Chapter 2.

Sugarcane (*Saccharum* spp.)

*This chapter deals with the biology of sugarcane (*Saccharum *spp.). It contains information for use during the risk/safety regulatory assessment of genetically engineered varieties intended to be grown in the environment (biosafety). It provides elements on commercial uses of the crop for producing sugar and other products, and on sugarcane payment schemes. It includes information on taxonomy; centre of origin; domestication and cultivation practices; morphological characteristics; reproductive biology; pollination and vegetative growth; genetics; abiotic interactions with nutrients, temperature, water and other stresses; interactions with weeds, pests and pathogens; hybridisation; and health considerations.*

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Introduction and uses

Sugar is commercially produced from either sugar beet (*Beta vulgaris*) or sugarcane (*Saccharum* spp.). Sugarcane is a tall-growing monocotyledonous crop that is cultivated in the tropical and subtropical regions of the world, primarily for its ability to store high concentrations of sucrose, or sugar, in the stem. Modern sugarcane cultivars that are cultivated for sugar production are founded on interspecific hybrids between *Saccharum spontaneum* and *S. officinarum* (*Saccharum* spp.) that were then subjected to repeated backcrosses to *S. officinarum*. Commercial varieties in use today are typically generated by crosses between other commercial or pre-commercial hybrids. Sugarcane is an ancient crop and its use as a garden crop dates back to around 2500 BC. The centres of origin for the ancestral species giving rise to sugarcane are thought to be Papua New Guinea, the People's Republic of China (hereafter "China") and India. At present, sugarcane is grown as a commercial crop primarily in South America (e.g. Argentina, Brazil and Colombia), North/Central America (e.g. Guatemala, Mexico and the United States), Asia (e.g. China, India and Thailand), Africa (e.g. Egypt, Kenya and South Africa), Australia and the Pacific Islands. Cultivation practices vary throughout the world, but this chapter aims to outline the main features of sugarcane cultivation. Sugarcane in this chapter refers to the *Saccharum* spp. hybrids as described above. The information presented is that which is available for each country after a comprehensive literature review.

Commercial uses

Sugarcane is grown for its sucrose content and is mostly consumed as refined sugar or other processed products (see below). Raw sugarcane can be squeezed or chewed to extract the juice, which is known as "*caldo de cana*" or "*garapa*" in Brazil, "*chediraz*" in northern India and "*aseer asab*" in Egypt. In some countries in which sugarcane is grown, it is bottled for local distribution or sold fresh from juice bars, cafes and restaurants.

Outside of commercial processing, artisanal processing of sugarcane occurs where sugarcane juice is boiled and cooled to make cakes of unrefined brown sugar, known as "*jaggery*", "*gur*" and "*khandsari*" in India; "*rapadura*" in Brazil; and "*panela*" in Colombia. In India it is estimated that 16.5 million tonnes (t) of sugar are produced compared with 10 million t of these traditional sweeteners (Kansal, 1998).

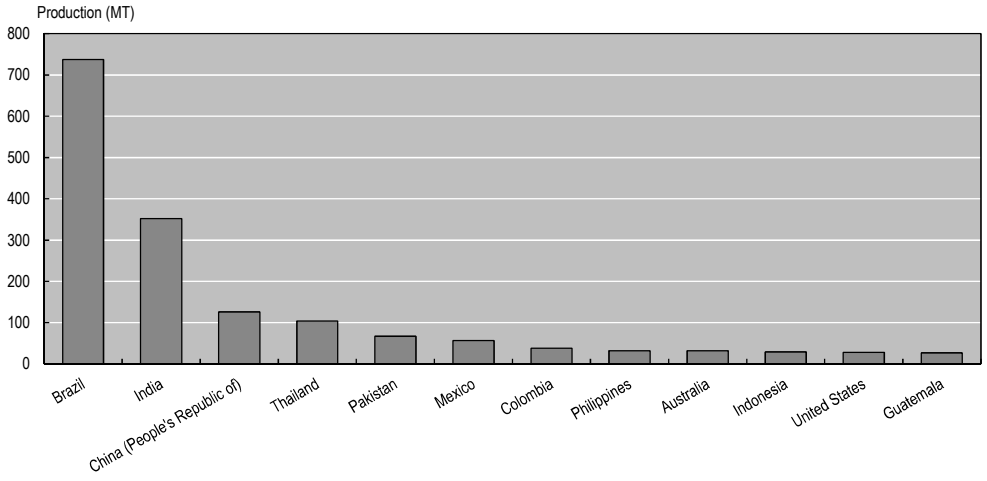
In 2014, world production of sugarcane was estimated to be about 1 900 million t, which was grown on approximately 27.2 million hectares. Brazil was the largest producer at 737 million t (FAOSTAT, 2014). The world production of sugar from sugarcane is approximately six times that from sugar beet, the other major source of sugar.

Figure 2.1 shows the production of the first 12 sugarcane producing countries in 2014. Other countries which were part of the top 20 producers in the same year included (in descending order of output) include Argentina, Viet Nam, South Africa, Cuba, Egypt, Peru, Myanmar and Ecuador (FAOSTAT, 2014).

Sugar production

Sugarcane is an established agricultural field crop with a long history of safe use. The process for extracting sugar from sugarcane is outlined below, and described in more detail in the OECD sugarcane document that deals with the safety of novel food and feeds (OECD, 2011).

Figure 2.1. **Sugarcane production by top 12 producing countries in 2014**



Source: Compiled from FAOSTAT (2014).

Sugar is initially extracted from the raw cane at sugarcane mills distributed throughout the growing regions. The cane is shredded and the juice extracted by crushing. The juice is then clarified by heating in the presence of lime ($Ca(OH)_2$). The lime complexes with phosphorus in the juice to produce a precipitate of calcium phosphate, which is allowed to settle out taking other impurities with it. Flocculants are added to speed up this precipitation process (Mackintosh, 2000). In some production schemes sulphur dioxide and small quantities of soluble phosphate may also be added to decrease juice viscosity and minimise colour development (Andrews and Godshall, 2002).

Clarified sugar juice is concentrated by evaporation to produce "syrup". The syrup then goes through multiple rounds of crystallisation to extract the sucrose. The syrup is boiled and the sucrose crystallises from the remaining molasses fraction as it cools. This mixture is known as massecuite, and the sugar crystals are separated from the molasses by centrifugation. This process is repeated three times. Thus, clarified sugar juice is boiled and centrifuged the first time to produce "A" sugar and "A" molasses. "A" molasses is then boiled again to produce "B" sugar and "B" molasses. The "B" molasses is boiled a third time to produce "C" sugar which is mixed with water and is used to seed the next round of crystallisation (Mackintosh, 2000). The "C" molasses is referred to as "final" or "blackstrap" molasses (Preston, 1988). The "A" and "B" sugars are dried to produce raw sugar. This may be consumed locally or shipped in bulk to sugar refineries worldwide for further refining, resulting in a highly purified product.

Sugarcane payment schemes

The method for calculating payment for sugarcane varies, although in many countries cane payment is based on the quality of the sugarcane (Lejars et al., 2010). In other countries including China, Pakistan and parts of India growers receive a fixed price per tonne (Todd, Forber and Digges, 2004).

In some countries such as Australia, Jamaica, Mauritius and South Africa there is compensation for yield and quality if cane is delivered at the beginning or end of the season to encourage growers to extend their harvesting period to extend the milling season. In other countries such as Brazil, the millers process their own cane in these off-peak periods (Todd, Forber and Digges, 2004).

Sugarcane quality may be measured at the mill. The formula to determine payment to the grower is complex and varies between countries; however, payment often uses two measures of cane quality, Brix and Pol. Brix is the percentage of dissolved solids on a weight per weight basis and is measured by refractometer or density meter. Pol is a measure of the degree of rotation of polarised light through a known quantity of clarified juice, which estimates sucrose content. In Japan, the Pol% cane is measured and a premium or reduced price is paid for the cane depending on whether this is higher or lower than the standard (13.1-14.3%) (Matsuoka, 2006). In Australia, Brix, Pol and fibre content are used to estimate the extractable sugar content or commercial cane sugar (CCS) of a grower's cane (Mackintosh, 2000), which determines the payment. The average CCS in Australia is around 13%, but can be as high as 18% (Jackson, 2005). A similar system in Louisiana (United States) and South Africa uses Brix, Pol, percent fibre and percent sediments to determine theoretically recoverable sugar (TRS) or recoverable value (RV), which forms the basis for grower payments (Dalley and Richard, 2010; Wynne, Murray and Gabriel, 2009). In Brazil before 1997, the government set sugarcane prices prior to harvest, but since deregulation, most of the mills use a payment system based on TRS (Valdes, 2011). The commercially recoverable sugar, which is actually recovered by the mill, varies depending on the mill efficiency, but is usually 95% of TRS (Dalley and Richard, 2010).

Other products from sugar production

Several other products are produced from crushing sugarcane at the sugar mill. In Cuba, it has been estimated that up to 31 products are produced from sugarcane. These include refined sugar, raw sugar, molasses, alcohol, rum, bagasse, syrups, dextran, confectionary, crude wax and glucose. One hundred tonnes of sugarcane is estimated to produce 14.3 t raw sugar, 27.2 t bagasse, 5.2 t filter cake, 2.6 t molasses and 50.7 t waste water (Allen et al., 1997).

Ethanol

In most countries, some of the sucrose is fermented to produce ethanol (Schubert, 2006). In 2006 in Brazil, 47% of the sugarcane crop was used for ethanol production, yielding 17.8 billion litres (summarised in Goldemberg and Guardabassi, 2009) and providing around 40% of fuel used in cars in Brazil (Orellana and Neto, 2006). In the 2010/11 season, ethanol production from sugarcane increased to 54% of the crop, producing 27.6 billion litres of ethanol (Conab, 2011). The residue of the fermentation, called vinasse, is used as fertiliser in fields in Brazil (Cheavegatti-Gianotto et al., 2011). In Thailand there are 12 ethanol production plants with a production capacity of 1.7 million litres/day, but in 2009/10 sugarcane was primarily used for sugar production (USDA FAS, 2009). In India, molasses is used to produce 3.2 billion litres of ethanol/year in 300 distilleries (Gopinathan and Sudhakaran, 2009).

Sugarcane juice is also fermented and distilled to produce alcoholic beverages such as *cachaça* in Brazil or rum (although in some countries this is made from molasses).

Bagasse

Bagasse is the fibrous portion of sugarcane that remains after the juice has been removed. It is estimated that 240-280 kg of bagasse is produced for each tonne of sugarcane processed (Cheavegatti-Gianotto et al., 2011). Bagasse consists of two types of fibre: the long fibres in the rind, and the shorter, softer fibres in the pith of the cane stem.

Bagasse cellulose fibres are longer (1-1.5 mm) than hardwood fibres (0.7-1 mm), but shorter than softwood fibres (2.5-5 mm) and are suitable for papermaking. Bagasse is used to make paper in many countries (Allen et al., 1997; Almazan, 1994). The pith material of the stem, which comprises 25-35 % of the bagasse dry weight, is considered a contaminant and it must be removed for high-quality paper making (Dunlap and Callihan, 1969). Internationally, bagasse has also been used to make particleboard, a construction panel that can be used for cabinets and laminate flooring (Nelson, 1998) and fibre board (Almazan, 1994). More recently, panels have been prepared using bagasse as the basis for both the resin and the fibres in the board (Hoareau et al., 2006).

Bagasse is used as an animal feed but its use is limited by low digestibility, even for ruminants. Steam treatment of the bagasse improves its digestibility so that it can be used in the fattening of cattle (Allen et al., 1997; de la Cruz, 1990; de Medeiros and Machado, 1993; Pate, 1982; Playne, 1984; UN Industrial Development Organisation, 2002). Bagasse has also been used as food for shrimp (Freeman, Duerr and Leber, 1992).

Bagasse is burnt for heat to produce steam as a source of power to run the sugar mills, with excess energy directed to the electricity grid in a number of mills, including those in Australia (Mackintosh, 2000), Brazil (Cheavegatti-Gianotto et al., 2011) and Mauritius (Deepchaud, 2005).

In the future, bagasse may also be used in the production of bio-fuels such as ethanol (Sainz and Dale, 2009).

Bagasse is also an effective bio-sorbent and may be used in waste water management. For example, common pollutants found in synthetic waste water such as chromium, cadmium, copper-nickel and dyes are effectively adsorbed by bagasse (de Matos et al., 2003; Khan and Amin, 2005; Khattri and Singh, 1999; Krishnani, Parimala and Meng, 2004; Sousa et al., 2009).

Molasses

Molasses is the thick syrupy residue left after the sucrose has been removed from the clarified sugar juice (syrup). The "C" molasses (final or blackstrap molasses) is used for alcohol fermentation, as a tock feed supplement and as a fertiliser for cane fields (Mackintosh, 2000; Sansoucy, Aarts and Leng, 1988; Sreenivasan et al., 1987).

Other products

Trash is the plant material left after harvesting of the sugarcane stalks. It is estimated that there are 10 t of trash produced per hectare of sugarcane (Karve et al., 2001). In parts of Australia, trash is generally retained in the field as mulch or it may be baled and used as garden mulch and as a low-grade cattle feed. In India, equipment has been developed to turn the trash into solid briquettes for use as fuel (Karve et al., 2001).

Sugarcane wax comprises both the waxy coating on the outside of the stalk – concentrated mainly at the nodes – and the lipids found throughout the cells (Allen et al., 1997). Sugarcane wax is used in cosmetics and pharmaceutical products, such as in products used to lower cholesterol.

Sugarcane ash (the residue produced when the sugarcane bagasse is burnt as fuel in the boilers) and filter cake or press mud (the solids left after filtering the cane juice) are often used as fertilisers on sugarcane farms (Cheavegatti-Gianotto et al., 2011; Qureshi et al., 2000). It is estimated that 1 t of sugarcane crushed in Queensland,

Australia produces 0.01 t of sugarcane ash and 0.05 t of mill mud (Qureshi et al., 2000). These provide a good supply of many plant nutrients, although nitrogen may need to be added (Calcino, 1994). In Australian banana plantations, sugarcane ash has been shown to enhance the growth of bananas (Broadley et al., 2004), and in Cuba improved sugarcane and maize (corn) growth was seen following ash application (Onelio et al., 2011). In Brazil, sugarcane ash has been used to replace sand in concrete and mortar for construction (Sales and Lima, 2010), and it has been investigated as an adsorbent for dye removal (Kanawade et al., 2010).

There have been some reports that very long chain fatty acids/alcohols (policosanols) from sugarcane wax lower cholesterol in humans (reviewed in Hargrove, Greenspan and Hartle, 2004). However, other studies reported no effects on cholesterol (EFSA Panel on Dietetic Products, Nutrition and Allergies, 2011; Kassis, Kubow and Jones, 2009; reviewed in Marinangeli et al., 2010). Policosanols have also been reported to decrease risk of cardiovascular disease (Janikula, 2002) and may have anti-inflammatory effects (Ledón et al., 2007).

Other beneficial phytochemicals from sugarcane include glycolic acid, which can be used in cosmetics, primarily for skin rejuvenation (reviewed in Allen et al., 1997).

Taxonomy of species

Classification and nomenclature

Sugarcane belongs to the genus *Saccharum* L., traditionally placed in the tribe Andropogoneae of the grass family (Poaceae). This tribe includes tropical and subtropical grasses and the cereal genera *Sorghum* and *Zea* (known as maize or corn). The tribe is further divided into groups, with sugarcane in the Saccharinae Benth. It then may be divided into two subtribes, with sugarcane in the Saccharastra, sometimes called Saccharininae, although this level of group is not an official International Code for Botanical Nomenclature (ICBN) designation (Daniels and Roach, 1987). The taxonomy and phylogeny of sugarcane is complicated as plants from five genera share common characteristics and form a closely related interbreeding group known as the "*Saccharum* complex". The *Saccharum* complex comprises *Saccharum*, *Erianthus* section *Ripidium*, *Miscanthus* section *Diandra*, *Narenga* and *Sclerostachya* (Daniels and Roach, 1987). These genera are characterised by high levels of polyploidy (polyploids have more than two sets of chromosomes) and frequently unbalanced numbers of chromosomes (aneuploidy), making it difficult to determine taxonomy and resulting in many revisions of the taxonomic relationships ((Daniels and Roach, 1987; Sreenivasan et al., 1987). More recent molecular analysis of the genera in the *Saccharum* complex has led to suggestions that the taxonomy should be rearranged as many of the divisions appear to be polyphyletic (Hodkinson et al., 2002).

The genus *Saccharum* traditionally comprises six species: *S. spontaneum*, *S. officinarum*, *S. robustum*, *S. edule*, *S. barberi* and *S. sinense* (D'Hont et al., 1998). However, Irvine (1999) has suggested that the genus should be reduced to just two species, grouping together *S. robustum*, *S. edule*, *S. barberi*, *S. sinense* and *S. officinarum* as the species *S. officinarum* and leaving *S. spontaneum* as a separate species. His proposal was based on the interfertility of the grouped species and the lack of diagnostic characteristics to separate them into individual species. Other authors have suggested that *Erianthus* is a synonym of *Saccharum* and the *Erianthus* spp. should be included in the *Saccharum* genus (Burner and Webster, 1994). This classification is in use in certain jurisdictions (USDA, 2013a).

Saccharum officinarum was named by Linnaeus in 1752 in *Species Plantarum* (Daniels and Roach, 1987). The word *Saccharum* is thought to have been derived from the Sanskrit "*sharkara*" (Ritter, 1841 as cited in Daniels and Roach, 1987). It is also known by the common name of noble cane. Sugarcane is thought to have resulted from complex introgression between *S. spontaneum*, *Erianthus arundinaceus* and *Miscanthus sinensis* (Daniels and Roach, 1987), although some data support it originating from *S. robustum* (as discussed in Amalraj and Balasundaram, 2006). *Saccharum officinarum* has a chromosome number of 2n=80, with a basic chromosome number of ten, making this species octaploid (having eight pairs of each chromosome). However, *S. officinarum* is not a simple polyploid, as it is both an autopolyploid (more than two sets of homologous chromosomes derived from a single species) and also an allopolyploid (possessing two or more unlike sets of chromosomes) (Sreenivasan et al., 1987). *Saccharum officinarum* has chromosomes in common with both of the genera *Miscanthus* and *Erianthus* section *Ripidium* (Besse, McIntyre and Berding, 1997; Daniels and Roach, 1987), although molecular data has suggested that this is due to common ancestry rather than any direct involvement of these genera in more recent introgression (Besse, McIntyre and Berding, 1997; Grivet et al., 2004).

Saccharum spontaneum is a highly polymorphic, disease-resistant, vigorous species with high fibre content. It has 2n=40 to 128 chromosomes and is a complex polyploid with a probable basic chromosome number of 8 or 10 (D'Hont et al., 1996; Panje and Babu, 1960; Sreenivasan et al., 1987). It can be distinguished from the cultivated *Saccharum* by thinner canes and a narrow inflorescence (Purseglove, 1972). Characteristics of the spikelets at the end of the tertiary branches of the inflorescence are also used by taxonomists to help distinguish this species from other *Saccharum* spp.

Saccharum barberi[1] and *S. sinense* have been in cultivation since prehistoric times in northern India and China, respectively. This has led to considerable interbreeding with other genera and species; consequently, these species are thought to be ancient intergeneric hybrids (Daniels and Roach, 1987). *Saccharum barberi* is thought to be the product of *S. officinarum* x *Erianthus* (sect. *Ripidium*) introgression, while *S. sinense* is thought to be derived from *S. officinarum* x *Miscanthus* introgression. Each contains chromosomes homologous to *S. officinarum* and *S. spontaneum* as well as to those from members of the *Erianthus* and *Miscanthus* genera, again indicating the complex origins and inter-relationships within the *Saccharum* genus (Daniels and Roach, 1987).

Saccharum robustum is a wild species. It is thought to have a most recent common ancestor with *S. officinarum* (Brown et al., 2007; D'Hont et al., 1998) and there is some speculation that it may be the product of introgression between ancestors of *S. spontaneum* and *S. officinarum* (as discussed in Daniels and Roach, 1987). It is a diverse riparian species that grows in the wet tropics as a vigorous perennial up to 10 metres tall and is often used for house and fence posts (Bakker, 1999). Two major groups within the species are known, those that have 2n=60 and 2n=80 chromosomes (Daniels and Roach, 1987).

Saccharum edule[2] is morphologically similar to *S. robustum* except that the flower spike or inflorescence is compacted and remains unopened and enclosed inside the leaf sheaths. It is cultivated as a vegetable in the islands of the Pacific and Papua New Guinea, where it is known as "*navisco*" in Vanuatu, "*pitpit*" in Papua New Guinea and "*duruka*" in Fiji (Grivet et al., 2004; Mudaliar, 2007). *Saccharum edule* is thought to be derived from introgression of *S. officinarum* or *S. robustum* with other genera (Daniels and Roach, 1987).

