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The Biology of the *Saccharum spp.* (Sugarcane)



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This document provides an overview of baseline biological information relevant to risk assessment of genetically modified forms of the species that may be released into the Australian environment.

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PREAMBLE

This document addresses the biology of the *Saccharum* spp, *S. officinarum* and *S. spontaneum* (Sugarcane) with particular reference to the Australian environment, cultivation and use. Information included relates to the taxonomy and origins of *Saccharum* species, general descriptions of its morphology, reproductive biology and biochemistry, biotic and abiotic interactions. This document also addresses the potential for gene transfer to occur to closely related species. The purpose of this document is to provide baseline information about the non-genetically modified parent organism for use in risk assessments of genetically modified *S. officinarum* that may be released into the Australian environment.

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 varieties that are cultivated for sugar production are founded on interspecific hybrids between *S. spontaneum* and *S. officinarum* (*Saccharum* spp.). Sugarcane is an ancient crop, its use as a garden crop dates back to 2500BC, at present it is grown as a commercial crop primarily in South America (Brazil), USA, Asia and Australia. Sugarcane in this document refers to the *Saccharum* spp hybrids as described above.

SECTION 1 TAXONOMY

Sugarcane belongs to the genus *Saccharum* L., of the tribe Andropogoneae in the grass family (Poaceae). This tribe includes tropical and subtropical grasses and the cereal genera *Sorghum* and *Zea* (corn). 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 of *Saccharum*, *Erianthus* section *Ripidium*, *Miscanthus* section *Diandra*, *Narenga* and *Sclerostachya* (Daniels & Roach 1987). These genera are characterised by high levels of polyploidy and frequently unbalanced numbers of chromosomes (aneuploidy) making it difficult to determine taxonomy and resulting in many previous revisions of the taxonomic relationships (Daniels & Roach 1987; Sreenivasan et al. 1987)

The *Saccharum* genus comprises six species *S. spontaneum*, *S. officinarum*, *S. robustum*, *S. edule*, *S. barberi*, and *S. sinense* (D'Hont et al. 1998).

S. officinarum is thought to have resulted from the complex introgression between *S. spontaneum*, *Erianthus arundinaceus* and *Miscanthus sinensis* (Daniels & Roach 1987). *S. officinarum* has a chromosome number of $2n = 80$ with a basic chromosome number of 10 making this species a polyploid (having more than two chromosome sets eg octaploid, $2n=80$ - eight complete sets of chromosomes). However, *S. officinarum* is not a simple polyploid. It is a complex hybrid of different species as it 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). This is indicated by whole chromosomes in *S. officinarum* that are homologous with those in the genera *Miscanthus* and *Erianthus* section *Ripidium* (Daniels & Roach 1987; Besse et al. 1997).

S. spontaneum is a smaller, highly polymorphic, disease resistant, highly 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 eight or 10 (Sreenivasan et al. 1987; D'Hont et al. 1996). It can be distinguished from the cultivated *Saccharum* by thinner canes and a narrow panicle (Pursglove 1972). Characteristics of the spikelets at the end of the tertiary branches of the inflorescence are also used by taxonomists to help distinguish the species from other *Saccharum* spp.

S. barberi and *S. sinense* are thought to be wild species but have been in cultivation since prehistoric times in northern India and China respectively. This had lead to considerable interbreeding with other genera and species, consequently these species are thought to be ancient intergeneric hybrids (Daniels & Roach 1987). *S. 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 & Roach 1987; D'Hont et al. 1996)

S. robustum is a wild species thought to be an intermediate step in the evolutionary pathway between *S. spontaneum* and *S. officinarum*. It is a diverse riparian species that grows in the wet tropics with many distinct populations.. Two major groups within the species are known, those that have $2n=60$ and $2n=80$ chromosomes respectively.

S. edule is morphologically similar to *S. robustum* except that the flower spike or inflorescence is compacted. It is cultivated as a vegetable in the islands of the Pacific and Papua New Guinea. *S. edule* is thought to be derived from introgression of *S. officinarum* or *S. robustum* with other genera (Daniels & Roach 1987). A summary of the genetic characteristics of the *Saccharum* species is shown in Table 1.

TABLE 1: SUGAR CANE MEMBERS OF GENUS *SACCHARUM* (BUZACOTT 1965; DANIELS & ROACH 1987).

Species	Classification	Sugar content	Chromosome number
<i>S. spontaneum</i>	Wild species	Nil	$2n= 40-128$
<i>S. robustum</i>	Wild species	Nil	$2n= 60\sim 200$
<i>S. officinarum</i>	Noble canes	High	$2n= 80$
<i>S. barberi</i>	Ancient hybrid	Low	$2n= 111-120$
<i>S. sinense</i>	Ancient hybrid	Low	$2n= 80-124$
<i>S. edule</i>	Wild species	Compacted inflorescence eaten as a vegetable	$2n= 60-80$ with aneuploid forms

SECTION 2 ORIGIN AND CULTIVATION

2.1 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 the *S. officinarum* L. and *S. spontaneum* L. species (Cox et al. 2000).

