assay of soils for major soil pathogens also provides information on soil health; corrective actions can then be affected.

One of the biggest farming system transformations came with the development of mechanical harvesters (used in some countries only). These cut the standing crop into short stalk pieces while at the same time removing much of the extraneous matter, such as soil and leaves. Removing this material minimizes contaminating materials in the milling and refining process, with a consequent improvement in sugar recovery. Harvesting became much faster, again providing the potential for increased cropping areas. Mechanical harvesters are now used in many countries where there are larger-sized farming operations. The cut cane is delivered to the sugar factory in a minimum time to reduce stalk deterioration. At the factory, the cane is shredded, then passed through a series of rollers that progressively squeeze more of the juice from the stalk material. The juice is then filtered and clarified to eliminate soil and other contaminants and then piped into evaporators where it is heated to eliminate water, leading to sucrose crystallisation. Centrifuges are used to separate the sucrose crystals from the remaining impurities (molasses) – forming the raw sugar that is the most common commodity sold on the world market.

The fibre remaining after the cane is crushed is used to fire the boilers that produce steam to power the sugar factory. Steam is also used to power generators that provide electricity to run other factory operations. Filer mud, a product of juice clarification, is rich in some nutrients and is returned to cane fields as a fertiliser. Sugar factories are generally self-sufficient and powered by renewable energy.

5.2.1 Monoculture associated with plantations: The factory requires a high crop throughput to ensure factory capital investments are profitable. A consequence is that all land close to the factory needs to be consistently cropped to sugarcane. Transport of the bulky harvest product over longer distances is an expensive process, thus reducing profits for both farmer and miller. This creates a strong incentive to maintain cane crops on the same land for extended periods – the land that is close to the sugar factory.

In countries such as Australia, the crop is annually harvested from the same planting (a plant crop followed by ‘raatoo’ crops) for 5-6 years or longer - before the crop is terminated and replanted. A monoculture is therefore maintained; only short breaks of 3-6 months separate one crop cycle from the next. A short 3-month fallow may occur therefore only once in every six or more years.

Monoculture is largely unheard of in almost all other agricultural cropping systems; sugarcane monoculture has contributed to poor soil and root health in the sugarcane industry (11). Soil pathogens and the build up in deleterious minor pathogens has been demonstrated in Australian commercial fields and these significantly limit crop productivity (12). Soil fumigation studies have shown the extent of this yield constraint (13). Soil and root health are considered one of the major limitations to sugarcane productivity improvements within this farming system.

5.3 Farming system developments
In Australia, research into farming systems (8, 9, 10) has led to recommendations addressing the following: i. soil compaction: matching row spacing (mostly 1.50-1.80m spacing) with machinery wheel spacing to create controlled traffic paths, ii. legume fallow: various legumes have been recommended (soybean, mung bean, peanuts, cowpea) in order to break the monoculture, to add organic matter and to fix nitrogen – reducing the application of inorganic N, iii. minimum tillage: reduced tillage operations,
both in terms of the number of operations and the extent of the profile disturbed leads to better soil physical structure, iv. trash blanket: maintaining harvest residues on the soil surface – to conserve moisture, to aid the build up in organic matter and to protect the soil surface from erosion. In addition, GPS instrumentation of equipment (tractors, harvesters) is providing the opportunity to apply precision farming principles – such as specific yield monitoring in cropped fields, more precise application of fertilisers, with adjustment for variation in fertility across individual fields. All these improvements aim to improve organic matter levels (aiding nutrient retention, improved soil physical structure and better soil biological health), reduce soil compaction, reduce reliance on applied nitrogen and to reduce soil erosion.

6. Product diversification

Crystal sugar has been the traditional sugarcane marketable product. In recent times, product diversification has come to the forefront – partly as a result of wildly volatile world market prices for crystal sugar and market oversupply of the same. The crop offers many possibilities in terms of marketable products (14); it also offers environmental benefits, particularly in terms of a reduced cropping ‘carbon footprint’.

6.1 Fibre

Sugar factories produce several by-products, including bagasse (fibre waste), filer mud (used as a source of nutrients to be applied to cane fields) and molasses (often used as a stock feed in Australia). Bagasse has been a traditional source of factory energy, through combustion in the boilers that produce steam to power the factory. In the past, inefficient boilers were built to ensure all the fibre was consumed, thus minimising fibre transport away from the factory. In recent times, with increasing energy prices, there has been greater incentive to install energy-efficient boilers to generate ‘green’ energy for sale to national electricity grids. There is much scope for breeding higher fibre contents into commercial varieties, if demand were to rise. Several sugar factories in Australia (and a number around the world) generate very significant amounts of fibre-sourced energy.

Sugarcane fibre is also used to make paper; some factories in China have a paper manufacturing plant in intimate association with the cane crushing and sucrose crystallisation component of their operations. Cane fibre is also used in building materials.