A summary of the members of the *Saccharum* genus is shown in Table 2.1.

Table 2.1. **Members of genus *Saccharum***

Species	Description	Sugar content	Chromosome number
S. spontaneum L.	Wild species	Very low-low	2n=40-128
S. robustum Brandes and Jeswiet ex Grassl	Wild species	Very low	2n=60-200
S. officinarum L.	Noble canes	High	2n=80
S. barberi Jeswiet	Ancient hybrid	Low	2n=111-120
S. sinense Roxb.	Ancient hybrid	Low	2n=80-124
S. edule Hassk.	Cultivated species	Low. Compacted inflorescence, eaten as a vegetable	2n=60-80 with aneuploid forms

Source: Buzacott (1965); Daniels and Roach (1987).

Origin and cultivation

Centre of diversity and domestication

Commercial sugarcane hybrid cultivars have arisen through intensive selective breeding of species within the *Saccharum* genus, primarily involving crosses between *S. officinarum* and *S. spontaneum*. *Saccharum officinarum* accumulates very high levels of sucrose in the stem but is highly susceptible to diseases (Cox, Hogarth and Smith, 2000; Lakshmann et al., 2005), whereas *S. spontaneum* accumulates little sucrose, has thinner stalks and higher fibre content but is a highly polymorphic species with resistance or tolerance to many pests and diseases (Bull and Glasziou, 1979; Jackson, 2005).

The origins of *S. officinarum* are intimately associated with the activities of humans, as *S. officinarum* is a purely cultivated or garden species which is not found in the wild (Sreenivasan et al., 1987). The centre of origin of *S. officinarum* is thought to be in the Indonesia/New Guinea area (Daniels and Roach, 1987), where it has been grown as a garden crop since 8000 B.C. (Fauconnier, 1993). It has been proposed that *S. officinarum* evolved from the selection of sweet forms of *S. robustum*. The canes may have previously been used for house building, fencing and archery (Daniels and Roach, 1987) and may have been selected with the aid of animals such as pigs or rats that would have a preference for sweeter individual plants (Daniels and Roach, 1987). Its cultivation spread along the human migration routes to South East Asia, India and the Pacific, hybridising with wild canes. It reached the Mediterranean around 500 B.C. (Fauconnier, 1993). From there it spread to Morocco, Egypt, the Syrian Arab Republic, Crete, Greece and Sicily, the main producers until the 15th century, followed by introduction to West Africa and subsequently Central and South America and the West Indies (Fauconnier, 1993). It is thought to have reached Australia in 1788 on the First Fleet, but did not become established until after it was reintroduced in 1817 from Tahiti (Bull and Glasziou, 1979).

The centre of diversity of *S. officinarum* is thought to be in Papua New Guinea (Daniels and Roach, 1987), a view supported more recently by amplified fragment length polymorphism (AFLP) marker analysis (Aitken et al., 2006).

S. spontaneum is believed to have evolved in southern Asia (Daniels and Roach, 1987). It accumulates little sucrose content and has thinner stalks and higher fibre content than *S. officinarum* (Jackson, 2005). *Saccharum spontaneum* is an adaptable species and grows in a wide range of habitats and at various altitudes in the tropics through to temperate regions, from latitude 8°S to 40°N extending across three geographical zones. These are: 1) the east zone which is Burma, China, Japan, Malaysia, the Philippines, Chinese Taipei, Thailand Viet Nam and the South Pacific Islands; 2) the central zone,

which includes Afghanistan, Bangladesh, India, the Islamic Republic of Iran, Nepal, Pakistan, Sri Lanka and the Middle East; and 3) the west zone which includes Egypt, Kenya, Sudan, the United Republic of Tanzania, Uganda and other countries in the Mediterranean (Panje and Babu, 1960; Tai and Miller, 2001).

Geographic distribution

Sugarcane is grown in over 100 countries on all continents worldwide (FAOSTAT, 2013) between latitudes 30°N and 30°S (Bull and Glasziou, 1979).

Commercial hybrid cultivars

Until the end of the 19th century most of the cultivars commonly grown were derived from *S. officinarum*, *S. sinense* and *S. barberi* (D'Hont et al., 1996).

Modern commercial hybrid cultivars of sugarcane are mainly descended from interspecific hybridisation between *S. officinarum* and *S. spontaneum* (Bull and Glasziou, 1979). The basic breeding concept involved the combination of vigorous growth, ratooning ability, and tolerance to abiotic stresses and disease resistance from *S. spontaneum* and high sucrose content from *S. officinarum* (Berding, Hogarth and Cox, 2004). However, other *Saccharum* species have also been used as parents. An analysis of plants used in breeding programmes in the 1980s determined that two *S. sinense*, *S. barberi* and *S. robustum*, 19 *S. officinarum* and "a few" *S. spontaneum* clones had been involved in the breeding of the commercial cultivars available at that time (Roach, 1989). Other authors have suggested that the modern cultivars are founded on only 20 *S. officinarum* and less than 10 *S. spontaneum* derivatives (Patade and Suprasanna, 2008). This interspecific hybridisation has increased the geographic range of economic sugarcane production (Berville et al., 2005).

Interspecific hybridisation between *S. officinarum* as the female parent plant and *S. spontaneum* as the male parent produces progeny that have a triploid chromosome number (2n + n=100 to 130) (Sreenivasan et al., 1987). This arises as the female parent transmits 2n chromosomes whereas the male *S. spontaneum* parent transmits the normal n chromosomes. Asymmetric transmission also occurs the first time that the hybrid is backcrossed to *S. officinarum* (Lu et al., 1994) and is thought to be either through endoreduplication or fusion of two nuclei during meiosis. This phenomenon facilitated the breeding of modern sugarcane cultivars as the "*officinarum*" qualities recovered more quickly in the hybrids, thus requiring fewer rounds of backcrossing to produce high sucrose cultivars (Sreenivasan et al., 1987). The process of backcrossing was termed "nobilisation" by Dutch breeders (Sreenivasan et al., 1987). Estimates of the origin of chromosomes in commercial hybrid cultivars using both genomic *in situ* hybridisation (GISH) and AFLP markers have suggested that approximately 80% are derived from *S. officinarum* and 10% from *S. spontaneum*, with the remainder being recombinant chromosomes from the two species produced by the natural process of synapsis during meiosis (D'Hont et al., 1996; Hoarau et al., 2001). However, a later study on different cultivars, using GISH and other methods, estimated their genetic complement as mainly *S. officinarum*, with approximately 15-20% *S. spontaneum* chromosomes and less than 5% translocated or recombinant chromosomes (Cuadrado et al., 2004).

Hybridisation between *S. officinarum* and *S. spontaneum* culminated with the release of a cultivar called POJ2878 ("Java Wondercane") in 1921 in Java (Indonesia), which became an important cultivar, allowing for a 35% increase in sugar production over the previous best cultivars (Cox, Hogarth and Smith, 2000; Jeswiet, 1929). This cultivar has provided the genetic heritage for many modern cultivars.

There is an international system for naming sugarcane cultivars, co-ordinated by the International Society of Sugar Cane Technologists (ISSCT). This comprises letters and numbers e.g. POJ2878. The first letters relate to the country where the cultivar was first selected and the breeding station, the numbers relate to the year the cultivar was first sown or the selection made, followed by a numerical sequence. For example, POJ refers to "Proefstation Oost Java" Indonesia. There are a number of international collections kept in the Brazil, India, South Africa and the United States to store important cultivars for use in breeding (Fauconnier, 1993).

Cultivation

Cultivation practices vary between countries and even between regions within a country depending on both the natural environment (e.g. climate, soil) and the human environment (e.g. population, history and mechanisation) (Figure 2.2).

Figure 2.2. **Sugarcane growing in Bundaberg, Queensland, Australia**

Source: Courtesy staff at OGTR, taken in 2007.

Commercial propagation

Propagation of sugarcane is different from the majority of other field crops since commercial sugarcane is propagated vegetatively. A variety or cultivar refers to the specific clone or genotype that has been vegetatively propagated through whole stalks or setts (shorter stem segments), also known as billets, seed pieces or seed canes. The term "seed cane" is used to distinguish them from true, sexually produced seed. The planting material is usually grown on-farm as transport is often not practical due to the large volume of material required and the short viability of the harvested cane (three to four weeks). In Australia, primary seed cane is raised in areas approved by the Cane Protection and Productivity Board as being free of disease and this cane is then distributed to the growers who multiply enough cane for their own crop planting (Croft, Magarey and Whittle, 2000). The number of propagules per stalk is about ten (Snyman et al., 2008b), so a large area is needed to grow seed cane. In Japan, 20 000-35 000 two-budded setts are planted per hectare (Matsuoka, 2006). In Brazil this is estimated at 8-12 t per ha of planting cane (Cheavegatti-Gianotto et al., 2011). In Australia, it is estimated that 880 million setts are produced annually for planting (Mordocco, Brumbley and Lakshmanan, 2009). In Brazil, there have been trials of the PLENE™ system which uses 4-centimetre single bud cuttings in conjunction with a mechanical planter. These are coated with chemicals to protect them against pests and diseases. This system uses significantly less planting material than conventional or billet planting systems (Syngenta, 2010).

Commercial sugarcane is also propagated by allowing the regrowth of the stems of the stools that remain in the soil after harvest of the previous crop (ratooning).

In Argentina, in the province of Tucuman, Project Vitroplantas has been using meristem culture and *in vitro* propagation to produce high-quality seed cane since 2000-01 (Sepúlveda Tusek et al., 2008). This has also been trialled in both Australia and South Africa; there have been some trials with sugarcane plants generated through *in vitro* micro-propagation (Meyer et al., 2009; Shannon, Pace and Di Bella, 2008; Snyman et al., 2008b). Micro-propagation of sugarcane provides a reliable and fast method for mass propagation of clonal material. Micro-propagation of meristem tissue has also been used to obtain disease-free planting material (Lakshmanan et al., 2005; Ramgareeb et al., 2010) and this is used in Brazil, the Philippines and parts of India for generating nursery material (Irvine, 2004; Jalaja, Neelamathi and Sreenivasan, 2008). Plants can be regenerated directly from meristem tissue or indirectly (*de novo*) from callus derived from meristem or non-meristematic cells. Thin cell layer culture of immature leaf or inflorescence tissue can also be used for the direct regeneration of plants (Lakshmanan et al., 2005; Snyman et al., 2006), and can be combined with an automated culture system to reduce labour costs (Mordocco, Brumbley and Lakshmanan, 2009). Plants generated through *in vitro* propagation may show phenotypic variation, although in some cases this is transient and may be due to epigenetic effects, possibly caused by *in vitro* stress (reviewed in Snyman et al., 2011).

Scale of cultivation

World average productivity of sugarcane is 61 t cane per ha, which produces an average of 5.82 t sugar per ha (Hussain et al., 2004b). According to the FAO statistical database, the world average productivity in 2014 was of 57.9 t cane per ha (FAOSTAT, 2014), however, with important differences among countries. Table 2.2 shows the range and diversity of yield reported for the top 12 producing countries in 2014. In 1999, Australia had the highest productivity at 88.97 t cane per ha (Baldani et al., 2002). In the period 1990-95, the highest average sucrose yield for the Queensland (Australia) sugarcane industry was 12 t sucrose per ha, with the highest maximum sucrose yield of the Burdekin region in Queensland, at 17.4 t sucrose per ha (Berding, Hogarth and Cox, 2004).

Table 2.2. **Sugarcane yield in top 12 producing countries in 2014**

Country	Cane production (million tonnes)	Area harvested (hectare)	Yield (tonnes of cane per hectare)
Brazil	737.2	10 437.6	70.6
India	352.1	5 012.0	70.3
China (People's Republic of)	125.6	1 738.1	72.3
Thailand	103.7	1 353.0	76.6
Pakistan	67.5	1 173.0	57.5
Mexico	56.7	761.8	74.4
Colombia	38.2	404.5	94.3
Philippines	32.5	432.0	75.1
Australia	30.5	375.0	81.4
Indonesia	28.6	472.7	60.5
United States	28.0	352.2	79.5
Guatemala	27.4	263.8	103.7

Source: Compiled from FAOSTAT (2014).

In Brazil, sugarcane is grown on approximately 10.4 million hectares (Table 2.2). The majority (70%) is grown in the south-east region, with other sugarcane producing areas in the northeast and midwest of Brazil (CONAB as cited in Cheavegatti-Gianotto et al., 2011). These areas are not generally irrigated, although production is now spreading to drier regions (Cheavegatti-Gianotto et al., 2011). In 2010, the cane crop had an average yield of 79.7 t per ha (Valdes, 2011). In São Paulo, the southeast sugarcane crops are high yielding, some producing over 100 t per ha (Yoneyama et al., 1997). Most of this is used for ethanol production due to the location of the distilleries, with the sugarcane from the northeast region used to produce sugar for export (Bolling and Suarez, 2001).

In Argentina, sugarcane is grown in the north. Production averages 18 million tonnes from 320 000 ha of land, with an average yield of 56 t cane per ha (Ferraro, Rivero and Ghersa, 2009). The FAO estimated the national production in 2014 of 24.6 million tonnes from 386 550 ha, with an average yield of 63.6 t cane per ha (FAOSTAT, 2014). However, average cane yields of 94.5 t cane per ha (from 33 500 ha) were recorded in 2005 from Jujuy Province (Gomez, Chapple and Mcdonald, 2007).

In India, which is the second producing country of the world, sugarcane is grown in both tropical and subtropical regions. The productivity of sugarcane in the tropical belt is 26.4% higher than in the subtropical belt (57.8 t per ha) (Singh et al., 2010b). The sub-tropical state of Uttar Pradesh occupies half of the total area in which sugarcane is cultivated (Gujja et al., 2009). The highest productivity is achieved in the tropical state of Tamil Nadu, with 105 t cane per ha, but the average productivity is low in India, with some regions producing only 40 t cane per ha (Gujja et al., 2009).

In China, sugarcane is grown in the south and southwest regions, with 68% of the production in Guangxi Province (Chen and Yuan, 2010). The average yield from 1990-95 was 58 t cane per ha (Greenfield, 1998). The crop was grown on 1.3 million ha in 2014 with an average yield having increased to 76.6 t cane per ha (Table 2.2).

In Thailand, in 1996 sugarcane was grown on approximately 1 million ha of either irrigated or rain-fed land, with an average yield of 58.7 t cane per ha (Greenfield, 1998). The crop was grown on 1.3 million ha in 2014 with an average yield having increased to 76.6 t cane per ha (Table 2.2).

In Pakistan, sugarcane is grown on about 1.2 million ha (Table 2.2), with 65% of this in the Punjab Province. According to Greenfield (1998), the average sugarcane yield was 46 t cane per ha, although with variation between regions. The FAO reports an average yield for the country having increased to 67.5 t cane per ha in 2014 (Table 2.2).

In Africa, South Africa is the largest producer, with sugarcane grown on 413 000 ha in 2008-09, predominately in KwaZulu-Natal (South African Sugar Association, 2011) while the FAO reports a total country acreage of 312 590 ha in 2014 (FAOSTAT, 2014) The following countries having important sugarcane acreages in the region are Egypt with 140 900 ha and Cameroon with 131 770 ha (FAOSTAT, 2014)

Sugarcane is grown in the United States in the southern states of Louisiana, Florida, Texas and in Hawaii (Greenfield, 1998). In the period 2002-07, the number of farms growing sugarcane in the United States decreased from 953 to 692, but the average area harvested per farm increased from 415 ha (1 027 acres) to 495 ha (1 224 acres) per farm (USDA ERS, 2013). It is also grown in 15 of the 23 states in Mexico, which ranked as the sixth global producer in 2014 (FAOSTAT, 2014). In Mexico, the average cane yields are 74.4 t per ha (Table 2.2), although this is variable depending on rainfall and region. The

industry has a large number of small growers, with each mill dealing with cane from 2 500 growers with an average of 6.4 ha each (Buzzanell, 1998).

Sugarcane is also grown on the two main islands of Fiji. In Indonesia, 75% of the 472 700 ha is grown on Java. In 1995, Malaysia had a small industry (approximately 20 000 ha) (Greenfield, 1998), with a larger industry in the Philippines (approximately 432 000 ha) and in Viet Nam (approximately 305 000 ha) (FAOSTAT, 2014). In the Philippines, sugarcane is grown in 17 provinces on 6 islands across the country, with 55% grown on Negros island (Zabaleta, 1998). Japan has a small sugarcane industry, with about 22 900 ha spread across the south-western islands, having produced an average of 89.72 t cane per ha in 2014 (FAOSTAT, 2014).

The scale of sugarcane farms varies both between and within countries. For example, on Réunion Island, the average farm size is 5 ha, which produces an average of 70 t per ha sugarcane, giving the island a total production of approximately 2 million t of cane (Lejars and Siegmund, 2004). Similarly, in South Africa, 43 500 of the 45 300 registered growers have less than 10 ha of land for growing sugarcane and produce only 11% of the crop (Snyman et al., 2008a). In the Philippines, 80% of the 41 000 farmers produce 29% of the crop on less than 10 ha of land each (Greenfield, 1998). In Viet Nam, the industry consists mainly of smallholders with between 0.3-1 ha of land (Greenfield, 1998) and in Japan the average farm size is 0.8 ha (Matsuoka, 2006). In China, there are approximately 5 million sugarcane farms, with an average farm size of 0.27 ha (Chen and Yuan, 2010). In India, average farm sizes are less than 1 ha, with only 25% of the farms greater than 4 ha in size (Gopinathan and Sudhakaran, 2009). Conversely, in Australia the size of the farms varies from 40-250 ha (Canegrowers, 2009).

Cultivation practices

Sugarcane will grow on a wide variety of soil types, although heavy soils are preferred (Purseglove, 1972). In the Philippines, it is grown on both sandy and clay loams, acidic volcanic soils and calcareous sedimentary soils (Zabaleta, 1998). In Australia, it is generally grown in fine-textured sandy loam, clay loam and clay soils (Blair and Stirling, 2007). As well as adequate soil fertility, it requires high temperatures and high rainfall (1 525 mm per year) or irrigation (Purseglove, 1972).

Setts are generally planted within a few days of harvest of the cane, in order to achieve a high frequency of germination (sprouting). Sugarcane is planted in a range of row spacing from 60-150 cm. Buds on planted setts, or on the plant bases remaining after harvest, germinate within two weeks. Sugarcane cultivars differ in their degree of temperature sensitivity, but in general germination is slow at soil temperatures below 18ºC and increases rapidly up to about 35ºC (Bull, 2000; Millard, 1974; Oliveira et al., 2001). Alternatively, in south India and Indonesia, single buds are planted out in a nursery and then the resultant young shoots are transplanted to the field. This is often used where the cane is grown in rotation with rice. The lateral buds on the setts are encouraged to germinate then planted out into the fields, ensuring early establishment and allowing extra time for the rice crop to grow (Fauconnier, 1993). Wider row spacing has also been recommended in India to reduce the amount of planting material required, and increase air and initial sunlight penetration into the crop (Gujja et al., 2009).

Cane can be planted mechanically, but manual planting is common in most parts of the world. In 2005 in Florida (United States), 95% of the land was planted manually (Glaz and Gilbert, 2005) and in Mauritius partially mechanised planting is used (Ismael et al., 2008).

Because sugarcane originated in the wet tropics, yields are much higher when the crop is supplied with adequate water, so sugarcane is grown under irrigation where water is available and rainfall is inadequate. It has been estimated that between 89-118 kg of water is required to produce 1 kg of sugarcane in Florida (Shih and Gascho, 1980).

The cultivation of sugarcane relies on the extensive use of fertilizers and pesticides. Nitrogen especially is widely used. Nitrogen is lost to surface runoff, groundwater, soil storage and the atmosphere (Bohl et al., 2000; Freney et al., 1994; Macdonald et al., 2009; Weier et al., 1996). In Australia, there has been a decline in nitrogen usage, from an average of 206 kg N per ha for the 1997 crop to 164 kg N per ha for the 2008 crop (Wood et al., 2010). The introduction of the "Six Easy Steps" approach is intended to reduce this further (Schroeder et al., 2009). A report from Japan suggests that nitrogen is applied at 200-300 kg per ha, phosphorus at 80-120 kg per ha and potassium at 50-120 kg per ha (Matsuoka, 2006). In Brazil, sugarcane is grown with low nitrogen inputs (50 kg per ha) (Boddey et al., 1991), leading to the suggestion that some cultivars of sugarcane can obtain nitrogen via biological nitrogen fixation.