S. officinarum or the 'noble canes' accumulate very high levels of sucrose in the stem but have poor disease resistance. *S. officinarum* itself is thought to be the product of complex introgression between *S. spontaneum*, *Eriathus arundinaceus* and *Miscanthus sinensis* (Daniels & Roach 1987). The origins of *S. officinarum* are intimately associated with the activities of humans, as *S. officinarum* is a purely cultivated or garden species with no members found in the wild (Sreenivasan et al. 1987). Sugarcane has been known in New Guinea since 6000BC. Its cultivation spread along the human migration routes to Southeast Asia, India and the Pacific, hybridizing with wild sugarcane to ultimately produce 'thin' canes. It reached the Mediterranean between 600-1400 AD. From there it spread to Egypt, Syria, Crete Greece and Spain followed by introduction to West Africa and subsequently Central and South America and the West Indies (Anon. 2007b). The centre of origin of *S. officinarum* is thought to be in Polynesia. The species was probably transported throughout south-east Asia by humans, leading to a modern centre of diversity in Papua New Guinea and Irian Jaya (Indonesia). The majority of specimens collected in the late 1800s for curating purposes come from these areas (Daniels & Roach 1987).

Hypotheses for the origin of *S. officinarum* involve selection of sweet forms of *S. robustum* for use as food, possibly with the aid of animals such as pigs or rats that were attracted to sweeter individual plants (Daniels & Roach 1987). The word sugar is thought to have been derived from the Sanskrit *sharkara* (Anon. 2007b).

S. spontaneum is believed to have evolved in southern Asia. *S. spontaneum* accumulates no sucrose but is a highly polymorphic species with much higher levels of disease resistance, adaptability and stress tolerance (Sreenivasan et al. 1987). *S. spontaneum* is a much more 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: a) the East zone which is South Pacific islands, Philippines, Taiwan, Japan, China, Vietnam, Thailand, Malaysia and Burma; b) the Central zone, which includes India, Nepal, Bangladesh, Sri Lanka, Pakistan, Afghanistan, Iran and Middle east and c) the West zone which includes Egypt, Sudan, Kenya, Uganda, Tanzania and other countries in the Mediterranean (Pursglove 1972; Daniels & Roach 1987; Tai & Miller 2001).

2.1.1 Commercial hybrid cultivars

Commercial hybrid cultivars of sugarcane descended from interspecific hybridisation between *S. officinarum* and *S. spontaneum* (Bull & Glasziou 1979). *S. officinarum* or the 'noble canes' accumulates very high levels of sucrose in the stem but have poor disease resistance. The modern cultivars are founded on only 20 *S. officinarum* and less than 10 *S. spontaneum* derivatives (Roach 1995). The basic breeding concept involves the combination and improvement of vigorous, disease resistance from *S. spontaneum* and high sucrose content from *S. officinarum*. Increasing sucrose content, while maintaining disease resistance of commercial hybrid cultivars, has been achieved through a number of back-crosses to several different cultivars of *S. officinarum* (Bull & Glasziou 1979). Consequently, *S. spontaneum* genetic component is reduced in commercial hybrid cultivars. Of the chromosomes in these commercial hybrid cultivars, approximately 80% are derived from *S. officinarum* and 10% are from *S. spontaneum*, with remainder being chromosomes from the two species produced by the natural process of synapsis during meiosis (D'Hont et al. 1996).

Modern cultivars have been shown using Genome In Situ Hybridisation (GISH) to contain approximately 15-20% *S. spontaneum* chromosomes and less than 5% translocated or recombinant chromosomes (D'Hont et al. 1996; Cuadrado et al. 2004).

Interspecific hybridisation between *S. officinarum* as the female parent and *S. spontaneum* as the male parent produces progeny that have a triploid chromosome number ($2n + n = 100$ to 130) (Sreenivasan et al. 1987; D'Hont et al. 1996). This phenomenon, thought to arise either through endoduplication or fusion of two nuclei during meiosis, facilitated breeding of modern sugarcane varieties as the '*officinarum*' qualities recovered more quickly in the hybrids, thus requiring fewer rounds of backcrossing to produce high sucrose varieties (D'Hont et al. 1996).

Hybridisation between *S. officinarum* and *S. spontaneum* culminated with the release of a variety called POJ2878 ('Java Wondercane') in 1921 in Java (Indonesia), which became an important variety, allowing for a 35% increase in sugar production over the previous best varieties (Jeswiet 1929; Cox et al. 2000). Most commercial cultivars used in Australia today can be traced to this variety (Cox et al. 2000). Sugarcane breeding for improved varieties is a time consuming process taking upwards of ten years from initial crosses to final agronomic assessment of elite varieties (Cox et al. 2000).

A list of cultivars approved for cultivation can be found on the Queensland government website (Anon. 2006c).

2.2 Commercial uses

2.2.1 Sugar production

Sugarcane is an established agricultural field crop with a long history of safe use. It is believed to have become established as a domestic garden crop possibly as early as 2500 BC (Daniels & Roach 1987). In Australia, sugarcane has been cultivated for over 100 years with the majority being grown in Queensland and some smaller areas in northern NSW (Canegrowers 2004). Sugarcane is primarily grown as a source of sugar. It is one of the world's major food crops providing about 75% of the sugar harvested for human consumption (Sreenivasan et al. 1987; FAO 2004).

Sugar is initially extracted from the raw cane at sugarcane mills distributed throughout the growing region. 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) which 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 (substances added to solutions to produce woolly looking masses of particles which assist with settling out suspensions) are added to speed up this process (Mackintosh 2000).

Clarified sugar juice is then concentrated by evaporation to produce 'syrup'. The syrup then goes through multiple rounds of crystallisation to extract the sucrose. It is boiled and the sucrose crystallises from the remaining molasses fraction. The product of this step is known as massecuite. The massecuite is then centrifuged to separate the sucrose from the molasses. This process is repeated three times in Australian sugar mills. 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' sugar are dried to produce raw sugar, which is shipped in bulk to sugar refineries worldwide for further purification resulting in a high quality, purified product.