6.2 Ethanol

Ethanol is another product commonly produced from sugarcane. Potential exists to ferment either sucrose, fibre-related products and molasses to produce ethanol. Brasil provides an excellent example; their huge sugarcane industry has strongly diversified into ethanol production for the powering of motor vehicles. This has provided options for the crop – with harvest products diverted either into crystal sucrose or ethanol, depending on the world market price for each. Ethanol production is estimated to have topped 30.755 billion litres in 2018 (13).

6.3 Electricity

Electricity generation from fibre is likely to be a profitable longer-term energy source. Gasification of products from fibre may lead to higher energy efficiencies. The broad-scale production of electric cars that lead to zero emissions is also looking more likely. The use of sugarcane to produce electricity, with the crop largely CO₂ neutral, is an attractive environmental proposition. The accumulation of fibre at sugar factories during harvest enables electricity generation for almost 12 months each year. Some factories are also looking at augmentation of power generation by supplementing cane fibre with non-sugarcane fibre sources.

6.4 Environmental qualities

Sugarcane, as an efficient fixer of carbon, with relatively high crop yields and a robust growth habit, offers many environmentally-friendly possibilities in a world challenged by climate change and
potential climatic disasters. The generation of ‘green’ energy will increasingly be a world priority; the sugarcane crop offers exciting possibilities in this regard.

7 Discussion
Sugarcane has a strong plantation history and this farming system remains a significant contributor to world sugarcane production. Plantations have dramatically changed in nature with the introduction of much improved technologies, principally the widespread adoption of mechanical planting, cultivation and harvesting systems. Added to that is the proliferation of multi-national companies that have invested in sugar factories and developed large company-owned farms. With more emphasis on globalisation, the historical sugarcane plantation system has given way to farms operated with world-leading technology and staff with experience in many different countries and regions.

Precision agriculture is also changing the face of production systems - in fertiliser application, yield mapping of each individual crop and in driverless technology (for instance, with GPS tractor-guidance systems and robotics). These no doubt will take an ever-increasing role in cane production systems.

In many countries, individual cane farmers continue to play an important role in sugarcane cropping. Some farms are very large; in Australia, it is not uncommon for individual cane farmers to cultivate over 250 ha of land, with minimal additional labour. The average farm size is approximately 100 ha.

In developing tropical countries, sugarcane continues to be an important crop. In some, plantations / large factory-owned farms make a significant contribution to the local sugarcane industry. However, in several SE Asian countries, it is not uncommon for many small-landholders to grow sugarcane in rotation with subsistence crops. In such cases, cane crop areas can be tiny. Under these circumstances, the opportunity to use larger machines to plant or harvest the crop is very limited and manual technologies continue to play a very significant role.

Sugarcane cropping provides significant and exciting opportunities. With potential to be carbon-neutral, the environmental qualities of this giant grass could place it well for expanded ‘green energy’ generation, at a time when fossil fuels are being phased out. Many industries around the world are constructing efficient power generators that utilise sugarcane fibre (bagasse). The production of ethanol also offers scope for use in applications where energy sourced from electricity is less appropriate, such as in the aviation industry. It is unlikely however that ethanol will become the main energy source of choice in general motor transport systems.

The Saccharum germplasm available in the centres of diversity offers much scope for breeding new lines, which may well position the industry for emerging crop uses. S. robustum phenotypes, with higher fibre contents, provide for higher yielding crops that are less prone to lodging and deterioration. In parts of PNG, tall lines growing 4-8m high remain erect; the incorporation of this germplasm into hybrids could take the brakes off current yield limitations. Australian commercial varieties tend to lodge and deteriorate in high-yielding circumstances, setting a limit on overall biomass production. With the selection of suitable hybrid varieties, biomass (rather than crystal sugar) production could increase accordingly, with much higher energy yields.

Sugarcane therefore has a bright future. Challenges for cane farmers and plantation owners vary greatly according to country, climate, location and farming system. The robustness of the crop, with a propensity to yield well under harsh conditions, lends itself to an ongoing role in agriculture. A challenge with higher world populations may well come with ‘should we grow crops for energy or for food?’ Such a question has already been raised in the Australian setting. The availability of productive agricultural land is likely to become a limiting factor on the Australian continent and in some other regions of the world. While sugarcane can tolerate relatively harsh environments, the need for irrigation in dry environments may lead to competition between food and energy; available water may be the key consideration.

The future for the crop looks set to rely less on crystal sugar and much more on energy production, at a time when global civilisation needs alternatives to the use of fossil fuels and higher net CO₂ production. Just how well the crop is utilised will depend on the innovation shown by key industry
researchers and leaders, as well as the acceptance of new technologies by sugarcane agriculturalists around the world.

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