It has been estimated that a crop of 74 tonnes of cane per ha removes 107 kg nitrogen, 60 kg phosphorus oxide and 300 kg potassium oxide per ha (Purseglove, 1972). The sugarcane plant requires nitrogen for optimum development for yield and sugar content of the canes. Symptoms of nitrogen deficiency are thin, stunted stalks; yellowing leaves with necrosis at the edge and tips; and reduced root mass (Calcino, Kingston and Haysom, 2000). However, excess nitrogen can prolong the crop maturation, resulting in a plant with an excessive leafy canopy, which in turn can make the plant more susceptible to leaf diseases and attack by pests (Bakker, 1999). It can also cause excess growth with little storage of sucrose (Irvine, 2004).

Phosphorus is required for optimum growth. Deficiencies may manifest as plants with short, thin stalks and stools with a low number of primary stalks, a poorly developed root system and sometimes leaves that are green-blue in colour. Conversely, an excess of phosphorus can lead to a deficiency of other trace elements such as zinc and iron, thus reducing sugar yields (Bakker, 1999).

Potassium is required for many physiological processes. It helps to promote the formation and translocation of sugars, and thus may improve the extraction and purity of the cane juice. Supplementing sugarcane plants that are exposed to excessive nitrogen with potassium can alleviate the symptoms of over-supply of nitrogen. Potassium deficiency results in depressed growth, thin stalks and yellowing of the older leaves with chlorotic spots and ultimately death of the leaf (Bakker, 1999). Potassium may also play a role in the ability of sugarcane to withstand dry conditions (Wood and Schroeder, 2004). An excess of potassium increases the ash content of sugarcane juice and reduces the recovery of sugar, and, as with phosphorus, it may also lead to a deficiency of other trace elements (Calcino, 1994).

Calcium is an important element for plant growth and also a regulator of soil acidity. A deficiency in calcium results in leaf chlorosis and reduced stem diameter. Increasing soil acidity, which can be ameliorated by lime application, can result in an increased fixation of phosphorus, aluminium, iron, manganese and nickel, which may lead to toxicity (Bakker, 1999).

Magnesium is important for photosynthesis, being required for chlorophyll function, and is responsible for the green colour in the leaves (it absorbs the blue and red light spectrum). Deficiencies result in leaf chlorosis and stalks of reduced diameter with internal browning (Bakker, 1999).

Other micro-element requirements include sulphur, iron, aluminium, zinc, copper, boron, silicon, molybdenum and manganese. Both deficiencies and toxicity to these elements can occur, resulting in symptoms such as reduced growth, reduced root development and a reduction in photosynthesis (Bakker, 1999).

Agricultural chemicals are widely used to protect the crop from a range of pests and diseases and to control weeds. In Australia, it is estimated that herbicides comprise 90% of the pesticides used on sugarcane farms (Christiansen, 2000). These are used both within the crop and in other areas on the farm to reduce nesting areas and food sources for rats (Christiansen, 2000). In addition, rodenticides and fungicides are used to control rodent pests and fungal diseases, respectively. Insecticides are also used to control pests. These include controlled release chlorpyrifos and imidacloprid to control canegrubs in Australia (Allsopp, 2010; Robertson et al., 1995) or carbofuran to control borers in Florida (Hall, Nuessly and Gilbert, 2007) and Pakistan (Rana et al., 1992). Chemicals may also be used to help ripen the sugarcane and increase sucrose accumulation in the stalk. In 1997, in South Africa, 37% of irrigated crop and 2% of non-irrigated crop were ripened with chemicals (Donaldson, 1999). Herbicides such as Fusilade Super (fluzifop-P-butyl), Gallant Super (haloxyfop-methyl) and Ethrel® ((2-chloro-ethyl) phosphonic acid), a growth regulator, are used in South Africa (Donaldson, 1999), Guyana and Swaziland. In Brazil, MODDUS (trinexapac ethyl), a plant growth regulator, is used. Glyphosate is used in Mauritius and the United States (discussed in McDonald, Morgan and Jackson, 2001), with application rates from 40-180 g per ha although legislation in the United States limits glyphosate use to final ratoon crops in Florida, Louisiana and Texas due to concerns over yield losses (Dusky et al., 1985). Ethrel® and MODDUS are also registered for use in Australia, but Ethrel® is not widely used due to variable yield responses between cultivars and the shorter harvest season (McDonald, Morgan and Kingston, 2000). Studies have shown inconsistent effects of ripeners due to the sugarcane variety, water deficit stress and the combination of chemicals used (Donaldson 1999, 1994; Donaldson and Inman-Bamber, 1982; McDonald, Morgan and Jackson, 2001; McDonald, Morgan and Kingston, 2000).

Planting dates for sugarcane depend on whether or not it is to be irrigated; planting of rain-fed sugarcane depends on the timing of the rain. In India, sugarcane is planted both at the start of the wet season (the eksali crop) and harvested 12 months later, and at the end of the wet season and harvested after 16-18 months (the adsali or monsoon crop) (Fauconnier, 1993). In most countries the plant crop (first crop from a planted sett) is harvested after 14-18 months, and ratoon crops after 12 months. In subtropical regions such as Pakistan and Louisiana, harvesting occurs after ten months, before the first frosts. In other countries such as Peru and South Africa, the sugarcane crop may be harvested at up to 24 months (Hussain et al., 2004b). In the Philippines, the harvest season begins in October-December and ends in May (Zabaleta, 1998). In Australia, sugarcane is harvested after either one or two years, depending on the region (McGuire et al., 2003). In order to keep the sugarcane mills supplied with sugarcane, harvesting is spread over as long a period as possible. In some countries such as Colombia, Kenya, Peru, Uganda and the United States (Hawaii), harvesting occurs almost continuously (Fauconnier, 1993).

Flowering is not desirable in commercial cane as it uses both energy and sucrose and may lead to pithy islands in the stems (Purseglove, 1972). The loss of apical dominance and consequent formation of side shoots leads to a reduction in the sucrose content in the stalk. However, if harvesting occurs within two to three months of flowering, this effect is negligible (Bakker, 1999). In Nigeria, flowering is stated as one of the most important factors responsible for low sugar production (El Manhaly et al., 1984). In Hawaii,

sugarcane is harvested after two years, but flowering may occur twice in this crop cycle, which may lead to losses in sucrose yield (Moore and Osgood, 1989). Consequently, diquat, a herbicide, was used in Hawaii to prevent flowering in commercial sugarcane crops for 15 years, although it has now been superseded by Ethrel® (2-chloroethylphosphonic acid) (Moore and Osgood, 1989). Ethrel® is also used in South Africa and Nigeria as in the latter instance the period between flowering and harvest often exceeds four months (Donaldson and Singels, 2004; Fadayomi, Abayomi and Olaoye, 1995). Trials in Sudan showed increased yields due to the prevention of flowering with ethephon of 30 t cane per ha and 4.1 t sugar per ha (Hardy et al., 1986). Low flowering is selected for in variety development programmes in Brazil (Cheavegatti-Gianotto et al., 2011) due to its effect on sucrose yield.

However, there are some conflicting data on the impact that flowering has on reducing sucrose content in sugarcane stems. As discussed in Moore (1987), some of the conflicting data are due to inappropriate comparisons. Different sugarcane cultivars are affected differently by flowering. Individual plants may flower due to altered physiology, which led to the flowering which complicates any assessment of the impact of flowering. For example, a series of 35 field trials using Ethrel® showed reduced flowering and an overall increase in cane weight and sugar yield. However, there was little correlation between reduced flowering and increased yield due to variability between fields (Moore and Osgood, 1989). More recent data from experimental plots in Australia have shown that cane yield, commercial cane sugar (CCS) and sugar yield all decreased following flowering (Berding and Hurney, 2005). Sugarcane is routinely harvested mechanically by cutting stems close to the ground, or by hand cutting in countries such as Malaysia, the Philippines and South Africa. In South Africa, in 2003, more than 90% of the annual harvest of 20 million t was harvested manually, partly due to the steep slopes used for planting (Meyer and Fenwick, 2003). In Brazil, cane harvesting is either semi-mechanised, where it is hand cut but mechanically loaded, or fully mechanised (Cheavegatti-Gianotto et al., 2011).

Sugarcane is harvested either green or burnt. Burnt cane harvesting was introduced in Australia during the 1940s in response to labour shortages (Christiansen, 2000) and to reduce the incidence of rat-borne diseases amongst cane cutters (Wood, 1991). This remained the main harvesting method in Australia until the 1980s when it was replaced by green cane harvesting and trash blanketing, where trash is left on the ground after harvest (Ridge and Norris, 2000). In Colombia, cane burning stopped in 2000 following pressure from environmental groups (Ellis and Merry, 2004). The amount of burning in the state of São Paulo (Brazil), also decreased by 20% from 2008 to 2009 (Silva et al., 2010) and the introduction of legislation in this area is aimed at discontinuing sugarcane burning by 2021 (Cheavegatti-Gianotto et al., 2011). In Mauritius, cool burning is used in the humid and subhumid areas whereby the cane burning is conducted in the mornings, which reduces emissions and the leaf moisture means that some unburnt green leaves remain (Ismael et al., 2008). In Argentina, over 70% of the sugarcane in the Tucumán Province is harvested green; however, some of the trash is then burnt after harvest (Digonzelli et al., 2011a).

In Australia, green cane harvesting and trash blanketing is known to dramatically reduce soil erosion (Prove, Doogan and Truong, 1995) and subsequent herbicide runoff (Kealley, 2009). However, in some situations trash blanketing can reduce yields. In Zimbabwe, trash blanketing reduced yields under conditions of full irrigation, but increased yields where lower levels of irrigation were used (Gosnell and Lonsdale, 1977). In South Africa, trash blanketing has been shown to result in fewer shoots from ratoons,

but they are thicker and longer than those from burnt plots and so the yield is increased in trashed compared to burnt plots (Thompson, 1966). In Argentina, trash blanketing also led to increased sugarcane production per hectare, but this was attributed to more shoots from ratoons with no changes in stalk weight (Digonzelli et al., 2011b). However, weed abundance was seen to be lower in fields that were burnt before harvest (Ferraro, Ghersa and Rivero, 2012). In Queensland and northern parts of New South Wales in Australia, trash blanketing may increase susceptibility to frosts and slow down the growth of ratoon crops due to decreased soil warming (Kingston, 2000). Studies have also shown autotoxic and allelopathic effects of sugarcane residues which delayed sugarcane leaf development, possibly due to the presence of benzoic acid (Viator et al., 2006). In Brazil, the reduction in burning of sugarcane has led to the increase in populations of spittlebug *Mahanarva fimbriolata* to become an important sugarcane pest (Korndörfer, Grisoto and Vendramim, 2011).

Sugarcane grows perennially and the root system, or stool that remains in the ground, will resprout. Ratoon crops grow faster than the original plant crop. Although several ratoon crops are possible, cumulative stool damage from harvesting and weed control operations and the impact of pests and diseases eventually leads to declining yield. The number of times a crop is ratooned varies worldwide and depends on the cost of replanting verses the declining sugar yield from the ratoon. Farmers may also plough-out ratoons early to plant newer, more productive cultivars (Cadet and Spaull, 2003). In Swaziland, on free-draining clay loam soil under irrigation, over 20 ratoons have been harvested, whereas in smallholder fields in Kenya only 2 ratoons are harvested (Ellis and Merry, 2004). Similarly in Thailand, farmers only grow one or two ratoons (Greenfield, 1998) and in Florida only 13% of the crop was in third ratoon or older in 2005 (Glaz and Gilbert, 2005). In Brazil, under rain-fed conditions, three to six harvests typically occur before replanting (Cheavegatti-Gianotto et al., 2011). In Australia, there is variation between regions (Chapman, 1988), but a maximum of four ratoon crops are typically grown before ploughing out the crop and replanting (Bull, 2000). Ratoons may also be removed by ploughing and treating with herbicide (e.g. glyphosate) (Willcox, Garside and Braunack, 2000).

After ploughing out the previous ratoons, another sugarcane crop may be planted immediately, within four to eight weeks or the ground left fallow. Alternatively, sugarcane may be grown in rotation with another crop. In 2005 in Florida, 63% of the sugarcane was not replanted immediately following the final harvest, but the ground was left fallow or planted with another crop such as sweet corn, rice, snap beans, leafy vegetables or radishes before replanting sugarcane the following season (Glaz and Gilbert, 2005). In Australia, legumes are grown as rotation crops, with sugarcane again planted the following winter (Willcox, Garside and Braunack, 2000).

Rotation with another crop helps to reduce the build-up of disease, may provide nitrogen for the next sugarcane crop and provides ground cover to prevent soil erosion (Garside et al., 2001). Experiments in Australia have indicated that including a legume crop to break the sugarcane monoculture enhances the yield of both the following sugarcane plant crop and the subsequent ratoon crops (Garside and Bell, 2007; Garside et al., 2001). This may be partly due to a reduction in soil nematodes. Experiments in Australia have also shown a reduction in most species of plant parasitic nematodes following soybean rotation, though many of these populations recovered quickly (Stirling et al., 2011). Research in South Africa showed that certain green manure crops reduced the populations of some nematode species but others led to increased nematode populations (Berry and Rhodes, 2006). An experiment in Zimbabwe showed

a reduction in nematode numbers in sugarcane fields following a soybean rotation (Shoko and Zhou, 2009).

Crops may be planted between the rows of sugarcane, and although this has been shown to reduce sugarcane yields, it provides extra income for farmers. These inter-row crops include black beans in Colombia, cucumbers and tomatillos in Mexico, sugar beets in Pakistan, potatoes in Louisiana and radishes in Java (Indonesia) (Irvine, 2004). Trials in India showed high yield when sugarcane was intercropped with rice as it enabled the sugarcane to be planted earlier in the season (Singh et al., 2010b). In contrast, studies in Pakistan showed a higher yield of sugarcane and greater overall income when sugarcane was grown alone compared to intercropping with wheat or lentil (Rasool et al., 2010; Sohu, Abro and Oad, 2010).

In Australia, the sugarcane industry is incorporating controlled traffic and minimum till practices. A single pass of heavy machinery over the planting area has been shown to cause soil compaction (Braunack and Peatey, 1999) and multiple passes reduce crop yields (Garside et al., 2009). The adoption of controlled traffic planting practices, where GPS guidance is used to direct machinery to the same path in the field, enables the planting beds to be kept separate from the vehicular traffic zones and thus avoid soil compaction and stool damage in the growing areas. This results in a reduced requirement to cultivate the beds, which reduces costs and may also reduce weed problems (Garside et al., 2004). Precision agricultural practices such as automatic pilot on machinery and variable rate application of soil ameliorants is also being adopted in the state of São Paolo in Brazil (Silva, de Moraes and Molin, 2011). Minimum tillage is used on sloping land in Mauritius (Ismael et al., 2008) and has been trialled in Thailand with higher yields than no-till or conventional treatments (Grange, Prammanee and Prasertsak, 2010).

Crop improvement

New varieties are generated through breeding programmes, which rely on the maintenance of germplasm stocks for breeding material. Lines with desirable genotypes are used for hybridisations to produce new lines. Sugarcane breeding for improved cultivars is a time-consuming process, taking upwards of ten years from initial crosses to final agronomic assessment of elite cultivars (Cox, Hogarth and Smith, 2000). More recently, breeding has explored a number of traits, including biomass production, stress tolerance, drought tolerance, low temperature stress tolerance and disease tolerance (Ming et al., 2006). There has been little increase in sugar content in modern cultivars (Jackson, 2005). Genetic modification techniques have been developed which may permit more economical and efficient development of novel genetically engineered (GE) sugarcane lines (see below; Lakshmanan et al., 2005). However, at the time of publication of the current volume, the release and commercialisation of GE sugarcane varieties is at the early stages and still very limited in the world.[3]

In India, the cane-growing regions are grouped into tropical and subtropical regions, with distinct agroclimatic regions within these regions. Cane varieties are bred specifically for these locations and none of the varieties are grown across all the regions (Nair et al., 2002). However, there is limited genetic diversity between different sugarcane cultivars. In India, the genetic distance between 28 varieties sampled was only 29% (Nair et al., 2002). Similar studies in South Africa found 10-28% genetic distance between 20 sugarcane hybrids (Harvey, Huckett and Botha, 1994). A study of 40 commercial cultivars grown around the world showed 61% average genetic similarity (Lu et al., 1994).

Breeding

Sugarcane breeding programmes rely on crossing of elite cultivars and usually involve cross-pollination. In the case of self-pollination, the arrows (inflorescence) containing the flowers are covered with bags or are kept separate from other clones (Sleper and Poehlman, 2006).

Lines used in breeding programmes are designated as male or female. The method of designation varies between countries, with some, such as Australia, Barbados and Cuba, relying on aceto-carmine or iodine staining to determine the relative amount of viable pollen produced (Cox, Hogarth and Smith, 2000; McIntyre and Jackson, 2001). Results of acetocarmine staining showed a good linear relationship with pollen germination from 20-100% staining (Midmore, 1980). Cultivars with <10% pollen viability are designated female and cultivars with >20% viable pollen (or 25% in Barbados) are designated male. Cultivars with intermediate levels of viable pollen (10-20%) are classified as bisexual and may be used as either male or female parents (McIntyre and Jackson, 2001). In other countries, staining for viability is used, but the amount of viable pollen allowed for a female is higher at 15-20% viable pollen (Guadeloupe) or less than 30% viable pollen (South Africa) (Zhou, 2013). In Florida and Louisiana, visual examination is used to determine pollen production, with females showing closed yellow anthers with no pollen on the stigmas (McIntyre and Jackson, 2001).

Emasculation using hot water or reduction in pollen viability by growing plants at low temperatures has been exploited to produce male sterile plants to use as female parents in breeding programmes (as discussed in Heinz and Tew, 1987; McIntyre and Jackson, 2001).

Crosses may be set up as polycrosses or biparental crosses. Polycrosses, or "melting pot crosses", involve crosses between several elite cultivars with an unshielded pollen source. Polycrosses are thought to be easier and more cost-effective (Berding, Hogarth and Cox, 2004), but there is lack of genetic control and limited information available on parentage (Tew and Pan, 2010).

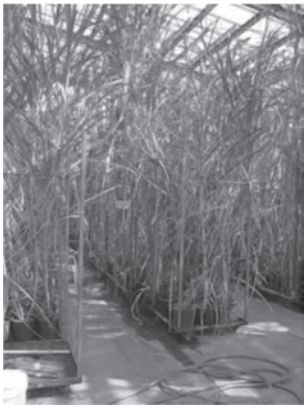
Sugarcane breeding programmes are severely limited by the nature of flowering of each sugarcane cultivar, particularly by a decrease in flowering and pollen viability at high latitudes (Moore and Nuss, 1987). Crosses can be made only between cultivars which have overlapping flowering periods. Various techniques have been developed to induce flowering including alteration of photoperiod so that flowers can be available for crossing when required (Bull and Glasziou, 1979). However, methods used to alter flowering time may also impact on fertility (Midmore, 1980).

Commercial breeding programmes produce assisted crosses between *Saccharum* spp. hybrids under highly favourable conditions. In one method, flowering stalks are cut off and maintained in buckets of crossing solution. The crossing solution consists of a dilute mixture of acids which help preserve the stalks and provide some nutrients (Cox, Hogarth and Smith, 2000). Male and female arrows are set up inside canvas lanterns (pollen impervious canvas bags) with the male set above the female to allow pollen to be shed downwards onto the female flowers (Cox, Hogarth and Smith, 2000). Once pollinated, the stalks are kept in the bucket of crossing solution and allowed to mature, a process taking 12-14 days (Buzacott, 1965). Marcotting or air layering of sugarcane stalks is also used to maintain stalks for crossing (Bischoff and Gravois, 2004). In more temperate climates, crossing houses with controlled temperature, light and humidity are used to perform specific crosses.

Figure 2.3 illustrates some of the steps involved in this process.

Figure 2.3. **Steps involved in artificial crosses performed in *Saccharum* breeding programmes**

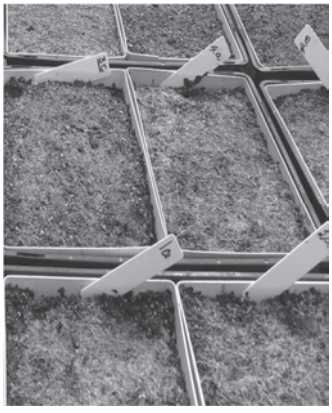
a) Sugarcane cultivars in the glasshouse ready for crossing



b) Cut male and female inflorescence bagged for crosses (2 weeks)

c) Fuzz developing for future seed harvest

d) Sugarcane seeds and small seedlings



e) Sugarcane seedlings in growing trays

f) Sugarcane seedlings in a field trial

Source: Courtesy staff at OGTR, taken in 2007.

To improve the efficiency of breeding and to reliably identify cultivars, modern molecular techniques are being used. Molecular markers can be used to tag genes which are associated with traits of interest, or used to better understand the diversity in the

parents used for breeding (Alwala et al., 2006; reviewed in Hotta et al., 2010; reviewed in Manners and Casu, 2011). Molecular markers have been identified for sugarcane for use in breeding and to identify genetic diversity (Alwala et al., 2008; Heller-Uszynska et al., 2011; Lakshmanan et al., 2005; McNeil et al., 2011; Selvi et al., 2003; Singh et al., 2010a).