Sugarcane quality is measured at the mill and partly determines the actual return the grower receives. The formula to determine payment to the grower is complex and outside the scope of this document. However, there are three measures of cane quality that are important, which will be briefly mentioned here. 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 passage of polarised light through the clarified juice. These two measures of juice quality (corrected for fibre content of the stem) allow determination of the level of impurities in the cane (ie. Brix minus Pol equals total impurities in the cane). Furthermore this allows estimation of the sugar content or commercial cane sugar (CCS) of a grower's cane (Mackintosh 2000)

To calculate CCS it is assumed that three quarters of the impurities remain after the juice is clarified. These impurities end up in the final molasses, which in turn consists of ~40% non-recoverable sugar and 60% impurities. Therefore:

$$\begin{aligned}\text{CCS} &= \text{Pol of juice (corrected for fibre content of stem)} - \frac{3}{4} (\text{impurities in cane} \times 40/60) \\ &= \text{Pol in cane} - \frac{1}{2} (\text{impurities in cane})\end{aligned}$$

CCS is a measure of how much pure sucrose can be extracted from the cane. The final return that the grower receives is determined by additional factors, see (Mackintosh 2000).

Garside et al. (1997) reported that the Australian sugar industry had reached a productivity plateau in the period 1970-1990. In that period, 50 new cultivars were released and plant

breeders estimated productivity gains of 1% per year (ie. 0.01tonne/ha/year). However, the CCS decreased by ~1 unit.

Australia is one of the major exporters of sugar to the rest of the world. Total production exceeded 5 million tonnes in 2005, to a value of \$2 billion. The sugarcane industry is a major employer and of economic importance in Northern NSW and Queensland and continues to expand (Plant Health Australia 2004).

Global production in 2004/05 was a total of 140 million tons, with Brazil the major producer followed by India, China and Thailand (FAO 2005; Anon. 2006b).

2.2.2 *Byproducts of sugar production*

Several by-products are produced from crushing sugarcane at the sugar mill. These primarily include bagasse (fibre) and molasses. Production of various fermented and chemical derivatives of cellulose and fermentation of bagasse to produce fuel ethanol may become more common in the future (Allen et al. 1997).

Bagasse is the fibrous portion of sugarcane that remains after the juice has been removed. It consists of two types of fibre, the cellulose fibre of rind, vascular tissue and the pith of the cane stem, which constitute 55% of bagasse dry weight. Bagasse cellulose fibres are longer (1-1.5mm) than hardwood fibres (0.7-1mm), but shorter than softwood fibres (2.5-5mm) and are suitable for papermaking. The pith material of the stem is considered a contaminant for papermaking and production of high quality paper consequently requires it to be removed. Bagasse is used to make paper in many countries although not in Australia (Allen et al. 1997).

Bagasse is used as an animal feed but is limited by the low digestibility, even for ruminants (~25%). Chemical, biological or thermo-mechanical treatment improves the digestibility to approximately 65% (Pate 1982; Playne 1984; de la Cruz 1990; de Medeiros & Machado 1993; Allen et al. 1997; UN Industrial Development Organisation 2002).

It can also be burnt to produce steam as a source of power to run the sugar mills with excess energy directed to the electricity grid. The ash produced is mixed with other impurities (mud) left over after the sugarcane juice is clarified. Fine bagasse, known as bagacillo is used to produce filter cake which is used as a fertiliser on cane farms (Sreenivasan et al. 1987; Mackintosh 2000).

Sugarcane bagasse can also be used in the production of bio-fuels such as ethanol, commodity chemicals and electricity. Key processing technologies such as pulping, pivotal in the bio-refinery area, are being developed by for example the Sugar Research Institute. Brazil has long been producing ethanol for use as fuel for years, from crops such as sugarcane eg (Schubert C 2006).

Bagasse has also been shown to be an effective bio-sorbent and shows great potential for its use in waste water management. For example, chromium, cadmium, nickel and dyes are common pollutants found in synthetic waste water; bagasse has been shown to be very effective as a bio-sorbent of these materials (Sreenivasan et al. 1987; Gill et al. 1999; Khattri & Singh 1999; Krishnani et al. 2004; Khan & Amin 2005).

Molasses is the thick syrupy residue left over 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 stock feed supplement and as a fertiliser for cane fields (Sreenivasan et al. 1987; Sansoucy et al. 1988; Mackintosh 2000). In the 19th and 20th centuries molasses was served as a sweetener stirred into milk used as a jam or jelly. It was also used for medicinal

purposes most likely because it has been found to be a rich source of micro- and macronutrients (USDA 2004).

The relative composition at various stages of production of molasses is shown in Table 2.

Table 2: Sugarcane by-products from the processing of sugarcane (adapted from (Preston 1988; Allen et al. 1997)).

Fraction	Approximate composition (% fresh weight basis)		
	Sucrose	Reducing sugars	Ash [†]
Cane Syrup ¹	45-55	5-10	1-2
High-test molasses ²	25-30	40-50	2-3
'B' molasses ³		5-8	80-90
Final molasses ⁴	33-37	15-19	10-15

glucose and fructose produced by the action of the enzyme invertase.

[†] mainly inorganic salts.

¹ clarified and concentrated cane juice (syrup) concentrated to the point where the sucrose is almost ready to crystallise.

² clarified and concentrated cane juice (syrup) from which no sugar has been crystallised that has been filtered and partially inverted (converted to reducing sugars) to avoid crystallisation.

³ concentrated soluble residue following the second centrifugation to remove the 'B' sugar.

⁴ concentrated soluble residue after the last centrifugation to remove the 'C' sugar, also known as 'C' or blackstrap molasses.

Note that the balance of the fraction in each case is mostly water.

Trash is the plant material left over after harvesting of the sugarcane stalks. It is generally retained in the field as mulch in northern Queensland. Baled trash is also used as garden mulch and as a low-grade cattle feed in the south-east Queensland growing region (Dawson 2002). Sugarcane wax is used in countries such as Nigeria as a compound to preserve fruit, vegetables and cheese (Khushk & Pathan 2006). Sugarcane most likely due to its high sugar content is edible and appetising to some, however the high fibre content does make it chewy and slow to process (FAO 2004).

Sugarcane ash has been shown to suppress nematodes and enhance the soil and root relations, reducing stress on the plant (Broadley et al. 2004).

2.3 Cultivation in Australia

It is believed that sugarcane was first brought to Australia in 1788 on the First Fleet but cultivation was not immediately successful. The first official record of sugarcane in Australia was in 1821 at Port Macquarie, NSW, but an industry did not develop until a cane plantation was established near Brisbane in 1862. The first Australian commercial sugar mill began operation in 1864. Sugarcane cultivation spread along the Queensland-New South Wales coastline and in 1870 a system of large central sugar mills, supplied with cane by independent farmers, was introduced by the Colonial Sugar Refining Company (now CSR Ltd) (Anon. 2002a).



Sugarcane growing in Bundaberg, Queensland. OGTR, August 2007.

2.3.1 Commercial propagation

Propagation of sugarcane is different to 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 setts, either whole stalks or stalks cut up into shorter segments or seedcane (Willcox et al. 2000).

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.

Micro propagation of clones of sugarcane with the required characteristics provides a reliable and fast method for mass propagation of clonal material. This *in vitro* method of propagation relies on using plant material from the meristem or non-meristemic cell or tissues. Subsequent plants can be regenerated directly (adventitious) or indirectly (*de novo*) from these explants. Thin cell layer culture of immature leaf or inflorescence tissue can also be used for the direct regeneration of plants (Lakshmanan et al. 2005).

More recently, in an attempt to produce large numbers of disease free sugarcane seedlings, the SmartSett® technology has been developed through a joint venture between BSES, Canegrowers and Lowes TC. Although not available commercially yet it is hoped that this technology can be offered in the near future. It is an alternative propagation method to the traditional sett-based seedling production; it regenerates plantlets directly from young leaf tissue. Pieces of leaf tissue are placed on nutrient media containing plant hormones and growth requiring chemicals. Plantlets can be produced in this manner in a period of 5-6 months for field planting. Using this method, one sugarcane stalk can produce between 400-2000 seedlings. (Anon. 2006a)

2.3.2 Scale of cultivation

Currently, in Australia sugarcane is commercially cultivated over a 2100 km stretch from northern New South Wales (approximately 30°S) to northern Queensland (approximately 17°S) with the actual planting area distributed unevenly across this range. A small industry also exists in the Ord district in Western Australia. About 98% of Australia's sugar exports originate in the Queensland coastal region (Canegrowers 2004). The Australian Bureau of Statistics indicate that Queensland's 2000-01 crop harvest was 25.8 million tonnes of sugarcane, from 382,000 hectares of cultivated land. This increased to 35.3 million tonnes,

from 411,000 hectares, in 2004-05. Each hectare of cane harvested yielded on average 67.8 tonne of cane and 8.94 tonne of sugar. Sugar production in Australia in 2000-2001 was approximately 27 million tonnes increasing to a total of 37.5 million tonnes in 2004-05 (Canegrowers 2004; Anon 2007b).

2.3.3 *Cultivation practices*

Setts (cuttings from mature cane stalks) are generally planted within a few days of harvest of the cane, in order to achieve a high frequency of germination. Row spacing is about 150cm. Buds on planted setts, or on the plant bases remaining after harvest, germinate within two weeks of planting (or after harvest of the preceding crop). Due to their high sugar content, setts are prone to fungal attack and are routinely treated with fungicide to protect them until germination. Sugarcane varieties differ in their degree of temperature sensitivity but in general germination is slow at soil temperatures below 18°C and increases rapidly up to about 35°C (Bull 2000). Because sugarcane originated in the wet tropics, yields are much higher when the crop is supplied with adequate water. Thus, sugarcane is usually irrigated (Ham et al. 2000).

The cultivation of sugarcane at present relies on the extensive use of fertilizers and pesticides. Nitrogen especially is used widely. In general only about 30% of the applied nitrogen is taken up by the crop, the remaining 70% is lost to surface runoff, groundwater, soil storage and the atmosphere (Freyney et al. 1994; Weier et al. 1996; Bohl et al. 2000; Reganzani & Armour 2000; Robertson & Thorburn 2000). Pesticides such as chlorpyrifos are used widely to control insect pests, and herbicides for weed control, include atrazine, diuron, glyphosate and paraquat (Hamilton & Haydon 1996). In addition, the use of rodenticides such as coumatetralyl and zinc phosphide, and fungicides such as triadimifon and propiconazole is widespread (Dyer 2005; Anon 2006). The planting of resistant cultivars dramatically reduces the use of pesticides and/or fungicides normally required for effective pest and disease management (Grice et al. 2003).

Sugarcane is planted in NSW in September-October and in the months of January-February in Queensland. All sugarcane in Australia is harvested 12–18 months after planting. In NSW this is usually from mid June to late November with most sugarcane crops in NSW harvested at two years old (McGuire et al. 2003). In Queensland harvesting occurs between June and December (Anon 2007a). The two most commonly used methods to harvest sugarcane are green cane harvesting and burnt cane harvesting. The majority of sugarcane is harvested using the green cane method. It allows the leafy tops of the cane to be left on the ground as a protective trash blanket layer. This in turn protects the soil from erosion and also acts as organic mulch, thereby retaining the nutrients in the soil (Canegrowers 2004). Green cane harvesting/trash blanketing especially is known to dramatically reduce soil erosion and subsequent sediment runoff (Prove 1991; Rayment & Neil 1997). Sugarcane is routinely harvested mechanically by cutting stems close to the ground before flowering as the process of flowering leads to a reduction in stem sugar content (Bull 2000).