Expressed sequence tags (ESTs) have been identified in South Africa from sugarcane meristematic tissue (Carson and Botha, 2000), in Australia and South Africa from sugarcane stem tissue (Carson and Botha, 2002; Casu et al., 2004, 2003) and in India from red-rot infected sugarcane (Gupta et al., 2010). A Brazilian consortium has developed an EST programme (SUCEST) which produced 238 000 ESTs from 26 cDNA libraries, covering different developmental stages and different organs and tissues (Arruda, 2001). ESTs have also been generated in the United States and compared with *Sorghum* and Arabidopsis EST libraries to look for common genes (Ma et al., 2004). These EST projects aim to help expand the knowledge of sugarcane biology and genomics by providing the sequences and possible functions of large numbers of genes that could be related to economically important traits.

In sugarcane, many traits are quantitatively inherited, so quantitative trait loci (QTL) markers are being developed for use in breeding programmes. QTLs have been obtained which are associated with stalk number and suckering (Jordan et al., 2004), sugar content (Aitken, Jackson and McIntyre, 2006; Hoarau et al., 2002; Ming et al., 2002) and yield-related stalk traits (such as stalk weight, stalk number and stalk diameter) (Aitken et al., 2008).

An international sugarcane genome sequencing collaboration is also underway to generate sequence data for *S. officinarum*, *S. spontaneum* and a commercial hybrid (Bonnett and Henry, 2011; Souza et al., 2011; De Setta et al., 2014[4]).

Mutation breeding has been used in sugarcane to add to the natural genetic variation (Patade and Suprasanna, 2008; reviewed in Snyman et al., 2011). This includes experiments using tissue culture to induce somaclonal variation (genetic or epigenetic variation). Somaclonal variants for resistance to eyespot disease (*Helminthosporium sacchari*) have been generated through the screening of plants after tissue culture (Larkin and Scowcroft, 1983). In some instances, selection for the desired trait has been used for example using eyespot toxin or for smut resistance (Rodriguez et al., 2001 as cited in Patade and Suprasanna, 2008). Mutagenesis has also been induced in tissue culture using radiation to produce plants with red-rot resistance, tolerance to water logging, delayed flowering and altered timing of maturity (reviewed in Patade and Suprasanna, 2008) and resistance to downy mildew and improved cane and sugar yield (reviewed in Larkin and Scowcroft, 1981).

Genetic modifications

Sugarcane has a highly complex genome and is vegetatively propagated. This has limited opportunities for crop improvement through conventional breeding of sugarcane (Lakshmanan et al., 2005) and genetic engineering is seen as an important alternative approach for the introduction of new traits. For an overview of methods and target traits for genetic modification of sugarcane see Brumbley et al. (2008).

Sugarcane can be genetically engineered by microprojectile bombardment (Bower and Birch, 1992), electroporation (Arencibia et al., 1995) or *Agrobacterium*-mediated transformation (Arencibia et al., 1998). Positive selection, using the phosphomannose

isomerase/mannose-selection system, has been used to produce GE sugarcane plants that do not contain an antibiotic resistance selectable marker gene (Jain et al., 2007).

Data show that introduced genes are stable in sugarcane and continue to be expressed after asexual and sexual propagation (Hansom et al., 1999; Harrison et al., 2001). However, there is some evidence from field-grown GE sugarcane that yield and CCS is reduced, which may be due to the effects of biolistic introduction of DNA into callus. Controls, which had been through the tissue-culture process but were not subjected to biolistic bombardment (i.e. not genetically engineered), performed better than the GE plants, but still showed reduced agronomic performance. This somaclonal variation is commonly observed after plant tissue culture, is not species specific and is irrespective of the morphogenic route or explant used (Larkin and Scowcroft, 1981).

Although some studies show that a reduced performance of the GE plants compared to controls persisted after ratooning (Arencibia et al., 1999; Gilbert et al., 2009; Vickers et al., 2005b), other field experiments have shown that the phenotypic variations in tissue-cultured sugarcane were temporary and some variants reverted to the original parental phenotype in the first ratoon crop (Burner and Grisham, 1995; Irvine et al., 1991; Lourens and Martin, 1987).

Somaclonal variation from *in vitro*-derived sugarcane has been consistently observed, particularly when plants are produced via a callus stage, which involves long exposure to high levels of certain plant growth regulators (Burner and Grisham, 1995; Irvine, 1984; Irvine et al., 1991; Larkin and Scowcroft, 1981; Lourens and Martin, 1987; Zucchi et al., 2002). The *in vitro* component of the sugarcane transformation process has the potential to generate somaclonal variation to the regenerated plants, and selection by antibiotics or herbicides can add to this increased polymorphism (Carmona et al., 2005). However, as discussed below, the effect may be epigenetic and, in addition, plants exhibiting tissue-culture-derived somaclonal variation are systematically culled during micropropagation-based seedling production systems.

Transposable elements, natural DNA sequences which cause mutations by moving within the genome, have recently been identified in sugarcane (de Araujo et al., 2005). These are expressed mainly in callus and may be the cause of the observed high somaclonal variation in this tissue (de Araujo et al., 2005). Epigenetic effects may also account for observed unusual growth patterns; however, these are often temporary and are usually resolved within a few generations of vegetative reproduction (Birch, 1997; Taylor et al., 1995).

To date, experimental work to genetically modify sugarcane has involved a range of traits including herbicide resistance (Enríquez-Obregón et al., 1998; Leibbrandt and Snyman, 2003), resistance to pests and pathogens (Arencibia et al., 1999, 1997; Arvinth et al., 2010; Braga et al., 2003; Hansom et al., 1999; Ingelbrecht, Irvine and Mirkov, 1999; Joyce et al., 1998; Kalunke et al., 2009; reviewed in Srikanth, Subramonian and Premachandran, 2011; Weng et al., 2006), reduction of browning of sugarcane juice (Vickers et al., 2005a; 2005b) and resistance to drought stress (Molinari et al., 2007).

Sugarcane has also been genetically engineered for the production of novel industrial compounds. Sugarcane is a C4 grass so it has a high growth rate and efficient carbon fixation. In addition to the C4 qualities, it has a substantial carbon flux through metabolic pathways, and the waste bagasse could be used to generate electricity needed for processing of the biofactory products (Twine, 2005). For example, GE sugarcane has been modified to produce altered sugars such as trehalose (Hamerli and Birch, 2011;

Zhang et al., 2006), isomaltose (Wu and Birch, 2007) and sorbitol (Chong et al., 2007) or industrial compounds such as poly-3-hydroxybutyrate (PHB) (Brumbley et al., 2002; Purnell et al., 2007) and p-hydroxybenzoic acid (pHBA) (McQualter et al., 2005). The first field trial in the United States to produce a human pharmaceutical product was conducted with sugarcane genetically engineered to produce human granulocyte macrophage colony stimulating factor (GM-CSF) (Wang et al., 2005).

In Australia, field trials of GE plants with altered sugar production, herbicide tolerance, altered plant architecture, enhanced drought tolerance and nitrogen use efficiency, altered sucrose accumulation and improved cellulosic ethanol production from sugarcane biomass are underway.[5] In Brazil, there have been a number of field trials for traits such as herbicide tolerance, viral resistance, insect resistance, drought tolerance, sucrose yield and inhibition of flowering (Matsuoka, Ferro and Arruda, 2009). In Cuba, field trials of GE sugarcane plants with resistance to insects, fungi and herbicide tolerance have been approved.[6] In the United States, permits have been issued for field trials of GE sugarcane plants with altered sugar storage, resistance to insects, viruses, herbicide tolerance and accumulation of pharmaceutical products.[7] Field trials with GE sugarcane have been conducted in South Africa[8] and the main traits evaluated to date include herbicide tolerance, viral resistance and sucrose metabolism perturbations (Watt et al., 2010). Field trials have been performed in China with GE sugarcane with insect resistance (Weng et al., 2011). In Argentina, field trials have been performed with herbicide-tolerant and virus-resistant varieties (Raney and Matuschke, 2011). At the time of publishing the current volume, the commercialisation of GE sugarcane was still at very early stage globally; one case of GE sugarcane, developed by the Indonesian public research for drought stress tolerance, was approved in Indonesia for food use and cultivation in 2013.[9]

Morphology

Plant morphology

The morphology and anatomy of sugarcane has been extensively reviewed and so will not be explored in great detail here. See Moore (1987), Bakker (1999) and Cheavegatti-Gianotto et al. (2011) for a comprehensive treatment of the morphology and anatomy of sugarcane and Matsuoka and Garcia (2011) for a review of the literature on sugarcane roots.

Sugarcane is a large tropical grass that produces multiple stems or culms, each of which consists of a series of nodes separated by internodes. Following germination (sprouting of sett), the terminal vegetative bud of each shoot lays down a series of nodes. Each node consists of a growth ring or intercalary meristem, the root band (containing root primordia) and a bud above the leaf scar where the leaf sheath attaches, which delimits the node from the internode below. The internodes consist of sucrose-storing parenchyma cells and vascular tissue (Moore, 1987).

The stem of sugarcane is similar to maize (corn) and sorghum in that it is filled with parenchyma cells and is not hollow like many grasses (Griffee, 2000). The stem is the major storage area for photosynthate (sucrose) within the sugarcane plant, rather than fruit or seed structures. Transverse sections through an internode reveal vascular bundles surrounded by parenchyma cells with a thick outer epidermis covered in an external layer of wax. Leaves and internodes develop in a basipetal direction in that the leaf blade expands at the base then the internode elongates. As the stem develops, the leaves

emerge, one leaf per node, attached at the base of the node, forming two alternate ranks on either side of the stem. At the top of the stem is an apical meristem set on top of a number of very short internodes. Mature stems consist of a number of immature leaves still enclosed in the leaf spindle, a dozen or so green leaves and a number of senescent leaves, increasing in number with increasing age of the plant. Leaves may be retained on the stem or they may be shed in some varieties, known as free-trashing. New leaves emerge and expand over a period of between one and three weeks. Internode length can reach over 30 cm, depending on growth conditions, and stems normally reach 2-3 metres in the normal growing season (Bull, 2000; Bull and Glasziou, 1979).

The leaf blade is pubescent (hairy) on the abaxial (under) side of the leaf and glabrous (without hairs) on the adaxial (top) side and terminates in a pointed tip. The leaf blade is 2-10 cm across and 60-150 cm long (Fauconnier, 1993). The base of the leaf blade is attached to the leaf sheath that encloses the internode, joining the stem at the node to which the leaf subtends.

Sugarcane uses a C4 mechanism of photosynthesis similar to other tropical grasses, where the carbon dioxide for photosynthesis is initially fixed by phosphoenolpyruvate (PEP) carboxylase to form a four-carbon compound (Hatch and Slack, 1966). The anatomy of the leaves reflects this underlying physiology; the vascular bundles are surrounded by a ring of bundle sheath cells and a ring of mesophyll cells, an arrangement known as Kranz anatomy.

Like most grasses, the sugarcane root system is fibrous and shallow. It has been estimated that the top 25 cm of soil contains 50% of the plant roots, with the next 35 cm containing a further 40% of the roots (Fauconnier, 1993). However, the effective root zone (i.e. the area of roots which are actively extracting water) varies depending on the soil type, from just the topsoil in sodic duplex soils, to 0.9-1.2 m in irrigated clay loam, to 1.8 m in rain-fed conditions (Ham, McGuire and Kingston, 2000). The root system is dynamic and the area of active root growth varies depending on the irrigation pattern (Inman-Bamber et al., 2008). The plant also develops buttress roots that serve to anchor the plant, and some deeply penetrating roots that grow downwards for up to four metres allowing for water absorption under water stress (Bull and Glasziou, 1979). Roots partially die-back after ratooning, although there is evidence that some roots can persist for at least four months after harvest and some of the new roots emerge from the old pre-harvest roots (Smith, Inman-Bamber and Thorburn, 2005).

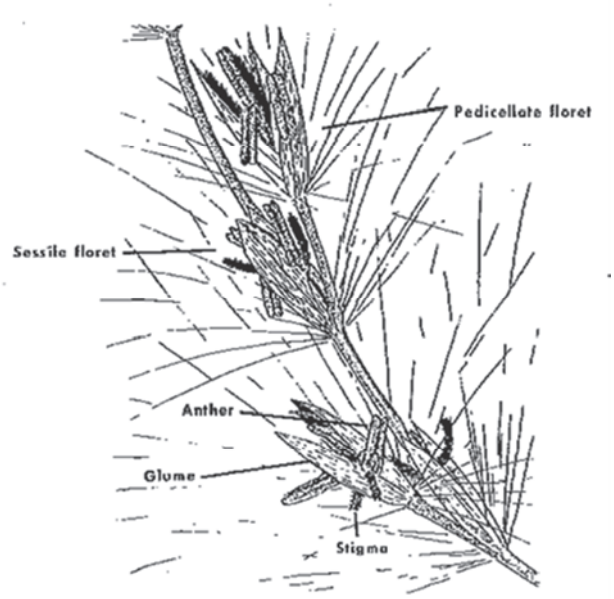
Reproductive morphology

The sugarcane inflorescence is an open branched panicle (a compound raceme), also known as an arrow, whose shape, degree of branching and size are highly cultivar specific (Figure 2.4). The arrow can bear thousands of flowers (Sleper and Poehlman, 2006), and is estimated to average 24 600 florets (Rao, 1980). The arrow consists of a main axis and first-, second- and third-order branches. Attached to the branches are spikelets arranged in pairs, one of which is sessile and one pedicellate, that bear individual flowers (Figure 2.5). At the base of each spikelet is a row of silky white hairs. Sugarcane flowers consist of three stamens (male) and a single carpel with a feathery stigma (female) typical of wind-pollinated flowers. Frequently, the male stamens may be abortive, resulting in reduced or absent pollen production (James, 2004; Moore, 1987; Sleper and Poehlman, 2006). Another colour varies from bright yellow to purple (Moore, 1987).

Figure 2.4. **Inflorescence of *Saccharum* spp. hybrid**

Source: Courtesy G. Bonnett, CSIRO, Australia.

Figure 2.5. **Diagram of a portion of a mature raceme of a sugarcane inflorescence showing the arrangement of sessile and pedicellate spikelets and callus hairs**



Source: Reprinted with permission from Moore (1987). Original figure from Engard and Larsen (1948).

Development

Reproductive biology

Sugarcane can reproduce both sexually and asexually. Sexual reproduction is via true seed, often called fluff/fuzz due to the presence of soft hairs. As discussed previously, the ability of sugarcane to reproduce asexually is exploited for the production of planting material.

Asexual reproduction

Asexual reproduction can occur via nodal buds which are found on setts, via rhizomes or via stools (Amalraj and Balasundaram, 2006). The parent species of *Saccharum* spp. hybrids differ in their ability to form rhizomes and tillers, with *S. spontaneum* forming dense mats of rhizomes and many tillers, whereas *S. officinarum* forms fewer tillers and rhizomes (Amalraj and Balasundaram, 2006; Moore, 1987).

Sexual reproduction

The ability of sugarcane to reproduce sexually was not recognised until the mid- to late 1800s due to its lack of importance as an economic product (Buzacott, 1965). Sugarcane flowering is a complex process consisting of a number of steps which are differentially regulated by photoperiod (Moore and Nuss, 1987), with the early steps having more precise regulation required than the later steps (Midmore, 1980). Flowering is dependent on interaction of genotypes and environmental factors such as day length and temperature.

Flowering is reliable and 80-100% of stalks produce flowers in tropical environments such as Malawi and Sudan (12-13° latitude), whereas it is sporadic at higher latitudes in sub-tropical environments such as South Africa (Donaldson and Singels, 2004). Flowering in the northern hemisphere is earliest closest to the equator (around the autumn equinox in mid-September). At higher latitudes it occurs later, with the peak in October in Coimbatore (India) and Barbados, November in Hawaii and December in southern Florida. In the southern hemisphere, flowering takes place from March through to June (Moore and Nuss, 1987), although flowering does occur outside this peak period (Bonnett et al., 2007). The flowering date of a particular cultivar varies by only a few days between years in the same environment (Midmore, 1980). Some cultivars can flower profusely in their natural environment but only sparingly when introduced to other regions (Bull and Glasziou, 1979). When grown together, cultivars that were selected for use at high latitudes usually flower earlier than those which originated at lower latitudes, suggesting that they require longer day lengths for floral initiation (Moore and Nuss, 1987). Experiments have also indicated that early flowering cultivars often flower more profusely than later flowering ones (Moore and Nuss, 1987).

Floral development is induced by photoperiods of approximately 11.5 hours, which often coincides with a natural day length of 12.5 hours. As a result, the period of floral initiation is more defined further from the equator (Bakker, 1999). Annual variations in flowering times in a given location are mostly attributable to differences in night temperature (Bakker, 1999). Cool night temperatures, high day temperatures and lack of moisture interfere with flower initiation. The older and more vigorous stems in a stool are the most likely to initiate flowering (Moore and Nuss, 1987). Flower initiation causes the apical meristem to switch from vegetative to floral development. Consequently, flowering of the crop can adversely affect yields (Bakker, 1999).

Pollen dispersal and pollination

Sugarcane spikelets open from the top of the panicle, with the outermost spikelets opening first. It takes 5-15 days for all the spikelets on the panicle to open. Spikelets open at sunrise, with anther dehiscence occurring about three hours later, although this is delayed by high humidity (Purseglove, 1972).

Sugarcane pollen grains are very small, hairy and wind dispersed. The round-ellipsoidal grains vary in size from 38.25 µm x 42.75 µm to 67.5 µm x 72.0 µm and are yellow in colour (Dutt, 1929).

Little data is available on sugarcane pollen viability under natural conditions. In Australia, studies have shown that pollen viability from commercial sugarcane fields varies between regions and cultivars, showing a range from 1.2-4.4% viability (Bonnett et al., 2007). Sugarcane pollen begins to lose viability rapidly in less than 30 minutes (Venkatraman, 1922). *S. spontaneum* pollen is rapidly desiccated after dehiscence, having a half-life of only 12 minutes, and is no longer viable beyond 35 minutes under unmodified environmental conditions (26.5°C and 67% relative humidity) (Moore, 1976). At higher humidity the pollen longevity was increased (Moore, 1976). Tests with another cane cultivar (Saratha Desi, which is thought to be derived from *S. barberi*) indicated that pollen viability was maintained for two hours in the lab, or one hour when exposed to sunlight (Dutt and Ayyar, 1928). Sugarcane pollen stored at 4°C under 90-100% relative humidity retains some viability for up to 14 days (Moore and Nuss, 1987).

Little data is available on sugarcane pollen dispersal. Information from breeding work in which plants were isolated by 20 m in open forest has shown that viable pollen is dispersed over this distance (Skinner, 1959). From this work, it was suggested that to prevent contamination of controlled crosses, plants should be isolated by 100 m in open forest or 300 m in open ground (Skinner, 1959).

Sugarcane is a cross-pollinating species, although selfing occurs at low levels (McIntyre and Jackson, 2001; Moore and Nuss, 1987; Tew and Pan, 2010). Sugarcane produces protogynous flowers, where the pistil matures before the anthers. Thus, an individual flower may be cross-pollinated prior to pollen shed from its own anthers (James, 2004). In seven experimental polycrosses, the selfing frequencies ranged from 0% to 45%. Progeny resulting from crosses with a high degree of self-pollination had a reduced ability to survive the winter, suggesting reduced vigour (Tew and Pan, 2010). The reduction in vigour following self-pollination has been observed previously (Skinner, 1959).

Sugarcane flowers often have reduced male fertility or are male sterile and some are self-sterile (Skinner, 1959).

Fruit/seed development and dispersal

After fertilisation, it takes approximately three weeks for the fruit to mature and to be shed (Purseglove, 1972). The seed at the top of the panicle, which was fertilised first, is also the first to mature (Breaux and Miller, 1987). These seed are shed as the inflorescence starts to disintegrate, before the seeds at the base reach maturity (James, 1980). The mature fruit contain whorls of silky hairs at the base and are adapted for wind dispersal (Purseglove, 1972) (Figure 2.6). No further information has been found in the literature on seed dispersal.

Mature fuzz consists of the mature dry fruit (caryopsis), glumes, callus hairs, anthers and stigma (Breaux and Miller, 1987). The additional parts of the inflorescence are generally handled, stored and sown with the seed because it is not practical to separate them. Although many commercial cultivars of sugarcane can produce seed, it is only used in breeding programmes, because the proportion of sugarcane seedlings with agronomic qualities near to those of the parental commercial cultivars is extremely low.

The naked seed (without fuzz) has been measured as 1.5±0.03 x 0.64 ±0.005 mm and weighing 0.54±0.05 mg, which is approximately 1 850 seeds per g (Rao, 1980). One of the sugarcane parent species, *S. spontaneum*, has seed which weighed 0.39 mg with fuzz, or 0.25 mg defuzzed (Ellis and Hong, 2007). In a crossing experiment, up to 30% of the seeds produced were smaller than average or shrivelled; however, many of these abnormal seeds still germinated (Rao, 1980).

Figure 2.6. ***Saccharum spontaneum* seed**

Source: Courtesy K. Saltonstall, Smithsonian Tropical Research Institute, Panama.

Data from crosses have suggested that a low percentage of florets set fertile seed. One estimate of seed germination showed a maximum of 17.2% in a "very heavy" germinator (Price, 1961). Another study showed germination rates of between 3.1% and 22.7% (Rao, 1980). In Australia, seed collected from commercial fields had variable germination, ranging from 0-53.3 viable seed per g (approximately 2.9%)[10] depending on the cultivar and growing region (Bonnett et al., 2007). In breeding work in Barbados, seed viability of one commercial cultivar was 266 fertile seeds per g (approximately 14.4%)[3] (Midmore, 1980).

Seed germination

Some wild species of sugarcane such as *S. aegyptiacum* (now classified as a subspecies of *S. spontaneum*) have significant seed dormancy, whereas some modern cultivars have little seed dormancy (Ellis, Hong and Roberts, 1985; Poljakoff-Mayber, 1959).

Sugarcane seed has short viability even under optimal storage conditions. No data are available on field viability. If stored in polythene at room temperature, fuzz remained viable for 90-120 days (Verma et al., 2002). Artificially dried sugarcane seed lost 90% of its viability in 70 days at 28°C if not desiccated (Rao, 1980). Modelling of seed longevity using data on germination at different temperatures and moisture contents has predicted that under hermetic storage at -20°C, seed from the parent species *S. spontaneum* will not last as long as ten other crop species, with only potato (*Solanum tuberosum*) showing shorter viability (Ellis and Hong, 2007).

Generally, in breeding programmes the fuzz is sown. However, the fuzz can encourage the growth of micro-organisms and a large mass of fuzz can prevent seed contact with the soil (Breaux and Miller, 1987).

Germination of sugarcane seed requires heat and humidity and takes 25 days for small seedlings to appear from seed spread on the soil surface (Buzacott, 1965; Itakura, Kudo and Nakasone, 1980) or lightly covered with peat moss (Zhou, 2013). The optimum temperature for sugarcane seed germination under lab conditions was determined to be 35°C or 38°C (Heinz, 1974; Itakura, Kudo and Nakasone, 1980). A more recent study confirmed that maximum germination was at 36°C, with much less germination at 24°C and none at 12°C. At the upper limit, germination was eliminated at 48°C (Bonnett, 2013).

As the seed germinates, the primary root emerges first followed by elongation of the plumule. The leaves of the plumule then emerge rapidly. Tiller branches emerge from a bud which forms in the axil of each leaf. Adventitious roots form near the leaf bases (Moore, 1987).

The young seedlings are delicate and require optimum temperature, moisture, nutrients and protection from fungal diseases (Breaux and Miller, 1987; Buzacott, 1965). Information obtained from a survey of sugarcane breeders suggests that the conditions required to germinate and grow sugarcane seedlings are exacting (Breaux and Miller, 1987). Constant care and attention are needed to give seeds and seedlings the conditions required for survival, especially in the first three to four weeks post-germination. In Brazil, seed germination is seen in the field in north-east regions when flowering and seed shed occurs in the wet season. In other areas, either the night-time temperatures or soil humidity is too low for successful germination (Cheavegatti-Gianotto et al., 2011).

Viviparity, when the seed germinates before it detaches from the parent plant, has been observed under experimental conditions in both the parent species *S. spontaneum* and in hybrid sugarcane (Ragavan, 1960). It is feasible that moist conditions similar to the experimentally induced ones could occur naturally.

Vegetative growth

As discussed previously, sugarcane is propagated from stem cuttings which are referred to as setts, seed, seed cane or seed pieces (Purseglove, 1972). During the initial stages of germination, root primordia around the nodes of the sett produce a flush of roots, known as sett roots (Bakker, 1999). These roots are not connected directly to the primary shoot but are important in maintaining the moisture in the sett. Following formation of the shoot roots, the sett roots blacken and die (Bakker, 1999). The primary shoot is made up of a number of closely spaced internodes and nodes below ground. Each node develops new bud and root primordia that are the basis of stool establishment. These root primordia germinate to produce the shoot roots that support further plant growth. The shoot is then independent of the original sett (Bull, 2000).

While the shoot roots are developing, some of the new buds below ground also germinate to produce secondary shoots or tillers. These, in turn, develop their own root systems and give rise to shoots (Bull, 2000). Shoots usually appear above the soil approximately 12 days after planting, with the first leaf unfurling approximately 8 days later (Bakker, 1999).

Stem elongation is initially rapid and during this phase the fibre content of the stem is relatively high, whereas the sucrose levels are still quite low.

At maturation, the growth rate slows and sucrose content increases (Bull, 2000). Maturation and ripening are reversible processes and are associated with the lower rainfall and cooler temperatures of the winter months. During stem growth, each internode operates as an independent unit. While it has a green leaf attached, the internode completes cell elongation and cell wall thickening, and fills with sucrose. Hence internodes generally complete their cycle by the time the attached leaf dies, and the lower internodes are essentially ripe while the upper part of the stem is still growing. The stored sugar is, however, available for translocation to support further tillering and/or growth when conditions are not favourable for photosynthesis (Bull, 2000).

As the stem matures, more internodes reach the same condition and sucrose content rises. During this period, the most recently expanded internodes near the top of the stem stop elongating and photosynthates are channelled into storage as sucrose. Factors that affect the maturation of the sugarcane stem include age, nitrogen status and moisture. Environmental factors that can influence sucrose accumulation include water stress, nutrient status and temperature (Bull, 2000).

Genetics

As described in the beginning of this chapter, members of the *Saccharum* genus are genetically complex, showing polyploidy with some autopolyploidy and allopolyploidy.

The sugarcane genome has also been shown to contain many expressed sequences as tandem repeats, introducing further complexity (Butterfield et al., 2004).

The haploid genome size of a number of *Saccharum* spp. has been measured using flow cytometry as 2 547-4 183 Mbp (Arumuganathan and Earle, 1991). DNA measurements from *S. officinarum* and *S. spontaneum* also fall within this range (Butterfield, D'Hont and Berding, 2001). The monoploid genome size is thus estimated at 926 Mbp for *S. officinarum* and 760 Mbp for *S. spontaneum*, approximately the same as *Sorghum bicolor* (760 Mbp). Comparisons with other genomes suggest that it is the amount of repetitive DNA that varies between genomes, with the *Saccharum* genes occupying about 20% of the genome (Butterfield, D'Hont and Berding, 2001).

Abiotic interactions

A recent review has provided an overview of studies on abiotic stress in sugarcane (Azevedo et al., 2011).

Nutrient stress

The cultivation of sugarcane relies on the extensive use of fertilizers. As discussed above, to grow sugarcane successfully requires high inputs. This may also limit its ability to grow outside of cultivation.

Temperature stress

Low temperatures

Sugarcane cultivars differ in their degree of temperature sensitivity, but in general sett germination (sprouting) is slow at soil temperatures below 18°C (Smit, 2011) and the setts may succumb to attack by fungal pathogens before they germinate. Sett germination is increasingly rapid up to about 35°C (Bull, 2000).

Experiments have shown that sugarcane plants grow more slowly and have fewer, shorter internodes and fewer leaves at 15°C than when grown at 27°C. The low temperatures also inhibited sucrose export from the leaves to the stalk so the leaves accumulated sugar and starch (Ebrahim et al., 1998).

Flowering is also affected by low temperatures. Cool night temperatures, high day temperatures and lack of moisture interfere with both flower initiation and sucrose accumulation. Temperatures below 18.3°C are non-inductive for flower development (Coleman, 1963). In temperate South Africa, pollen fertility has been shown to be limited at temperatures below 21°C (Zhou, 2013). In Queensland (Australia), artificially increasing the night-time temperature of sugarcane plants to 22-23°C led to increased and earlier flowering (Berding, 1981). Experiments have also shown that heated pollen lanterns, used for crossing, can increase seed setting, due to improved fertilisation and embryo development (Berding and Skinner, 1980).

Experiments have shown that seed germination is markedly reduced at temperatures below 30°C (Itakura, Kudo and Nakasone, 1980).

Sugarcane is susceptible to frost damage (Griffee, 2000). Freezing reduces yields by delaying crop development in spring and by terminating sugar accumulation in autumn (Moore, 1987). In Australia, frost damage is seen in southern areas with about a third of the cane affected by frost, leading to yield losses of 10-30% annually (Weaich, Ludlow and Nielsen, 1993). Frosts may also affect production in southern Florida (Code and Ulloa, 1991). In 2008, almost all of the sugarcane crops in Guangxi Province in China suffered severe cold and freezing injury, leading to a decrease in sucrose content of 0.2-0.5% in plant cane, with a larger decrease in ratoon cane (Tan et al., 2010). Frosts are also a problem in high altitude regions in the Midlands of KwaZuluNatal (South Africa) and Louisiana, leading to early harvesting of the cane due to frost damage (Van Heerden et al., 2009). The degree of damage varies with the severity of the frost. Leaf browning occurs at temperatures from 0°C to -2°C, with temperatures down to -4°C causing damage to terminal and lateral buds and death of some young internodes. If the temperatures reach -11°C, this can cause freezing and subsequent cracking of entire stalks. The cracks or damaged buds can allow entry of anaerobic bacteria such as *Leuconostoc mesenteroides*, which can replicate in the damaged tissues and produce dextran. Dextran intefers with the crystallisation of sucrose at the mill (Irvine, 2004). Frost damage varies between sugarcane cultivars, and this is thought to be due to differences in tolerance rather than differences in morphology, which might protect against frosts (avoidance) (Weaich, Ludlow and Nielsen, 1993). Management practices such as retention of a trash blanket increases the susceptibility to frost by preventing radiation of warm air from the soil (Kingston, 2000).

High temperatures

The literature suggests that sugarcane can survive temperatures as high as 45°C, or higher for short periods of time but growth slows at temperatures above 40°C (Moore, 1987). However, in Iran sugarcane is grown in the Hapft Tappeh region where the average temperature over the summer months is 45.8°C (Sund and Clements, 1974). Sugarcane grown in the Ord River region of Australia, which has mean temperatures in November of 39.4°C (Australian Bureau of Meteorology, n.d.), has been shown to have a lower sucrose content than that grown in cooler regions. Experiments in which sugarcane was exposed to temperatures between 25°C and 38°C showed that these plants had a larger number of shorter internodes which contained lower sucrose levels than similar

sugarcane plants grown at 23-33°C (Bonnett, Hewitt and Glassop, 2006). High daytime temperatures (above 31°C) may also inhibit flowering, and very high temperatures at anthesis may reduce seed set. However, it has been suggested that these responses to high temperatures may be due to a water stress effect (as discussed in Moore and Nuss, 1987).

Water stress

Sugarcane is relatively drought resistant but water stress results in a reduction of sugar production (FAO, 2004). It is estimated that irrigation can add 3 t sugar per ha, a figure modelled on an average irrigation of 500 mm (Meyer, 1997). Sett germination (sprouting) does not occur in dry soil (Smit, 2011). Sugarcane flowering is also reduced by water stress (Moore and Nuss, 1987), with watered crops showing a greater number of panicles and a higher percentage of plants flowering (Berding, 1995).

Other abiotic stresses

Waterlogging

Sugarcane plants can withstand short periods of flooding (FAO, 2004). After four days, the growing point of the sugarcane plant will die, but it may continue to grow from side shoots once the water has receded (BSES Ltd., 2012d). Generally, yield loss will be 15-20% after 5 days submergence, 30-60% yield loss after 10 days and 37-100% after 15 days, but this depends on the height of the stalks, with younger cane being more affected than those at 2.5 m tall (BSES Ltd., 2012d). However, a pot study in Florida showed that some sugarcane varieties were able to sustain growth during short periods of flooding (Glaz, Morris and Daroub, 2004). Prolonged periods of waterlogging will result in a decline in sugar content (FAO, 2004). Waterlogging also results in cooler soil temperatures so germination (sprouting) of setts will be slower and losses from disease may be higher (Ridge and Reghenzani, 2000).

Altitude

Sugarcane is grown in a range of altitudes from just above sea level to as high as 3 000 m above sea level (FAO, 2004).

Wind

High winds, especially when combined with heavy rain, can lead to lodging of cane stalks in the field. This leads to problems with harvesting, reduced cane yield and reduced sugar content. In Australia, in northern Queensland, a 15-35% decrease in sugar yields has been recorded in a lodged crop compared to an unaffected crop (Singh et al., 2002; 2000). This may be due to rat damage, suckering, and stalk and stool death following lodging (Inman-Bamber et al., 2008).

Breeding for high, above-ground biomass in modern sugarcane cultivars means the plant is very top heavy and consequently sugarcane is prone to lodging. Plants recover from lodging by curving of the stem to again grow upright. Yield losses observed following lodging may be due to rat damage, suckering, stalk and stool death as well as poor ratooning in the following crop (Inman-Bamber et al., 2008). Lodging also leads to reduced light interception.

Soil pH

Sugarcane prefers a soil pH of 5.0-5.8, although it will tolerate a pH of 4-10 (Fauconnier, 1993).

Salt tolerance

Sugarcane is sensitive to soil salinity. It has been estimated that it will show no reduction of growth in soil with salinity up to 1.1 decisiemens per metre (dS per m) and a 10% growth reduction at 2.2 dS per m (Evans, 2006). Sugarcane production is not economic in areas with soil salinity above 4.0 dS per m (Rozeff, 1995). It has been further estimated that there are 1 million ha globally on which sugarcane is grown which are affected by salinity (Hunsigi, 1993) In Pakistan, it has been estimated that 6.3 Mha out of a total land area of 79.6 Mha is salt-affected (Hussain et al., 2004a) and in 1994 this led to significant yield losses (Wahid, Rao and Rasul, 1997). Salinity problems have also been experienced in cane growing areas of south Texas (United States) (Gerard, 1978), the Haft Teppeh region in Iran (Sund and Clements, 1974) and Australia (Christiansen, 2000). Salinity affects both growth rate and yield of sugarcane, but also the sucrose content of the stalk (Rozeff, 1995). Shoot growth has been shown to reduce, although the severity varies between cultivars (Akhtar et al., 2001b), and root growth may be stimulated by increased salinity (Gerard, 1978). High salinity has been shown to reduce stalk height and weight, due to a reduction in both the number of internodes and the internode length, but not the number of stalks, and may be related to reduced water content (Akhtar et al., 2001a; Lingle et al., 2000). Leaf dry weight and area also decrease with increasing salinity (Plaut, Meinzer and Federman, 2000). Different life stages may have different sensitivities to salinity, with seed germination showing the least sensitivity (Wahid, Rao and Rasul, 1997). In experiments under saline conditions, ratoon crops have shown 2.2-3.7 times greater yield loss compared to plant crops (Bernstein, Francois and Clark, 1966). The addition of potassium and silicon have been shown to help ameliorate the decreases in plant growth and juice quality caused by salinity, and actually have more effect on salt-sensitive genotypes compared to salt-tolerant genotypes (Ashraf et al., 2009).

Aluminium tolerance

High aluminium levels are associated with acid soils, and aluminium toxicity can cause a major reduction in yield in many crops (Delhaize and Ryan, 1995). Sugarcane is relatively tolerant of high aluminium levels, although differences in tolerance have been seen between cultivars (Hetherington, Asher and Blamey, 1986). Cultivars of the *S. officinarum* parent species generally have higher levels of tolerance than the *S. spontaneum* parent species (Landell [1989] as cited in Drummond et al., 2001). In an experiment comparing the aluminium tolerances of sugarcane, navy beans, soybeans and maize (corn), which may be grown in rotation with sugarcane, the sugarcane cultivars showed the greatest tolerance. The concentrations of aluminium which led to a 10% reduction in root growth were up to ten-fold higher for sugarcane than the other crops tested (Hetherington, Asher and Blamey, 1988). Symptoms of toxicity include root stubbing, which leads to susceptibility to water stress and yield loss (Calcino, 1994).

Other metals

Sugarcane has been shown to tolerate up to 100 μM copper in laboratory experiments (Sereno et al., 2007). Tolerance to cadmium is higher, with laboratory experiments showing no toxicity at 500 μM cadmium (the highest concentration tested). Plant damage was seen in other experiments at 2 mM cadmium (Fornazier et al., 2002). The high tolerance to cadmium and the observation that the sugarcane plants can accumulate cadmium have suggested its use in phytoremediation (Sereno et al., 2007).

Biotic interactions

Weeds

Weeds are one of the major problems in sugarcane crops due to wide row spacing, slow germination (sprouting) and initial growth, heavy fertilisation and frequent irrigation (Raskar, 2004). Weeds lead to yield reduction caused by competition or allelopathy and interference with harvesting machinery, which reduces product quality (McMahon, Lawrence and O'Grady, 2000). In India, weeds are reported to cause greater yield loss than all pests (Raskar, 2004). Experiments have shown that herbicides applied at planting time can more than double the yield of an untreated crop (Akhtar and Ahmed, 1999) and weed removal leads to increased yield in ratoons (Singh and Tomar, 2005). In Ethiopia, weeds cause a yield loss of 41-51% (Firehun and Tamado, 2006). In Sudan, cane yields were 40% less in unweeded cane than cane fields in which the weeds had been removed (Ibraham, 1984). Other data have suggested that a single species, such as Bermuda grass (*Cynodon dactylon*) in Louisiana, can account for 32% reduction in sugar yield due to reduced sugarcane stalk numbers and height (Richard and Dalley, 2007). Weeds may also act as a reservoir for plant pathogens or pests. As well as controlling weeds within the crop, it is important to control weeds around the farm to reduce any high protein food, such as weed or grass seeds, which rats need to breed (McMahon, Lawrence and O'Grady, 2000). See below for a discussion of rats as a pest of sugarcane.

There are a number of weeds that infest sugarcane plantations including grasses, broadleaf weeds, vines and sedges. The paragraphs below discuss those weeds that are a major problem worldwide. However, the weed population can vary significantly; for example, surveys in Ethiopia concluded that the weed flora varied depending on soil type, fertiliser application and crop cycle, and from year to year in the same region (Firehun and Tamado, 2006).

Imperata cylindrica (lalang or blady grass) is a perennial species that commonly grows on degraded or burnt-off land in most Australian sugarcane-growing districts (Lazarides, Cowley and Hohnen, 1997). It is also listed as a noxious weed in a number of states in the United States (USDA-NRCS, 2013). It is an alternate host to ratoon stunting disease (RSD) in Pakistan (Jabeen and Ahmed, 2010).

One of the most important and prevalent weeds of sugarcane is sedge nut grass (*Cyperus rotundus*, also known as purple nutsedge), although in wetter areas other sedges also occur (McMahon, Lawrence and O'Grady, 2000). It spreads mainly by tubers, which are produced in very large numbers and are carried in soil and by flood waters. It also reproduces by seed, although apparently only rarely. It withstands cultivation extremely well, and this process rapidly spreads the tubers around and between fields (DPIW-Tas, 2009). The FAO lists this as a weed of sugarcane in Colombia.[11] In two studies in India it was the dominant weed species (Murugan and Kathiresan, 2010; Raskar, 2004), and it was identified as a weed in Ethiopian, South African and Argentinean sugarcane fields (Ferraro, Ghersa and Rivero 2012; Firehun and Tamado, 2006; Leibbrandt, 1997). In Ethiopia, Kenya and South Africa it has been identified as one of the three most serious weeds (Bendixen and Nandihalli, 1987). Its prevalence in sugarcane fields in Louisiana has been increasing due to inadequate control during the fallow period (Etheredge, Griffin and Boudreaux, 2010a; 2010b). Pasture grasses can also be problematic when the land is subsequently used to grow sugarcane (McMahon, Lawrence and O'Grady, 2000).

Broadleaf weeds such as blue top/billygoat weed/tropic ageratum (*Ageratum* spp.) and purslane/pigweed (*Portulaca oleracea*) tend to be less of a problem and can be controlled relatively easily if targeted when the plants are young. Broadleaf weeds tend to be more regional and soil specific (McMahon, Lawrence and O'Grady, 2000). In India, the parasitic plant *Aeginetioa pedunculata* causes crop losses of up to 37% due to reduced stalk growth and juice quality (Ray and Dasgupta, 2006).