Sugarcane grows perennially and the root system or ratoon that remains in the ground will resprout from each stalk. Consequently 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 lead to declining yield. Thus a maximum of four ratoon crops are typically grown before ploughing out the crop and replanting (Bull 2000). After ploughing the previous ratoons out, another sugarcane crop is planted immediately, or the ground is left fallow, or planted with legumes, with sugarcane again planted the following winter. Planting a legume crop has been shown to improve soil fertility for subsequent sugarcane crops. Removing ratoons with herbicide (glyphosate) rather than by tillage reduces soil compaction and improves soil structure (Willcox et al. 2000).

Sugarcane killing practices often result in inadequate eradication of the old crop (Leibrandt 1993). The efficacy of glyphosate for killing sugarcane is affected by various factors such as cane varieties, 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 0.4-0.75m compared with older cane that has produced stalks (Turner 1980).

Research showed 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 (Leibrandt 1993).

A variety of crops are used as a rotation crop. Soybean is deemed especially suitable as a rotation crop. Other promising crops include; peanuts, mung beans and navy beans. Forage crops such as sorghum and fibre crops such as Kenaf and hemp also show potential in a rotation system with sugarcane (Sparkes 2007).

2.4 Crop improvement

Crops can be improved through conventional breeding programs which rely on the maintenance of germplasm stocks. These stocks form the source for breeding material; lines with desirable genotypes are then used for subsequent hybridisations to produce new lines.

More recently the development of *Agrobacterium*-mediated transformation has permitted the more economical and efficient development of novel GM sugarcane lines.

2.4.1 Breeding

Modern sugarcane breeding programs rely on extensive crossing of elite cultivars and usually involve cross-pollination. In the case of self pollination the arrows containing the flowers are covered with bags, or the arrows are isolated from other clones (Sleper & Poehlman 2006). Cross pollination is performed by bringing the arrows of the male and female together in isolation thus allowing for natural cross-pollination, alternatively, the pollen is manually dusted onto the flowering arrow of the female clone. In more temperate climates crossing houses, with controlled temperature, light and humidity, are used to perform specific crosses. Here the male and female clones are placed in isolated cubicles, with the arrow of the male clone placed above the arrow of the female clone. Tapping of the male clone ensures that the pollen is scattered over the female flower. In breeding experiments, the seeds are often collected in bags applied 15-20 days after the crosses have been made as to prevent any losses of the seed. (Sleper & Poehlman 2006)

Parents used in breeding programs are classified as male or female depending on relative amounts of viable pollen produced. Sex is often determined by aceto-carmin staining to determine the viability of pollen. Clones with <10% pollen viability are designated as female, clones with >25% viable pollen are designated as male. Clones with intermediate levels of viable pollen (10-20%) are classified as bisexual and may be used as either male or female parents (McIntyre & Jackson 2001).

Commercial breeding programs produce artificial crosses between *Saccharum spp.* hybrids under highly favourable conditions. 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 et al. 2000). Figure 1 illustrates some of the steps involved in this process. However, sugarcane is not an ideal candidate for crossing in conventional plant breeding due to its characteristic non-synchronous flowering and low sexual seed viability (Selman-Housein et al. 2000).

Fig.1: Photographic illustration of the steps involved in artificial crosses performed in *Saccharum* breeding programs.



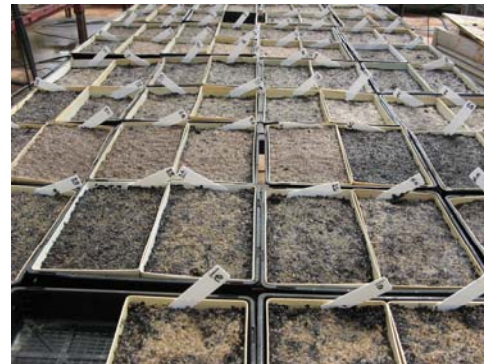
a) Sugarcane clones in the glasshouse ready for genetic crossing



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



c) Fuzz developing for future seed harvest



d) Sugarcane seeding



e) Sugarcane seedlings in growing trays



f) Sugarcane seedlings in a field trial

Attempts have been made to improve sugar yield, with little success. To date, conventional breeding (and genetic modification) methods have not been able to increase the stored sucrose content in this crop (Lakshmanan et al. 2005). More recently genes have been identified that

are associated with stress, a process that is correlated with sucrose concentration (CRC SIIB 2006).

Field trials are underway of crosses between *S. spontaneum* and *Erianthus spp*. These are expected to offer increased genetic diversity to current breeding programs in Australia (CRC SIIB 2006).

DNA fingerprinting techniques such as AFLP (Amplified Fragment Length Polymorphism) and SNP (Single Nucleotide Polymorphism) analyses are being used to investigate the generating of markers associated with specific traits. In current research programs DArT (Diversity Array Technology) is being used to improve the efficiency of the breeding programs. Sugarcane has a highly complex genome, making it more challenging to obtain a complete understanding of the genome in relation to quantitative traits of the different cultivars. DArT has been successfully used in identifying genetic patterns/polymorphisms between cultivars that may ultimately be related to specific quantitative traits (Heller-Uszynska et al. 2006). Similarly these genetic patterns/polymorphisms could be used to identify pest resistant traits in the future (CRC SIIB 2006).