Vines have become an increasing problem after the adoption of trash-blanketing, although a thick layer of trash has been shown to inhibit their growth (Fillols and Callow, 2010). They have the potential to grow rapidly and if left uncontrolled can impede the harvesters (McMahon, Lawrence and O'Grady, 2000). The most problematic vines in sugarcane include bindweed (*Convolvulus* spp.), passionvine (*Passiflora* spp.) and morning glory (*Ipomoea* spp.) (McMahon, Lawrence and O'Grady, 2000).

Weeds may be controlled either by herbicide use or by mechanical removal. In some countries this is by hand-hoeing, but animal- or tractor-drawn equipment may also be used (Fauconnier, 1993). In most sugarcane growing countries, herbicides are used to control weeds (Cheavegatti-Gianotto et al., 2011). There are a number of herbicides that can be used to control weeds in sugarcane. These include pre-emergent herbicides such as isoxaflutole, imazapic or a diuron/hexazinone mix (Fillols and Callow, 2010). Herbicides such as 2,4-D amine can be used on broadleaf weeds. Paraquat, a non-selective herbicide, can be used on broadleaf, grassy and other weeds (McMahon, Lawrence and O'Grady, 2000).

Pests and pathogens

Pests and pathogens can have a major impact on sugarcane production worldwide. For example, in Australia the cost of controlling the major pests and diseases of sugarcane was estimated to be AUD 111 million in 1996 (McLeod, McMahon and Allsopp, 1999). This included AUD 14 million in lost production and control costs for pests, and AUD 97.4 million in loss and control for diseases (McLeod, McMahon and Allsopp, 1999). This is low compared to other countries, where it can be 10-15% of the crop (as quoted in Plant Health Australia, 2009).

The distribution of sugarcane pests appears to be more specific to a particular country or region, whereas diseases are more ubiquitous across the international sugarcane industry, although the impact of diseases may vary between countries. The major pests and pathogens of international relevance to the sugarcane industry are discussed below.

Pests

Invertebrate pests

There are many invertebrate pests of sugarcane and some insects such as plant hoppers (*Perkinsiella saccharicida*) are also known vectors of diseases (Allsopp, Cox and Nutt, 2002; Croft, Magarey and Whittle, 2000). The impact of invertebrate pests can be large, or be widespread without causing large losses; for example, in China, borers and soil-borne pests were found in 60% of sugarcane plantations but only caused 0.5% loss in sugar content (Chen and Yuan, 2010).

Annex 2.A1 gives an overview of these invertebrate pests.

Plant parasitic nematodes are an important factor in the worldwide decline in sugarcane production (Cadet and Spaull, 2003). A large number of species have been identified from sugarcane fields, with one study in Pakistan identifying 25 different

species from newly planted sugarcane crops (Qureshi et al., 2002) and a Kenyan study identifying 14 different genera from sugarcane fields (Chirchir et al., 2011). The impact of nematodes varies between countries, but has been estimated to cause annual yield losses of between 0.2% in Australia, through >5% in South Africa, to 14% in Burkina Faso (Magarey, 1996). However, other estimates of yield losses have suggested that they may cause a 10% loss in plant crops and a 7% loss in ratoon crops in Australia (Blair and Stirling, 2007).

Nematodes also affect the longevity of the crop, with high levels of nematode damage reducing the number of times a field can be economically ratooned (Cadet and Spaull, 2003). The main tools for control are crop management practices such as crop rotation and mulching, but nematicides may also be employed in some countries (Cadet and Spaull, 2003). In Brazil, application of nematicides can increase crop productivity by up to 30% (Copersucar as cited in Cheavegatti-Gianotto et al., 2011) and experiments using nematicides in South Africa showed an 85% increase in yield over untreated fields for some sites with large *Meloidogyne* populations (Cadet and Spaull, 2003). There are also varying amounts of resistance between different sugarcane varieties to attack by nematodes (Chirchir et al., 2011). It has been suggested that the practice of hilling-up used in Australia may reduce nematode damage on ratoon crops due to a larger, below-ground stool (Berry, Spaull and Cadet, 2007). Pre-trashing with stubble retention altered the proportion of nematodes, with an increase in less pathogenic nematodes and therefore reduced crop damage (Berry, Spaull and Cadet, 2007).

Borers are a major pest in sugarcane worldwide, with stalk borers, shoot borers and internode borers having different impacts in different regions of the world. It has been estimated that stem borers account for 10% of world yield losses in sugarcane (Fauconnier, 1993). The moths lay eggs on young leaves and the larvae burrow into the stem, emerging as adults. In young plants, the inner whorl of leaves can be killed resulting in "dead heart", whereas in older plants the tops may die (Capinera, 2010). This leads to a reduction in sucrose content, reduced tillers and provides entry points for diseases (Purseglove, 1972). In South Africa, the stalk-boring pyralid moth *Eldana saccharina* is highly damaging, with economic impacts of this pest in the order of ZAR 60 million/year (Snyman et al., 2008a). A survey in 2006/07 suggested that 40% of fields were affected, with infection rates varying between <10 to >90% between mill areas (Van den Berg et al., 2008).

In India, the borers *Chilo infuscatellus* (shoot borer), *Chilo sacchariphagus* (internode borer) and *Scripophagua excerptalis* (early shoot borer) are major insect pests of sugarcane (Kalunke et al., 2009). The shoot borers (*Chilo* spp.) are major pests in Asia and Africa (Berding, Hogarth and Cox, 2004) The shoot borer (*Chilo infuscatellus*) attacks the crop early in the season (Arvinth et al., 2010) and some control by the parasitoid *Sturmiopsis inferens* has been reported (Srikanth et al., 2009). The sugarcane stem borer *Diatraea saccharalis* has been described as the most important pest of sugarcane (Bennett [1977] as cited by Arencibia et al., 1997) and inflicts severe losses in Brazil (Braga et al., 2003) and Louisiana (Beuzelin et al., 2011). A second *Diatraea* spp., *D. flavipennella*, is also important in Brazil, as is the giant sugarcane borer (*Telchin licus*) (Cheavegatti-Gianotto et al., 2011). *Diatraea* spp. are controlled by release of the parasitoids *Cotesia flavipes* and *Trichogramma galloi* or by chemical sprays, but these are not effective against the giant sugarcane borer (Cheavegatti-Gianotto et al., 2011). Contact insecticides are not effective as the borers are inside the stems (Kalunke et al., 2009). Sugarcane cultivars differ in their resistance to borers (White, 1993).

Sugarcane thrips *Fulmekiola serrata* are widespread in many areas including Asia, Barbados, Madagascar, Mauritius, Réunion, Trinidad and Tobago, and the Bolivarian Republic of Venezuela (summarised in Way et al., 2006). In South Africa, they were first detected in 2004 (Way et al., 2006) and many fields are affected, although the extent of the damage caused is not known (Van den Berg et al., 2008). In South African field trials, some fields showed yield losses of 18-27 t cane per ha (Way et al., 2010). They are thought to have been transferred to South Africa from Mauritius by wind, or via infected planting material (Way et al., 2006). The thrips cause leaf necrosis due to feeding and in young cane leaf tips can become tied together, or brown and wither (Way et al., 2006).

Cane grubs (melolonthine white grubs, larvae of the endemic melolonthine beetle) are major pests affecting the sugarcane industry in some countries. They destroy the roots of the sugarcane plants, preventing water and nutrient uptake and causing lodging (Allsopp, Samson and Chandler, 2000). In Australia, there are 19 native species of cane grub, which cause significant damage in cane fields in different regions, with the greyback canegrub (*Dermolepida albohirtum*) showing the most widespread damage (Robertson et al., 1995). This was estimated to cause a crop loss of 1 million t of cane in the 2000-01 season (Chandler and Tucker, 2010). In Florida, the white grub (*Ligyrus subtropicus*) has been estimated to cause sugarcane yield reduction of 39% (Cherry, 2008).

Several methods can be used for the control of cane grubs (Robertson et al., 1995). In Australia, the application of insecticide or the biological control agent *Metarhizium anisopliae* (a fungus that attacks the larvae) soon after planting controls the species for two to three years. However, in Florida, insecticides and *M. anisopliae* have not shown to be effective in the field so cultural methods such as disking and flooding are used (Cherry, 2008).

In Florida, the corn wireworm (*Melanotus communis*) is a major pest of sugarcane. They are a pest of plant cane and feed on buds and root primordia causing shoot death and also providing an entry-point for disease (Cherry, 2011). One study showed that one wireworm feeding per 1.5 m row of cane leads to 6.2-7.8% stand reduction at 12 weeks, with a larger study showing a 3.8% reduction in yield at harvest (Hall, 1990). In Okinawa and Kagoshima prefectures in Japan, the wireworm known as the sugarcane click beetle larvae (*Melanotus okinawensis*) is a destructive pest (Ohira, 1988; Setokuchi et al. [1990] as cited by Arakaki, Hokama and Yamamura, 2010).

Spittle bugs or frog hoppers (*Mahanarva fimbriolata*) have become a major pest of sugarcane in Brazil following the decrease in cane burning (Korndörfer, Grisoto and Vendramim, 2011). Infestation reduces stalk productivity and in some cases stalk quality (by reducing sugar content and increasing fibre content) (as discussed in Dinardo-Miranda, Pivetta and Vilela Fracasso, 2008). The shorter and thinner stalks have a concomitant yield reduction of up to 16% per ha (de Souza Rossato Jr. et al., 2011).

In Brazil, borers, termites including *Heterotermes tenuis*, migdolus beetle (*Migdolus fryanus*), spittlebugs/froghoppers (*Mahanarva fimbriolata* and *Mahanarva posticata*), sugarcane weevil (*Sphenophorus levis*) and leaf-cutting ants (*Atta* spp. and *Acromyrmex* spp.) are also important pests (Cheavegatti-Gianotto et al., 2011). Brown burrowing bugs (*Scaptocoris castanea*, *S. carvalhoi* and *Atarsocoris brachiariae*) are secondary pests which cause root damage at high infestation levels. Other insect pests of sugarcane which are important in other countries include sugarcane and yellow soldier flies (*Inopus rubriceps* and *Inopus flavus* respectively), wireworms (*Melanotus communis* in Florida (Cherry, 2011), *Agrypnus variabilis*, *Heteroderes* spp. and *Conoderus* spp.,

armyworms including day and night feeding species, as well as loopers (Allsopp, Samson and Chandler, 2000), aphids (e.g. *Melanaphis sacchari* and *Sipha flava* in Louisiana; Akbar et al. [2010]), weevils (e.g. *Metamasius hemiptera sericeus* in West Indies and Florida; Weissling and Giblin-Davis [2010]) and oriental cinch bug (*Cavelerius saccharivorus*) in Japan.

Vertebrate pests

Vertebrate pests including rodents, pigs, birds and large mammals can cause both eating and trampling damage to sugarcane. In some countries rats are a serious pest of sugarcane. They cause yield loss directly by gnawing the cane, but the damage also allows the cane to dry out and provides entry points for bacterial and fungal attack (Dyer, 2005). In addition, rats are known to be carriers of diseases such as the bacterium *Leptospira*, which can result in Leptospirosis disease in humans. Surveys of rodents in sugarcane plantations in Ethiopia identified eight species of rats, with the highest numbers occurring in young plantations (Serekebirhan et al., 2011). Small mammal damage has been seen on up to 4.7% of stalks in the Wonji area of Ethiopia (Serekebirhan et al., 2011). In South America, three species of rat have been implicated in causing damage to sugarcane plantations (Stenseth et al., 2003).

In Australia, during the 1999 and 2000 seasons, ground rats (*Rattus sordidus*) and climbing rats (*Melomys burtoni*) destroyed 825 000 t of sugarcane valued at AUD 25 million (Dyer, 2005). Integrated pest management is now widely employed to discourage and control these economically damaging pests (Smith et al., 2002). Strategies such as controlling crop weeds have been shown to reduce juvenile rat numbers by 50% and reduce crop damage by 60% (Dyer, 2005).

In Pakistan, wild pigs (*Sus scrofa*) are the most important vertebrate pest in sugarcane. They cause damage by knocking over stalks and tearing away the rind to access the soft inner pith. Damage to sugarcane in one district was estimated at 11% of the crop (Brooks et al., 1989). Other vertebrates such as hippopotami (*Hippopotamus amphibius*), warthogs (*Phacochoerus africanus*) and vervet monkeys (*Chlorocebus aethiops*) cause damage to sugarcane crops in Africa (Serekebirhan et al., 2008), wild pigs are important in Australia and Africa, and jackals (*Canis aureus*) cause damage in India (Purseglove, 1972). Warthogs eat lower internodes of cane and also destroy stalks whilst moving through the plantations. Vervet monkeys remove younger cane and carry it to trees to eat (Serekebirhan et al., 2008).

Pathogens

Various biological agents including bacteria, fungi, viruses and phytoplasma cause diseases of sugarcane. Important diseases of sugarcane that have been identified worldwide are listed in Annex 2.A2. Diseases often lead to large yield losses. For example in China, sugarcane smut, ratoon stunting disease (RSD), mosaic and other diseases cause a greater than 20% reduction in production (Chen and Yuan, 2010). In Australia, losses due to disease are AUD 67 million from a gross value for sugarcane of AUD 2 100 million (Chakraborty et al., 1998).

In South Africa, the fungal pathogen *Usilago scitaminea* (causal agent of smut) and the sugarcane mosaic virus (SCMV) were listed as amongst the most important biotic challenges that sugarcane faces along with the insect stalk borer *Eldana saccharina* (Butterfield et al., 2004; Rutherford et al., 2003).

Disease control in sugarcane is based on resistant cultivars and management procedures. Short-term spraying options are available, but their economic viability may not be sustained. Hygiene is important to disease management strategies, particularly for diseases transmitted through cuttings such as RSD and leaf scald. Cutting one infected stalk may lead to significant infection to the next 100 cuttings, which are subsequently cut by the same blade (Croft, Magarey and Whittle, 2000). Machine harvesters can also transmit disease.

Many sugarcane diseases are also managed through the use of disease-free planting material. Hot-water treatments are used to disinfect planting material. In Australia, long hot-water treatment (three hours at 50ºC) is used to control RSD. Soaking in ambient temperature running water for ~40 hours followed by 3 hours at 50°C is used to control leaf scald bacteria. Short hot-water treatment (50ºC for 30 minutes) is used to control chlorotic streak and some insect pests (Croft, Magarey and Whittle, 2000). In Brazil, a shorter, hotter treatment is used for RSD (52ºC for 30 minutes) (Fernandes Jr. et al., 2010).

Predictions have been made on the impact of climate change on the spread and importance of sugarcane diseases. It has been suggested that the major diseases of sugarcane will not be affected by climate change as they are systemic and spread by human intervention; however, for some diseases such as leaf scald the increased severity and frequency of cyclones and storms may allow it to spread more readily (Sanguino, 2008 as discussed in Ghini, Bettiol and Hamada, 2011). Conversely, the predicted reduced soil temperatures in some regions may reduce the range of diseases such as pineapple disease (*Ceratocystis paradoxa*) (Chakraborty et al., 1998).

Bacterial diseases

RSD is probably the most important disease of sugarcane. It is a highly infectious disease caused by *Leifsonia xyli* (formerly named *Clavibacter xyli* subsp *xyli*), which infects vascular tissues of sugarcane. It has been identified in most countries that grow sugarcane. The symptoms are poor growth and stunted shoots, which might not be obvious if most plants in the field are infected. It has been suggested that a 5-15% yield loss can occur without growers realising that they have the disease (Comstock and Gilbert, 2009). The visual symptoms of red-orange dots in the vascular tissues can be seen only when the stalks are cut and sliced (Croft, Magarey and Whittle, 2000). The disease is transmitted by healthy plants coming in contact with diseased plant material or contaminated cutting implements. Yield loss is higher in dry weather and often becomes more severe in subsequent ratoon crops (Frison and Putter, 1993). In Florida, resistant clones have been used to control the disease (Comstock and Gilbert, 2009).

Leaf scald is caused by the bacterium *Xanthomonas albilineans*, which infects the vascular tissues of sugarcane. It is found in many countries and is thought to have originated in the Old World but had spread to Brazil by 1944 and Guyana by 1950 (Purseglove, 1972). However, it is hard to identify and the disease often has a latent period after infection. Leaf scald is characterised by a long white to cream streak on the leaves. Severely infected leaves appear scalded and roll inwards, with the top of the shoots becoming chlorotic. Yield loss occurs through the death of infected cane stalks and poor ratooning (BSES Ltd., 2012c). Leaf scald can spread by windblown rain, plant material and contaminated cutting equipment such as planters and harvesters (Croft, Magarey and Whittle, 2000; Daugrois et al., 2011). Leaf scald can infect many other grasses which are alternate hosts and act as a reservoir for the disease. Extremes of moisture and temperature favour disease transmission. In Australia, resistant cultivars are

used to curb the spread of the disease and susceptible plants are not used in breeding programmes (BSES Ltd., 2012c).

Fungal and oomycete diseases

The two major rusts in sugarcane are orange and brown (previously known as common) sugarcane rusts (Braithwaite et al., 2009). Orange rust is caused by *Puccinia kuehnii* and is not generally as economically important as the common rust, caused by *P. melanocephala*. These are both obligate parasitic fungi spread by windblown spores. The disease symptoms of the two rusts are distinct. Pustules of the orange rust are orange and tend to be grouped in clusters, while those of brown rust are reddish brown and are distributed evenly on leaves. Pustules rupture the leaves and allow water to escape from the plant, leading to moisture stress (Croft, Magarey and Whittle, 2000). Both diseases are most severe in humid environments with temperatures below 25°C (Walker, 1987).

Brown rust appeared in Australia and the Caribbean in the 1970s. Yield loss from brown rust depends on environmental conditions and was estimated to cause an economic loss in Australia of AUD 3.5 million in 1996 (McLeod, McMahon and Allsopp, 1999) and a yield loss of 20-40% in the United States (Raid and Comstock, 2006). In South Africa, brown rust is common in the Midlands area of KwaZulu Natal (Zhou, 2013).

In the 1999-2000 season, sugarcane crops in Australia were affected by an outbreak of orange rust, which severely damaged the most widely grown commercial cultivar, Q124 (Croft, Magarey and Whittle, 2000). Orange rust was identified from 2007-09 in Mexico, Florida and Central America (Chavarría et al., 2009; Comstock et al., 2008; Flores et al., 2009) and recently in Brazil (Cheavegatti-Gianotto et al., 2011). These diseases are usually controlled by the use of resistant cultivars (Berding, Hogarth and Cox, 2004), although some resistant cultivars have been overcome, presumably due to rust variants (Raid and Comstock, 2006). Yield losses occur due to reduction in leaf photosynthetic components (Zhao et al., 2011).

Sugarcane smut, caused by *Ustilago. scitaminea*, is a serious disease of sugarcane that can reduce yields by 30-100% (BSES Ltd., 2012e). Infection occurs through the sugarcane buds from windblown spores (Walker, 1987). The disease causes severe stunting and multiple thin stalks. It is characterised by black, whip-like structures that form at the growing points of sugarcane plants (Croft, Magarey and Whittle, 2000) (Figure 2.7).

These whips replace the spindle leaves and are formed in the shoots developing from infected cane cuttings (Frison and Putter, 1993). The whips break open to release the mature spores which are spread by wind (BSES Ltd., 2012e). Smut was confined to Asia and southern Africa until the 1970s when it spread to other countries, reaching Australia in 1998, and now only Fiji and Papua New Guinea do not have the disease (Berding, Hogarth and Cox, 2004). In South Africa, smut is more common in northern irrigated areas with losses varying depending on the variety, crop stage and growing conditions (Van den Berg et al., 2008).

In Australia, the spread and occurrence of the disease is being controlled through planting resistant cultivars, using uninfected seed canes and removing infected crops (BSES Ltd., 2012b). In South Africa, the disease is partly controlled by a compulsory plough-out if greater than 10% of the crop is affected (Van den Berg et al., 2008). In Brazil, pre-plant fungicide treatment and rogueing of infected plants are used to control smut (Cheavegatti-Gianotto et al., 2011).

Figure 2.7. **Smut on *Saccharum* spp. hybrid in Bundaberg**

Source: Courtesy staff at OGTR, taken in 2010.

Other fungal diseases of sugarcane are minor (see Annex 2.A2) and cause less impact on yield.

Viral diseases

Sugarcane can be affected by a number of viral diseases (see Annex 2.A2).

Chlorotic streak is thought to be caused by a virus. The disease occurs in many countries, especially in wet and poorly drained fields (Croft, Magarey and Whittle, 2000). The symptoms are yellow to white streaks on the leaf, midrib and leaf sheath. Older streaks change to yellow and are more visible than younger streaks. This is followed by the appearance of chlorosis in the middle of the leaves. Internal vascular bundle tissues may be reddish in colour (Croft, Magarey and Whittle, 2000). The disease is transmitted by soil water and diseased seed cane. In Australia, a lower incidence of the disease is generally found in drier areas (Croft, Magarey and Whittle, 2000). Yield losses may be up to 40%, with waterlogging compounding the losses. Ratooning may also be poor (BSES Ltd., 2012a).