Conventional breeding programs for the generation of disease resistant varieties, has been very successful to date in combating smut. Currently the 'one-eye-set' propagation and tissue culture methods are being used to produce large numbers (40,000-90,000) of plantlets for commercial plantings (Anon. 2007a).

2.4.2 Genetic modifications

Sugarcane has been genetically modified through the introduction of genes affecting a number of traits described below. Some of these GM sugarcane lines have been approved for limited and controlled release in Australia. Some of the traits that have been targeted for improvement through genetic modifications include. Altered sugar content, improved nitrogen efficiency, improved water use efficiency, altered plant architecture and pest resistance (CRC SIIB 2006; Wu & Birch 2007).

Recently sugarcane has been genetically modified to produce bioplastics; poly-hydroxybutarates (PHB) and para-benzoic acid. These compounds were produced in the cane leaves, are biodegradable and have commercial applications (Purnell et al. 2007).

The use of C4 grasses such as sugarcane has in the recent years been tested for their use as bio-factories. Their high growth rate and efficient carbon fixation with relatively few growth penalties makes this type of grass an ideal candidate for the production of a variety of products ranging from therapeutic to silks to polymers and metabolites. Sugarcane is seen to be particularly advantageous because in addition to the C4 qualities it also accumulates sucrose, providing a ready supply of carbon based compounds negating any deleterious effects on the plant associated with the production of the product (PATENT no 20060259998 Ma et al 2005 see also (Grice et al. 2003; Brumbley et al. 2004; Ma et al. 2006).

SECTION 3 MORPHOLOGY

3.1 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) and Bakker (1999) for a comprehensive treatment of the morphology and anatomy of sugarcane.

Sugarcane is a large tropical grass that produces multiple stems or culms each of which consist of a series of nodes separated by internodes. Following germination the terminal vegetative bud of each shoot lays down a series of nodes, each with a dormant bud and one or more rows of root primordia, and a growth ring (intercalary meristem). The internodes consist of sucrose storing parenchyma cells and vascular tissue (Moore & Nuss 1987).

The stem of sugarcane is filled like maize and sorghum and is not hollow like most grasses (Griffie 2000). 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 seven 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. 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 two to three metres in the normal growing season (Bull 2000).

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. Sugarcane uses a C4 mechanism of photosynthesis similar to other tropical grasses and consequently the anatomy of the leaves reflects this underlying physiology. The base of the leaf attaches to the stem at the node but then wraps the stem to form a sheath that loosely encloses the internode to which the node subtends (Moore & Nuss 1987; Griffie 2000).

The stem of sugarcane is the major storage area for photosynthate (sucrose) within the sugarcane plant, rather than fruit or seed structures. Transverse cross section through an internode reveals vascular bundles surrounded by parenchyma cells with a thick outer epidermis covered in an external layer of wax (Moore & Nuss 1987). Developing leaves and internodes develop in a basipetal direction in that the leaf blade expands from the tip to the base then the internode elongates (Moore & Nuss 1987).

The 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.

Like most grasses the sugarcane root system is fibrous and shallow. However, the plant develops buttress roots that serve to anchor the plant and some deeply penetrating roots that grow downwards for 5-7 metres allowing for water absorption under water stress (Moore & Nuss 1987).

3.2 Reproductive morphology

Sugarcane forms an open branched panicle, also known as an arrow, whose shape, degree of branching and size are highly variety specific. The arrow can bear thousands of flowers (Sleper & Poehlman 2006). The inflorescence or arrow consists of a main axis and first, second and third order branches. Attached to the branches are spikelets arranged in pairs that contain individual flowers. 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 (Moore & Nuss 1987).

SECTION 4 DEVELOPMENT

4.1 Sexual reproduction

The occurrence of flowering under field conditions is variable, influenced by varietal as well as environmental conditions. Flowering is mostly reliable and occurs earliest between latitudes 7° and 12° and later northward and southward in the tropical region (Moore & Nuss 1987; Fauconnier 1993). Flower initiation causes the apical meristem to switch from vegetative to floral development, causing stalk elongation to cease; consequently flowering of the crop can affect yields. The older and more vigorous stems in a stool are the most likely to initiate flowering (Moore & 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, this makes the period of floral initiation more defined, further from the equator (Bakker 1999). Variations observed in flowering times in a given location are mostly attributable to the differences in temperature and /or night time temperature (Bakker 1999).

The ability of sugarcane to reproduce sexually was not recognised until 1888. Floral development is initiated by shortening day length and occurs in Australia from mid February to mid March. Cool night temperatures, high day temperatures and lack of moisture interfere with flower initiation. Flowers take two to three months to mature after initiation (Cox et al. 2000).

4.2 Pollination and pollen dispersal

Sugarcane is a cross-pollinating species although selfing occurs at low levels (Moore & Nuss 1987; McIntyre & Jackson 2001). Although sugarcane flowers often have reduced male fertility they are rarely male sterile. Sugarcane pollen is very small, hairy and wind dispersed. It 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) (Venkatraman 1922; Moore 1976). As a result, viable pollen is not expected to disperse far in the field. Sugarcane pollen stored at 4°C under 90-100 % relative humidity retains some viability for up to 14 days (Moore & Nuss 1987).

Saccharum flowering is dependent on interaction of cultivars and environmental factors such as daylength and temperature, some varieties can flower profusely in their natural environment but flower sparingly when introduced to other regions (Bull & Glasziou 1979). Sugarcane breeding programs are severely limited by the nature of flowering of each sugarcane variety, particularly by a decrease in flowering and pollen viability at high latitudes (Bull & Glasziou 1979; Dunkelmann & Legendre 1982; Moore & Nuss 1987). However, controlled breeding is also possible when cultivars of low pollen viability are used as a female parent, while low seed viability cultivars are used as a male parent (Bull & Glasziou 1979). Crosses can often be made but only between varieties which have overlapping flowering period. Various techniques have been developed including alteration of photoperiod which can induce flowering so that flowers can be available for crossing when required (Bull & Glasziou 1979).

4.3 Fruit/Seed development and dispersal

Sugarcane seed or 'fuzz' is the entire flower panicle without the main flower axis and larger lateral axes. The small seeds, 200-300 seeds per gram, often poorly develop and are not viable (Sleper & Poehlman 2006). Mature fuzz consists of the mature dry fruit (caryopsis), glumes, callus hairs, anthers and stigma. 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 varieties of sugarcane can produce seed, fuzz is only used in breeding programs, as the proportion of sugarcane seedlings with agronomic qualities near to those of the parental commercial clones is extremely low. Sugarcane fuzz is short lived, losing 90% of its viability in 80 days at 28°C if not desiccated (Rao 1980).

4.4 Seed dormancy and germination

Some wild species of sugarcane such as *S. aegyptiacum* have significant seed dormancy. The modern cultivars however have little seed dormancy. There is some evidence that conditions of maturation on the parent plant, including after-ripening, can improve germination and generally allow for better germination when the seed subsequently become exposed to light (Pursglove 1972; Simpson 1990).

4.5 Vegetative growth

During the initial stages of germination, root primordia around the nodes of the sett produce a flush of roots. These roots are not connected to the primary shoot but are important in maintaining the moisture in the sett. 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 tertiary shoots (Bull 2000).

Stem elongation is initially rapid and during this phase the fibre content of the stem is high whereas the CCS levels are still quite low. Breeding for high above ground biomass in modern sugarcane varieties 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. Only in wetter areas is lodging associated with yield losses.(Bull 2000)

Growth rate slows and sucrose content increases approximately 120 days after planting (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 can influence sucrose accumulation including water stress, nutrient status and temperature.(Bull 2000)

SECTION 5 BIOCHEMISTRY

5.1 Toxins

Sugarcane is a well-established agricultural crop with a long history of safe use, it has been cultivated in Australia for over 100 years. Commercial sugarcane is grown as a source of sugar (sucrose) for human food. By-products from processing sugarcane into sugar such as molasses and bagasse have been mainly used as food additives in stockfeed.

Sucrose is the primary product of plant photosynthesis and, therefore, common in food crops consumed regularly by humans and animals. Sucrose has an exceedingly long history of human

dietary exposure. It has been classified as a non-toxic substance to humans (MSDS 2004). The LD₅₀ of sucrose for rats is 30 g/kg body weight (MSDS 2004). Consuming sucrose in extremely large oral dosages may produce gastrointestinal disturbances. Although there is no direct evidence that links sucrose consumption with toxicity, there are several studies indicating that sucrose intake should be limited because it may be associated with health problems (Howard & Wylie-Rosett 2002). Studies found that a high intake of sucrose was associated with cardiovascular diseases, development of type II diabetes, obesity and hypertension (Howard & Wylie-Rosett 2002). In addition, it is well established that sucrose consumption increases the risk factor for dental caries (Sreebny 1982; Rugg-Gunn & Murray 1983).

A mixture of bagasse and molasses is used as a food source for cattle. When fed in large quantities and incorrectly, molasses may be toxic. The symptoms of molasses toxicity include; reduced body temperature, weakness and rapid breathing and the animal may have difficulty standing (Perez & de Azucar 2004). Molasses toxicity often affects eye-sight and the animal may become blind. This indicated damage to the brain and the clinical syndrome was similar to that of cerebro-cortical necrosis. Necrosis in the brain readily develops and allows rapid diagnosis. The necrosis is likely to be caused by either a decrease in energy supply to the brain because of thiamine deficiency or glucose deficiency (Preston 1988).

Bagasse like many other agricultural by-products such as cereal straws, is high in ligno-cellulose and may have a depressing effect on feed intake. The digestibility of bagasse is very poor because of the presence of lignin which protects carbohydrates from being digested by the rumen microbes (de la Cruz 1990; Leng 1991). To improve the nutritive value of ligno-cellulose materials for livestock, physical or chemical pre-treatments are required (Playne 1984; de la Cruz 1990).

5.2 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 by Chakraborty (2001) using skin tests, 70.58% of field workers with respiratory disorders showed highly reactive skin tests. The authors also tested rice and several other plant species and concluded that sugarcane pollen was the most significant allergenic type. However, there are no reports of any major allergic responses to the commercial hybrid cultivars of sugarcane in Australia (Chakraborty et al. 2001).

Hypersensitivity pneumonitis is the term applied to a group of allergic lung diseases; it can result from recurrent exposure and sensitisation through repeated exposure to organic dusts such as those present in mouldy sugarcane. Bagassosis, an occupational lung disease of the extrinsic allergic alveolitis type, is caused by breathing dusts containing fungal spores, thermophilic actinomycetes (*Thermoactinomyces sacchari*) which grow in stored, mouldy bagasse (Lacey & Crook 1988). Prolonged, repeated exposures can lead to permanent lung damage and scarring, and significant disability (Phoolchand 1991; Hur et al. 1994; Anon. 2003a).

5.3 Beneficial phytochemicals

Blackstrap molasses, its most concentrated form, is high in essential minerals, amino acids, linoleic acid and the majority of the vitamin B complex, and was used for the therapy of a variety of diseases, including cancer (Scott 1980a; Scott 1980b; Serrano & Thompson 1991; Thompson et al. 1996; Ames 2001).