Fiji leaf gall (previously called Fiji leaf disease) is caused by Fiji disease virus (FDV) and can lead to stunting and death of infected plants (Ridley et al., 2006). The initial symptoms are whitish galls raised on the underside of the leaf blade and midrib. Galls are produced due to the disorder of cell proliferation in the phloem and xylem. Galls can vary from white to green and the surface is usually smooth. When the gall is old, the epidermis may be ruptured and appear brown. At an advanced stage of infection, stem development slows down. Successive leaves become smaller and stiffer with the whole top part of the stem developing a fan-like appearance (Croft, Magarey and Whittle, 2000). Fiji disease can be transmitted by infected cuttings and plant hoppers (*Perkinsiella saccharicidae*) are a known vector for the disease. The disease originated in Fiji and has spread to Australia and Madagascar (Berding, Hogarth and Cox, 2004; Walker, 1987). Significant yield loss was recorded in the 1970s in Australia (Croft, Magarey and Whittle, 2000), but due to the intensive management programme put in place, there have been no reports of disease incidence since the 1980s.

Worldwide, sugarcane mosaic is caused by a number of potyviruses, such as SCMV.

The mosaic symptom pattern appears in young growing leaves. Once the leaves are older, infected leaves may appear relatively normal as the mosaic becomes green. Aphids transmit the disease, as can seed produced by infected cane. Mosaic is a serious problem in sub-tropical countries such as Argentina, Pakistan, South Africa and in southern Brazil and Louisiana (Butterfield et al., 2004; Walker, 1987). Currently in Australia, only the SCMV strain A is present, which is a mild form of the virus (BSES Ltd., 2012f). However, yield loss caused by sugarcane mosaic was 40% in some fields in Australia (Croft, Magarey and Whittle, 2000). Another virus, sugarcane streak mosaic virus (SCSMV), which produces similar symptoms, has been identified in Indonesia (Damayanti and Putra, 2011).

Sugarcane yellow leaf virus (ScYLV) causes yellowing of leaves and in severe infections the plant growth is stunted (Gilbert et al., 2009). It is caused by a luteovirus which is transmitted by aphids (Scagliusi and Lockhart, 2000) or by infected stem pieces. High rates of infection have been reported from sugarcane growing regions of South and Central America as well as in the United States (as reviewed by Gilbert et al., 2009) Thailand (Lehrer, Wu and Komor, 2009; Lehrer, Kusalwong and Komor, 2008), Réunion Island (Rassaby et al., 2003) and northern parts of South Africa (Rutherford, Brune and Nuss, 2004). In Brazil, losses of up to 50% in one variety in cooler regions have been reported (Comstock et al., 1994) and up to 37% yield reduction in Réunion Island (Rassaby et al., 2003).

Phytoplasma diseases

Sugarcane can be affected by a number of diseases caused by phytoplasmas (see Annex 2.A2). Phytoplasmas are small wall-less prokaryotes which infect phloem tissues. In sugarcane they cause a number of diseases including sugarcane white leaf (SCWL), sugarcane grassy shoot (SCGS), sugarcane green grassy shoot (SCGGS), sugarcane yellow leaf syndrome (SCYLS) and Ramu stunt (SCRS). The diseases are transmitted by insect vectors feeding on phloem which include leaf hoppers, plant hoppers and psyllids (Marcone, 2002).

Sugarcane white leaf disease occurs in Asia, is a major disease in Thailand and was confirmed in 2001 in Sri Lanka (Kumarasinghe and Jones, 2001). Infected leaves appear white and are narrower and smaller than uninfected leaves; the plants show stunting and profuse tillering (Marcone, 2002). The disease is spread between plants by a leaf hopper (*Matsumuratettix hiroglyphicus*), which acts as a reservior for the phytoplasma and transmits it transovarially to its offspring (Hanboonsong et al., 2002).

Sugarcane grassy shoot is a major disease in India, but also occurs in Bangladesh, Malaysia, Nepal, Pakistan, Sri Lanka and Sudan (reviewed in Marcone, 2002). Disease symptoms include the formation of many overcrowded, thin, soft-textured tillers with chlorotic or yellow leaves. After ratooning, the infected crop resembles a field of grass due to the short tillers (Marcone, 2002). A similar disease has been observed in Thailand, but without the associated leaf coloration, named sugarcane green grassy shoot (Marcone, 2002).

Other biotic interactions

Sugarcane may have symbiotic relationships with a number of bacteria that fix nitrogen (de Carvalho, Gomes Ferreira and Hemerly, 2011).

In Brazil, sugarcane is grown with low nitrogen inputs (50 kg per ha) compared to some other countries, which use >200 kg per ha (Boddey et al., 1991). Until recently, cane was burnt before harvesting in Brazil (see above), so little nitrogen was returned to the field. This low level of nitrogen fertiliser has led to the suggestion that some cultivars of sugarcane can obtain nitrogen via biological nitrogen fixation (BNF). The occurrence of BNF has been suggested in several pot studies where some cultivars of sugarcane have thrived for several generations without the addition of nitrogen (Boddey et al., 1991; Urquiaga, Cruz and Boddey, 1992). Differences were seen between plant genotypes, but it was estimated that BNF could account for 25-60% of the nitrogen assimilated in one study (Boddey et al., 2001) and up to 70% in another study (Urquiaga, Cruz and Boddey, 1992). The organisms responsible for this have not been unequivocally determined. Studies have focused on endophytic bacteria such as *Gluconacetobacter diazotrophicus* (previously called *Acetobacter diazotrophicus*); however, these bacteria were not shown to be producing nitrogenase *in planta* (James et al., 2001). Despite this, a study using *G. diazotrophicus*-inoculated plants found large increases in nitrogen fixation under nitrogen-deficient conditions. This nitrogen fixation did not occur after inoculation with a mutated nitrogenase deficient form of the bacterium (Sevilla et al., 2001).

G. diazotrophicus may also play a role in defence against sugarcane pathogens. It inhibited *in vitro* growth of *Colletotrichum falcatum* (red-rot) (Muthukumarasamy, Revathi and Vadivelu, 2000) and *Xanthomonas albilineans* (leaf scald) (Blanco et al., 2005; Piñón et al., 2002). Additionally, *G. diazotrophicus*-inoculated sugarcane stems were resistant to infection by *X. albilineans* (Arencibia et al., 2006). Inoculation with *G. diazotrophicus* also improved sett germination (sprouting), tiller number and plant height (Suman et al., 2005). There is also some evidence that it may promote sugarcane growth by production of a growth-promoting factor (Sevilla et al., 2001), such as auxin (IAA; indole-3-acetic acid) or by solubilisation of mineral nutrients (as reviewed in Saravanan et al., 2008).

Other bacterial species have been isolated from sugarcane that may play a role in nitrogen fixation including *Agrobacterium diazotrophicus* (Xing et al., 2006), *Herbaspirillum* spp. (Reis, Lee and Kennedy, 2007), *Azospirillum* spp. (Baldani et al., 1997), *Bradyrhizobium* spp. and *Azorhizobium caulinodans* (Thaweenut et al., 2011) and *Burkholderia vietnamiensis* (Govindarajan et al., 2006). Experiments have shown that co-inoculation of *G. diazotrophicus* and *Herbaspirillum* spp. gave enhanced sugarcane biomass compared to inoculation with either the single species, or to uninoculated controls (Muthukumarasamy et al., 2006). Inoculation with an endophyic *Pantoea agglomerans* strain isolated from eucalypts also showed growth promotion in glasshouse trials (Quecine et al., 2012). Field surveys in Brazil, Japan and the Philippines suggested that up to 70% of plant nitrogen was from BNF (Boddey et al., 2001; Yoneyama et al., 1997). Newly developed sugarcane farms showed lower amounts of BNF than some of the established farms (Yoneyama et al., 1997). However, a field-based experiment and surveys of sugarcane fields in Australia showed no evidence of BNF as a source of nitrogen (Biggs et al., 2000). Similarly in South Africa, BNF fixation was not shown to contribute to the available nitrogen (Hoefsloot et al., 2005).

Vesicular-arbuscular mycorrhizal fungi (VAM) have been found in sugarcane fields in association with sugarcane roots. These fungi are known to colonise plant roots and may supply the plant with mineral nutrients, especially phosphorous. Pot experiments, using soil and mycorrhizal spores from cane fields, showed that the addition of VAM increased the yield of soybean and maize (corn) plants. However, no effects have been seen on sugarcane growth from addition of the VAM *Glomus clarum* at various

phosphorus levels in pot experiments (Kelly et al., 2005; 2001). Similar experiments in wheat have shown that although there is no increased yield following root colonisation with VAM, 50% of the phosphorus in the plants had been absorbed via the VAM (Li et al., 2006). Field experiments in South Africa have observed a correlation between soils with high VAM and improved nutrient levels in sugarcane plants (Jamal et al., 2004). In Pakistan, VAM colonisation has also been correlated with reduced severity of red rot (*Colletotrichum. falcatum*) disease (Nasim et al., 2008).

Weediness

Weeds are plants that spread and persist outside their natural geographic range or intended growing areas such as farms or gardens. Weediness is often correlated with weediness of the plant, or a close relative, elsewhere in the world (Groves, Boden and Lonsdale, 2005; Panetta, 1993; Pheloung, Williams and Halloy, 1999). The likelihood of weediness is increased by repeated intentional introductions of plants outside their natural geographic range that increase the opportunity for plants to establish and spread into new environments (e.g. escapes of commonly used garden plants) (Groves, Boden and Lonsdale, 2005).

Modern *Saccharum* spp. hybrid cultivars do not possess many of the attributes commonly associated with problematic weeds such as seed dormancy, persistence in soil seed banks, germination under adverse environmental conditions and a short life cycle (Baker, 1974; Keeler, 1989; Keeler, Turner and Bolick, 1996).

Weediness status on a global scale

An extensive compilation of the world's weed flora is produced by Randall (2002). Most of the information contained in this book has been sourced from Australia and North America, but also includes numerous naturalised floras from many other countries. Randall (2002) lists 12 species of *Saccharum* which have been identified as having a documented weedy history. However, due to species reclassifications, many of these species are now known by alternative names and are no longer in the *Saccharum* genus as described in Table 2.1. The sugarcane parent species, *S. officinarum*, is listed as naturalised, introduced, a casual alien, an economic weed and a quarantine weed in some countries, but has not been recorded as a major weed (Berville et al., 2005; Holm et al., 1997; Lazarides, Cowley and Hohnen, 1997; USDA, 2013b).

The other sugarcane parent species, *S. spontaneum*, is listed by Randall (2002) as naturalised, introduced, a casual alien, an economic and environmental weed, a noxious weed and a quarantine weed in some countries. *Saccharum spontaneum* is listed as one of the 104 most important world weeds by Holm et al. (1997).

S. spontaneum is native to India and recorded as a weed in 33 countries. It has adapted to diverse environments throughout the world, ranging from tropical to sub-tropical regions, most commonly found in central and south-eastern Asia (Holm et al., 1997). *Saccharum spontaneum* is a serious agricultural weed in India, Indonesia, the Philippines and Thailand where it competes vigorously on disturbed sites (Holm et al., 1997). It occurs in wastelands, fallow fields, marshes, on banks of streams and ponds, on sand dunes, along railroads and highways, and in or around agricultural fields. Pure stands of *S. spontaneum* can be found in poor agricultural soils, degraded by fire and overuse (Hammond, 1999; Holm et al., 1997). It is present in Central and South America, Puerto Rico, Florida and Hawaii. In the Panama Canal watershed, it dominates land that is not under cultivation (Hammond, 1999). It is recorded as a noxious

weed in the United States (USDA-NRCS, 2013). Naturalised populations of *S. spontaneum* have been recorded at several locations in Queensland and the Northern Territory in Australia (Bonnett et al., 2008; Magarey et al., 2007), some which have been deliberately planted.

The hybrid of these two species grown as cultivated sugarcane has not been recorded as a major weed (Berville et al., 2005; Holm et al., 1997; USDA, 2013b).

In both Australia and Brazil, sugarcane has been reported as occurring almost exclusively in managed cultivation. In sugarcane growing districts, transient sugarcane plants may occur around fields, but there is no indication that these form self-perpetuating populations (Bonnett et al., 2007; Cheavegatti-Gianotto et al., 2011). Thus, sugarcane does not appear to be a problem as a volunteer weed (Berville et al., 2005).

Saccharum spp. hybrids are not generally recognised as weeds. They have lost many of the critical weedy attributes such as profuse tillering, adaptability to biotic stresses and resistance to pests and diseases that were present in the parental species from which the cultivated sugarcane hybrids were derived. Setts need adequate soil fertility, soil moisture and temperature for germination (sprouting) (Smit, 2011). As discussed earlier in this chapter, most of the cultivated cultivars exhibit low fertility of both pollen and ovules, so flowers in commercial fields rarely set seed (James, 2004). However, data from Bonnett et al. (2008) and Cheavegatti-Gianotto et al. (2011) suggest that viable seed production does occur at low levels in commercial fields in both Australia and Brazil. The literature also suggests that sugarcane seeds need optimum conditions for germination and survival of the resulting seedlings. These conditions may only occur sporadically in natural ecosystems, thus limiting the spread and persistence of sugarcane.

Control measures

Sugarcane plants can be killed by ploughing out the stools and then treating with herbicide (glyphosate) (Willcox, Garside and Braunack, 2000). However, minimum tillage practices often result in inadequate eradication of the old crop (Leibbrandt, 1993). The efficacy of glyphosate for killing sugarcane is affected by various factors, such as cane being in active growth, cane cultivars, soil type and stage of cane growth (Turner, 1980). Sugarcane grown in light soils is more susceptible to herbicide treatment than that grown on heavy soils. The plant is killed more easily when the height of the leaf canopy is between 0.4-0.75 m compared with older cane that has produced stalks (Turner, 1980). Glyphosate is ineffective on recently cut ratoons until germination (sprouting) of buds is completed and tillering is advanced (Chedzey and Findlay, 1985). Rain may also affect the efficacy of herbicide, so it is more effective when used during the dry season (Owende et al., 1995). Research has shown that slashing of cane suppresses apical dominance and generally enhances chemical cane killing action on the regrowth. In addition, considerable improvement of eradication was also obtained when a mechanical under-cutter was used to shear the roots following herbicide application (Leibbrandt, 1993).

Hybridisation

The possibility of genes transferring from *Saccharum* spp. hybrid to other organisms is addressed below. Potentially, genes could be transferred to: cultivated sugarcane populations, other cultivated and naturalised *Saccharum* species, other plant genera and other organisms. For gene transfer beyond the species, potential barriers must be overcome before gene flow can occur successfully. Pre-zygotic barriers include

differences in floral phenology, different pollen vectors and different mating systems, such as stigmatic or stylar incompatibility systems. Post-zygotic barriers include genetic incompatibility at meiosis, selective abortion, lack of hybrid fitness, and sterile or unfit backcross progeny. Even where pre-zygotic and post-zygotic barriers do not exist, physical barriers created by geographic separation can still limit gene transfer to other plants.

Successful gene transfer requires that three criteria are satisfied. The plant populations must: 1) overlap spatially; 2) overlap temporally (including flowering duration within a year and flowering time within a day); and 3) be sufficiently close biologically that the resulting hybrids are fertile, facilitating introgression into a new population (den Nijs, Bartsch and Sweet, 2004).

Intraspecific crossing

The fertility of the commercial sugarcane cultivars is currently poorly understood. This is mainly because seeds are not the primary product of this crop, nor are they used for propagating sugarcane. In addition, asynchronous flowering, both within and between cultivars, makes hybrid seed production in the field ineffective (James, 1980).

As indicated earlier in this chapter, sugarcane flowering is variable in the field and the crop is exclusively vegetatively propagated. Different cultivars of sugarcane produce different amounts of pollen. Self-pollination does occur, which can prevent outcrossing. The frequency of self-pollination can vary widely depending on the parent, with two studies showing 20-100% and 83-100% outcrossing rates in controlled crosses (Hogarth, 1980; McIntyre and Jackson, 2001).

No insect or animal vectors for sugarcane pollen are known. Pollen viability is low and of short duration under natural environmental conditions (Moore, 1976). Even under artificial conditions, storage of sugarcane pollen is difficult and has been the subject of intensive investigations by sugarcane breeders, where the aim is to store valuable pollen. Little data are available on sugarcane pollen dispersal. Information from breeding work in which plants were isolated by 20 m resulted in 3% and 50% of the offspring respectively being the result of out-crossing (Skinner, 1959). From this work, it was suggested that to prevent contamination of controlled crosses, plants should be isolated by 100 m in open forest, or 300 m in the open (Skinner, 1959).

Flowering and viable pollen production are both temperature dependent, which impacts on the degree of crossing expected in different areas.

Natural interspecific and intergenic crossing

Sugarcane is closely related to the genera *Erianthus*, *Narenga*, *Miscanthus* and *Sclerostachya*. These genera and *Saccharum* are collectively known as the *Saccharum* complex and are expected to be sexually compatible at some levels (Bull and Glasziou, 1979; Daniels and Roach, 1987; Grassl, 1980). There are also reports of sugarcane crossing under controlled conditions with species outside of the *Saccharum* complex (discussed below).

Natural interspecific crossing

As discussed above there is likely to be sexual compatibility between *Saccharum* spp. These species are indigenous to different regions of the world, for example *S. barberi* is native to India and *S. sinense* to China (Sreenivasan et al., 1987). *Saccharum robustum* is

indigenous to Papua New Guinea and adjacent islands of Melanesia (Sreenivasan et al., 1987). *Saccharum spontaneum* has a very wide distribution, extending from Afghanistan in the west to the Malay Peninsula, Chinese Taipei and the South Pacific Islands in the east. The final *Saccharum* species, *S. edule*, is restricted to Papua New Guinea and neighbouring islands, but is unable to reproduce sexually due to the immature unopened (aborted) inflorescence (Nair and Ratnambal, 1970).

Many of these species may also be found elsewhere in the world. Some of these species are maintained within sugarcane research stations as germplasm stocks and have been used in breeding programmes to produce new cultivars. In many countries they are likely to be close to areas in which *Saccharum* spp. hybrid is cultivated. However, no published data have been found on the natural occurrence of interspecific hybrids of modern cultivars.

Natural intergenic crossing

As indicated above, the genera *Erianthus*, *Imperata*, *Narenga*, *Miscanthus* and *Sclerostachya* are expected to be sexually compatible at some levels with sugarcane (Bull and Glasziou, 1979). However, in order to cross naturally with the *Saccharum* spp. hybrid the two species need to be located in close proximity and flower at the same time.

Erianthus spp. are distributed discontinuously in Asia, America, the Mediterranean, and the Polynesian islands (Sreenivasan et al., 1987). *Erianthus rockii* is a wild species originating in the Yunnan, Sichuan and Tibetan regions of China (Aitken et al., 2007). *E. alopecuroides*, *E. strictus*, *E. contortus*, *E. coarctatus* and *E. giganteus* are all native to North America (Burner and Webster, 1994). *E. arundinaceus* is distributed in Bhutan, India, Indonesia, Laos, Malaysia, Myanmar, Sri Lanka, Thailand, Viet Nam, the Ryukyus in Japan and south China (Anon, 2011; Chen and Phillips, 2006). They may also be present in sugarcane research station germplasm collections for use in sugarcane breeding.

Miscanthus is distributed from India to Japan (Sreenivasan et al., 1987). A number of *Miscanthus* species are sold as garden plants, so may be more widely distributed. Some groups of *S. robustum* are thought to be products of a spontaneous hybridisation event between *S. spontaneum x Miscanthus* hybrids, in areas where both species occur naturally (Sreenivasan et al., 1987).

Imperata spp. have a wide distribution worldwide and have been identified as a weed of cultivation (Sreenivasan et al., 1987). Some species are sold as garden plants so may be more widely distributed.

Narenga porphyrocoma is found widely in north-east India (Janaki-Ammal, 1942). It has been suggested that the wild cane Hitam Rokan, collected in Sumatra, is a naturally occurring hybrid of *Saccharum* and *Narenga* (Janaki-Ammal, 1942). This suggestion was based on morphological similarity to known synthetic hybrids but has not been confirmed by molecular methods.

Sclerostachya fusca is found widely distributed in India from Kashmir to Bengal and Assam and also in the western Ghats (Parthasarathy, 1948).

Other species which have reports of sexual compatibility outside the *Saccharum* complex such as maize (corn) and sorghum are present in countries in which sugarcane is grown.

This suggests that many of these species are present in sugarcane growing areas, so there may be potential for crossing to occur. However, no modern natural hybrids have been recorded and, as discussed in the next section, viable hybrids with these species have only been produced under experimental conditions using large numbers of plants, often with male sterility to prevent self-pollination.

Crossing under experimental conditions

Species in Saccharum *complex*

There is limited data available on crosses between *Saccharum* spp. hybrid and other species. Data are presented on crosses with *Saccharum*, *Erianthus*, *Miscanthus*, *Bambusa*, *Sorghum* and *Imperata*. Information on crosses performed with the parent species, *S. spontaneum* and *S. officinarum* is included in this section as it may be indicative of the potential for successful crossing with the hybrid.

Saccharum

Successful controlled crosses have been obtained using pollen from commercial *Saccharum* spp. hybrid and *S. spontaneum* as the female parent. This required heat emasculation of *S. spontaneum* to reduce self-pollination (Pan et al., 2004). No data are available on natural crossing with fertile parents.

Erianthus

A number of species of *Erianthus* have been used for crossing with sugarcane. There is an early report of a cross between *S. spontaneum* and *E. ravennae*, which produced fertile hybrids, although these were not confirmed by molecular methods (Janaki-Ammal, 1941).

Crosses between *Erianthus arundinaceus* and *Saccharum* spp. hybrid produced putative intergenic hybrids which had characteristics from the male *Erianthus* parent. However, these were shown to be selfed progeny which did not possess isozyme marker bands characteristic of *Erianthus* (Lee et al., 1998). A small number of successful crosses were made between *Saccharum* spp. hybrid and *E. arundinaceus* (Lee, Berding and Bielig, 1993). Of 96 attempted crosses between *E. arundinaceus* and *S. officinarum* or hybrid *Saccharum* spp., 26 were successful producing over 1 000 seedlings. Thirty-seven of the seedlings were identified as genuine hybrids, but only 19 survived, all derived from *S. officinarum* as a female parent and *E. arundinaceus* as a male parent. All of these hybrids had poor vigour, were sterile and showed chromosome elimination (Piperidis et al., 2000). Nonetheless, Cai et al. (2005) have successfully identified a fertile intergeneric cross between *E. arundinaceus* and *S. officinarum* using microsatellite markers and 5S rDNA. Genomic slot blot hybridisation (GSBH) has also been used to confirm hybrids between *S. officinarum* (as the female parent) and *E. arundinaceus* (as the male parent) and to determine that 43% of the F_1 progeny were selfs (Besse et al., 1997). Isozyme electrophoresis, sequence-tagged PCR, RFLP and GISH have also been used to confirm intergenic hybrids of *S. officinarum x E. arundinaceus* (D'Hont et al., 1995).

Crosses have been performed with *E. rockii*. These used *S. officinarum* or *S. officinarum* x *S. spontaneum* as the female parent to produce viable hybrids (Aitken et al., 2007). Seed was tested using DNA markers which confirmed the following crosses: *S. officinarum* with *E. arundinaceus*; *Saccharum* spp. hybrids with

E. arundinaceus; and *Saccharum* spp. with *E. rockii* (Foreman et al., 2007). Similarly, crosses between *Saccharum* spp. hybrids and *E. fulvus*, using the *Saccharum* spp. as the female parent, have produced hybrids, confirmed using sequence-characterised amplified region (SCAR) markers (Wang et al., 2009). Hybrids of *S. officinarum* and *Erianthus procerus* have also been generated (Rajeswari et al., 2009).

Crosses have also been performed using elite sugarcane cultivars as the female parent with North American *Erianthus* spp. *E. alopecuroideum*, *E. contortus* and *E. giganteus*. Seed was produced, but it is not known if the progeny were true hybrids (Burner and Webster, 1994).

Narenga

Crosses have been made between *Narenga porphyrocoma* and *S. spontaneum* (Kandasami, 1961). Analysis of hybrids between *N. porphyrocoma* and *S. officinarum* showed intermediate characteristics and low male and female fertility (Janaki-Ammal, 1942). Hybrids from a cross between *S. officinarum* and *N. porphyrocoma* showed viable pollen in tissue culture, although were not verified by molecular methods (Krishnamurthi, 1993).

Miscanthus

Hybrids have been reported from crosses between *Miscanthidium violaceum* (= *M. flavescens*) and *Saccharum* spp. hybrids (Brett, 1954) and crosses and backcrosses between *Miscanthus sinensis*, *Miscanthus floridulus* and *Saccharum* spp. hybrids (Tai et al., 1991). Other crosses with *Miscanthus* have been verified by *Alu*-PCR, using short interspersed nuclear elements (SINE) (Alix et al., 1999).

Sclerostachya

Parthsarathy (1948) reported a cross between *Saccharum officinarum* and *Sclerostachya fusca*. Further crosses between *Saccharum officinarum* and *Sclerostachya fusca* have also been performed. An F_1 hybrid with these two parents has been described as containing 55 chromosomes, and used in tissue culture to regenerate plantlets (Sreenivasan and Sreenivasan, 1984). Four crosses between *Saccharum spontaneum* and *Sclerostachya fusca* have been described, which produced 79 offspring (Kandasami, 1961).

Species outside *Saccharum* complex

Hybridisation with *Saccharum* has also been attempted with some members of distantly related genera belonging to tribe Andropogoneae, such as *Imperata cylindrica* (blady grass or lalang), *Sorghum* spp. and *Bambusa arundinaceae* (bamboo) (Janaki-Ammal, 1938a; Nair, 1999; Rao et al., 1967; Thomas and Venkatraman, 1930) as well as *Zea mays* (maize) from the tribe Maydeae (Janaki-Ammal, 1941; 1938a). In some of these reports, intergenic hybrids were claimed; however, some could not be accepted as true hybrids (Bonnett et al., 2008; Grassl, 1980). As discussed in Bonnett et al. (2008), altered morphological characters and chromosome numbers can occur in self-pollination and are not in themselves proof of hybrid production.

Maize (corn)

A cross was reported between *Zea mays* and *Saccharum officinarum*, using male sterile sugarcane as the female parent (Janaki-Ammal, 1941; 1938a). This plant was sterile, had 52 chromosomes, was morphologically different from both parents and

resolved from both parents based on cluster analysis of random amplification of polymorphic DNA (RAPD) markers (Janaki-Ammal, Jagathesan and Sreenivasan, 1972; Janaki-Ammal,1941, 1938a; Nair et al., 2006, 2005). Another report suggested that the hybrid embryos of maize and sugarcane aborted during development. This was partially overcome by embryo culture, although all the seedlings died when transferred to soil (Hrishi and Marimuthammal, 1968).

Bamboo

Early crosses of *Bambusa arundinacea* with two *Saccharum* spp. hybrids produced 29 hybrids (Venkatraman, 1937). Histological analysis showed that the hybrids had altered chromosome numbers from the parents, and many of the hybrids were male sterile (Janaki-Ammal, 1938b). A cross of *B. arundinacea* with *S. officinarum* produced two progeny (Raghavan, 1952). However, it has been suggested that neither of these were genuine hybrids (Grassl, 1980; Nair and Ratnambal, 1970). Histological analysis of crosses between *B. arundinacea* and *S. officinarum*, *S. robustum*, *S. spontaneum* or seven *Saccharum* hybrids indicated that with *Saccharum* as a female parent, the hybrid embryos aborted during the early embryogenic stage (Rao et al., 1967). Four mature putative hybrid seeds were obtained from 960 crosses using *B. arundinacea* as a female parent, all with either *S. spontaneum* or *S. robustum* as male parents. These either failed to germinate from seed or produced abnormal seedlings which did not survive (Rao et al., 1967).

Sorghum

Sorghum species have been artificially crossed with *Saccharum* spp. hybrids and *S. officinarum* (Grassl, 1980; Gupta, Harlam and de Wet, 1978; Nair, 1999; Thomas and Venkatraman, 1930). These studies used *Saccharum* spp. as both the female or male parent and often used large numbers of sterile lines. Four hybrids were produced using *S. officinarum* as the male parent (Nair, 1999). One of the sterile hybrids was induced to flower by gamma irradiation of calli, and appeared to be female fertile, although male sterile (Sobhakumar and Nair, 2005).

Generally, the hybrid offspring have been of low vigour and fertility, but backcrossing to both parents has been achieved (Grassl, 1980; Sreenivasan et al., 1987). However, Grassl (1980) recorded that after the fourth to fifth generation of backcrossing to *Sorghum*, the sugarcane chromosomes had been eliminated from the intergeneric hybrids. The initial reports used morphological and cytological characteristics to identify hybrids, but more recent work has used RAPD molecular markers to confirm that the hybrids are genuine (Nair et al., 2006; 2005).

Experiments using different *Sorghum* species have shown that pollen-pistil incompatibility is the major barrier to the production of *Sorghum* hybrids (Hodnett et al., 2005). Consequently, breeding work using a *Sorghum* IAP (inhibition of alien pollen) mutant in which the incompatibility is removed as the female parent has produced a number of hybrids with *Saccharum* spp. The hybrid seed produced needed careful management to avoid either vivipary or lack of germination due to an impenetrable seed coat. The hybrids had varied phenotypes from very poor growth to very vigorous, though two of the vigorous plants were male sterile (Hodnett et al., 2010).

Imperata

There is one report of an experimental cross between *Imperata cylindrica* and a *Saccharum* spp. hybrid producing triploid progeny resembling sugarcane, which could

apparently self-fertilise to produce F_2 progeny (Janaki-Ammal, 1941). However, other authors have suggested that these may not have been true hybrids (Nair and Ratnambal, 1970).

Thus, intergeneric gene transfer involving existing commercial sugarcane hybrids may be possible, by hand-pollination under experimental conditions designed to overcome natural barriers to cross-pollination, but such hybrids have not been observed in the wild.

Health and biosafety

Sugarcane is a well-established agricultural crop with a long history of safe use. Commercial sugarcane is grown as a source of sugar (sucrose) for human food. By-products from sugarcane processing include molasses and bagasse, which are mainly used for industrial purposes such as ethanol production and power generation, but also have minor food and stockfeed uses.

Information on processing of sugarcane and its major products (whole cane, sugar, sugarcane juice, molasses, bagasse), as well as food and feed safety considerations including composition in terms of key food and feed nutrients, anti-nutrients and toxicants, have been summarised by the OECD as part of the series dealing with the safety of novel foods and feeds (OECD, 2011) so will not be included here.

Environmental allergens

Sugarcane pollen is transported by wind and therefore has the potential to act as an airborne allergen. The allergenicity of sugarcane pollen was evaluated in India where 70% of field workers with respiratory disorders showed positive reactions to sugarcane pollen in skin tests (Chakraborty et al., 2001). The authors also tested rice and several other plant species and concluded that sugarcane pollen was the most significant allergenic type. A study in Japan of children known to be sensitive to allergens showed less than 3% reacted to sugarcane pollen in tests (Agata et al., 1994).

Exposure to organic dusts, such as those present in mouldy sugarcane, can cause bagassosis. Bagassosis is an occupational lung disease of the extrinsic allergic alveolitis type and is caused by breathing dusts containing fungal spores and/or thermophilic actinomycetes which grow in stored, mouldy bagasse (Lacey and Crook, 1988). In Australia, bagasse may be stored covered with tarpaulins at the end of the crushing season to be used to fuel the boilers at the beginning of the next season before fresh bagasse is available (Dawson, Scott and Cox, 1996). The stored sugarcane bagasse contains approximately 50% water and 5% sucrose, so is colonised by bacteria, causing it to heat up and create ideal conditions for fungi and thermophilic bacteria such as *Aspergillus fumigatus*, *Thermoactinomyces vulgaris* and *Thermoactinomyces sacchari* (Lacey and Crook, 1988). In India, it is thought that *T. sacchari* and *Saccharopolyspora rectivirgula* are the most likely cause of bagassosis (Khan et al., 1995). Prolonged, repeated exposures can lead to permanent lung damage and scarring, and significant disability (Hur et al., 1994; Phoolchund, 1991). However, a study at two Australian sugar mills did not identify very high levels of airborne bacterial spores and none of the 271 mill workers surveyed showed any symptoms of bagassosis (Dawson, Scott and Cox, 1996). In Puerto Rico, a study showed a four-fold increase in risk of cancer of the oral cavity amongst sugarcane farmers and farm workers, which may be due to exposure to actinomycetes (Coble et al., 2003).

There are no reports in the literature of sugarcane causing allergic reactions in humans through consumption (OECD, 2011).

Notes

1. In some taxonomic classifications, *S. barberi* is classified as a subspecies – *S. officinarum* subsp. *barberi* (Jeswiet) Burkill; other classifications do not distinguish between *S. barberi* and *S. sinense* as separate species (*www.theplantlist.org*) (WCSP, 2013).
2. In some taxonomic classifications, *S. edule* is classified as *Saccharum spontaneum* var. *edule* (Hassk.) K. Schum. & Lauterb (*www.uniprot.org/taxonomy*); other classifications do not distinguish between *S. edule* and *S. robustum* (*www.biodiversitylibrary.org*).
3. This sentence was updated in February 2016.
4 This reference was added in February 2016
5. See: *www.ogtr.gov.au*.
6. See: *http://bch.cbd.int/database/lmo-registry.*
7. See: *www.aphis.usda.gov/brs/status/relday.html.*
8. See: *www.daff.gov.za.*
9. This sentence was updated in February 2016.
10. Calculated assuming 1 850 seeds per g (Rao, 1980).
11. See: *www.fao.org/agriculture/crops/core-themes/theme/biodiversity/weeds/db-countries.*

Annex 2.A1.
Major invertebrate pests of sugarcane and their control

Table 2.A1.1. **Major invertebrate pests of sugarcane and their control**

Common name	Species	Affected plant part	Control
Cane grubs	Many species of beetle larvae including *Antitrogus consanguineus* (Australia), *Dermolepida albohirtum* (Australia) and *Holotrichia serrata* (India)	Roots – significant root damage destabilises stool leading to lodging	Primarily insecticide sprays, biocontrol agents, cultural practices and light traps (Japan)
Cicadas	3 species, nymphs	Roots – sap feeding	No chemical control, plough out and leave bare fallow for a season
Ants	*Aphaenogaster pythia, Atta* spp. and *Acromyrmex* spp.	Roots – weakens stools	No chemical control, plough out
Symphylans	*Hanseniella* spp.	Roots – poor crop establishment	Encourage rapid germination, insecticides
Nematodes	Several genera including *Meloidogyne*, *Pratylenchus* and *Helicotylenchus*	Roots – interfere with water and nutrient absorption	Nematicides, crop management practices, resistant varieties
Wireworms (click beetle larvae)	*Agrypnus variabilis, Heteroderes* spp., sugarcane click beetle (*Melanotus okinawensis*: Japan) and *Melanotus communis* (United States)	Shoots – bore into the buds of setts or the growing point	Insecticides in plant crops (none for ratoon crops), flooding, sexual pheromone traps (Japan)
Adult beetles	*Heteronychus arator*, *Metanastes vulgivagus*, *Rhyparida* spp. and *Migdolus fryanus*	Shoots – chew into young shoots causing death of the shoot	Plough out and leave bare fallow for a season, insecticides
Spittle bugs/ froghoppers	*Mahanarva fimbriolata* (Brazil), *M. postica*, *Tomaspis saccharina*, *Aeneolamia varia saccharina* and *Deis flavopicta*	Feed on shoots and leaves	Biological control (including *Metarrhizium anisopliae* in Brazil), insecticides
Weevils	*Stenocorynus* spp., *Naupactus leucoloma*, *Sphenophorus levis* and *Metamasius hemiptera sericeus*	Shoots – also bore into setts and ratoons (occurs rarely)	None available
Shoot borers	African stem borer (*Eldana saccharina*: South Africa), Asian spotted stem borer (*Chilo saccharaphagus*: Mauritius, Réunion, Madagascar and Mozambique), early shoot borer (*Chilo infuscatellus*), internode borer (*Chilo sacchariphagus*), top borer (*Scripophagua excerptalis*: India), sugarcane stem borer (*Diatraea saccharalis*: Americas), sugarcane giant borer (*Telchin licus*: Americas), *D. flavipennella, Ephysteris promptella*, guaspur borer (*Bissetia steniellus*: Pakistan), Mexican rice borer (*Eoreuma loftini*: United States) and *Proceras venosatus* (China)	Shoots – chew into young shoots causing death of the shoot	Parasitoids (including *Cotesia flavipes* to control *D. saccharalis* in Brazil), chemical control, sexual pheromone traps (Japan)
Thrips	*Fulmekiola serrata*	Leaf necrosis, young cane tips tied together, brown and wither	None available
Sugarcane weevil borer	*Rhabdoscelus obscurus*	Stem – bore into stems allowing other diseases in	No chemical control, quarantine between growing areas of sugarcane and palms
Termites	Several species including *Heterotermes tenuis* (Brazil)	Stem – hollow out stems	No chemical control, remove dead wood from cane fields, biological control (*Beauveria bassiana* in Brazil)
Locusts	Several species	Leaf and stem – chewing	Cultivation before eggs hatch
Armyworms and loopers	Various species	Leaf and stem – chewing	Plants usually recover from early damage
Planthopper	*Perkinsiella saccharicida*	Leaf and stem – sap feeding, vector for Fiji disease	Fiji disease-resistant cultivars

Table 2.A1.1. **Major invertebrate pests of sugarcane and their control** (*continued*)

Common name	Species	Affected plant part	Control
Mealybug	Many species including *Saccharicoccus sacchari* and *Pseudococcus sacchari*	Leaf and stem – sap feeding	Natural enemies
Aphids	Several species including woolly aphid (*Ceratovacuna lanigera*: Asia) and sugarcane aphid (*Melanaphis sacchari*: United States)	Leaf and stem – sap feeding	Natural enemies
Scale insect	Many species including *Aulacaspis madiunensis* and *Melanaspis glomerata*	Leaf and stem – sap feeding	Disease-free planting material

Annex 2.A2.
Major diseases of sugarcane

Table 2.A2.1. **Major diseases of sugarcane**

Common name	Causal agent	Distribution	Control
Bacterial			
Leaf scald	*Xanthomonas albilineans*	Worldwide	Resistant cultivars
Ratoon stunting disease (RSD)	*Leifsonia xyli* (previously called *Clavibacter xyli* subsp. *xyli*)	Worldwide	Disease-free planting material
Gumnosis	*Xanthomonas vasculorum*	Widespread in windswept regions	
Red stripe (top rot)	*Acidovorax avenae* subsp. *avenae*	Australia, Iran, Japan, Mexico, the United States and Central America	Resistant cultivars, planting dates
Fungal			
Rusts	*Puccinia melanocephala* and *P. kuehnii*	Africa, Asia and Latin America	Resistant cultivars, fungicide
Downy mildew	*Sclerospora sacchari*	Australia, China (People's Republic of), the Philippines and Chinese Taipei	
Red rot	*Glomerella tucumanensis* (previously called *Colletotrichum falcatum*)	Worldwide, wet and cold regions	Resistant cultivars
Yellow spot	*Mycovellosiella koepkei* (previously called *Cercospora koepkei*)	Widespread in South and East Asia, also in Australia and Oceania. In Africa: Ghana, Mauritius, Réunion Island, South Africa, Tanzania and Uganda	Resistant cultivars
Pachymetra root rot	*Pachymetra chaunorhiza*	Australia	Resistant cultivars
Sugarcane smut	*Ustilago scitaminea*	Worldwide (except some islands)	Resistant cultivars, hot water treatment
Pineapple disease	*Ceratocytis paradoxa*	Worldwide	Fungicide applied to setts
Eye spot	*Bipolaris sacchari*	Many sugarcane growing regions	Resistant cultivars
Pokkah boeng ("tangle top")	*Fusarium monoliforme* (*Gibberella fujikuroi*) and *F. subglutinans* (*G. subglutinans*)	Most sugarcane growing regions	Plants usually recover without need for disease control
Viral			
Chlorotic streak	Unknown, probably virus		Disease-free planting material, good drainage
Fiji disease	Fiji disease phytoreovirus (FDV)	Australia, Fiji, Madagascar, the Philippines and Thailand	Resistant cultivars
Mosaic diseases	Potyviruses: sugarcane mosaic virus (SCMV), *Sorghum* mosaic virus (SrMV), maize dwarf mosaic virus (MDMV), Johnson grass mosaic virus (TGMV) and striate mosaic associated virus	More serious in temperate regions. Not in Guyana, Mauritius and West Africa	Disease-free planting material and resistant cultivars
ScYLV	Sugarcane yellow leaf virus	Australia, Brazil, Colombia, Guadeloupe, Hawaii, Malawi, Mauritius, Réunion Island, South Africa and the United States	Disease-free planting material and resistant cultivars
Phytoplasma			
Sugarcane white leaf		Thailand	Control of insect vectors
Sugarcane grassy shoot		India	Control of insect vectors
Sugarcane yellow leaf syndrome		Australia, Cuba, Mauritius, South Africa and United States	Control of insect vectors
Ramu stunt		Papua New Guinea	Resistant cultivars

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