SECTION 6 ABIOTIC INTERACTIONS

6.1 Abiotic stresses

6.1.1 *Nutrient stress*

The cultivation of sugarcane at present relies on the extensive use of fertilizers and pesticides. Nitrogen especially is used widely; imbalances in nitrogen levels in the soil can affect sugarcane stem maturation and thus sucrose accumulation. The sugarcane plant requires nitrogen for optimum development for yield and sugar content of the canes. Excess nitrogen however can prolong the crop maturation, resulting in a plant with an excessive leafy canopy, which in turn can make the plant more susceptible leaf diseases and attack by pests (Bakker 1999). A lack of nitrogen will show up as a plant with stunted, yellow, thin stems and narrow leaves and could lead to death of the leaves (Bakker 1999).

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

Potassium is required in greater amounts than nitrogen and phosphorus. It promotes the formation and translocation of sugars, improving the 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, see above. Potassium deficiency results in depressed growth, thin stalks and colouration of the leaves from dark green of young leaves to yellowing of the older leaves with chlorotic spots and ultimately death of the leaf (Bakker 1999).

Calcium is an important regulator of soil acidity, deficiencies can result in an increased fixation of phosphorus, aluminium, iron manganese and nickel (Bakker 1999). A deficiency in calcium results in stem diameter reduction. Magnesium is important for photosynthesis as it is responsible for the green colour in the leaves (it absorbs the blue and red light spectrum), deficiencies result in stalks of reduced diameter with internal browning (Bakker 1999).

Other micro element requirements include iron, aluminium, zinc, copper, boron, silicon 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).

6.1.2 *Temperature and light stress*

Sugarcane varieties differ in their degree of temperature sensitivity but in general germination is slow at soil temperatures below 18°C and will be increasingly rapid up to about 35°C (Bull 2000).

Cool night temperatures, high day temperatures and lack of moisture interfere with flower initiation and sucrose accumulation. Sugarcane breeding programs are severely limited by the nature of flowering of each sugarcane variety particularly by a decrease in flowering and pollen viability at high latitudes (Bull & Glasziou 1979; Dunkelman & Legendre 1982). Various techniques have been developed including alteration of photoperiod which can induce flowering so that flowers could be available for crossing when required (Bull & Glasziou 1979).

6.1.3 Water stress

Because sugarcane originated in the wet tropics, yields are much higher when the crop is supplied with adequate water. In Australia sugarcane is irrigated, a lack of adequate water affects sugarcane stem maturation and sucrose accumulation (Ham et al. 2000).

6.2 Abiotic tolerances

Sugarcane is relatively drought resistant but it results in a reduction of sugar production (FAO 2004).

Fire is often used to facilitate easier harvesting, it does not destroy the suckers and the plant will subsequently shoot from the nodes or regrow from the stools (FAO 2004).

The sugarcane plant can withstand shady conditions but sugar production will be reduced as it relies heavily on photosynthesis to produce sugar (FAO 2004). Similarly it can withstand periods of flooding, but prolonged periods of waterlogging will result in a decline in sugar content (FAO 2004).

Sugarcane can be grown in a range of altitudes from just above sea level to as high as 3000 metres above sea level (FAO 2004).

SECTION 7 BIOTIC INTERACTIONS

7.1 Weeds

There are a number of weeds that infest the sugarcane plantations including; grasses, broadleaf weeds and sedges. Grasses that occur in sugarcane growing districts include; Bermuda grass (*Cynodon dactylon*), wild sorghum (*Sorghum spp.*) and Guinea grass (*Panicum maximum*). Pasture grasses in particular can be problematic when the land is subsequently used to grow sugarcane (McMahon et al. 2000). Broadleaf weeds such as agerum (*Agerum spp.*) and purslane (*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 unlike sedges, which occur in all sugarcane growing regions and all soil types (McMahon et al. 2000). Vines have become an increasing problem after the adoption of trash-blanketting. They have the potential to grow rapidly and if left uncontrolled impede on the harvesters (McMahon et al. 2000).

Other weeds such as hymenachne and giant sensitive plant can also be a problem. Hymenachne is an aquatic grass to 2.5m tall and has been declared a *Weed of National Significance*. It has been planted extensively in northern Queensland and the Northern Territory as a fodder crop and has since escaped from its cultivation. It can block irrigation and drainage channels in sugarcane plantations and contaminate sugarcane crops. Spraying with herbicides every three months is used to control Hymenachne (Anon. 2003b). The Giant sensitive plant also known as tropical blackberry (*Mimosa diplotricha*) is a serious weed in northern Queensland and has been identified as weed that can invade sugarcane crops (Anon. 2007c).

Imperata cylindrica has also been reported in Australia, *I. cylindrica* is a perennial species that commonly grows on degraded or burnt-off land in most Australian sugarcane-growing districts (Clifford & Ludlow 1978; Hartley 1979; Hnatiuk 1990). It is a common weed in Queensland, and although it occurs in all Australian states it is not listed as a noxious weed in any jurisdiction (Kleinschmidt & Johnson 1977; Auld & Medd 1987; National Weeds Strategy Executive Committee 2002; Australia's Virtual Herbarium 2007).

Herbicides such as 2,4-D amine can be used on broadleaf weeds and paraquat, a non selective herbicide can be used on broadleaf, grassy and other weeds (McMahon et al. 2000).

7.2 Pests and pathogens

The cost of controlling the major pests and diseases of sugarcane to the sugarcane industry in Australia was estimated to be \$111 million in 1996 (McLeod et al. 1999). The major pests and diseases that cause losses in sugarcane production include cane grubs, feral pigs, ratoon stunting disease (RSD), sugarcane rusts, chlorotic streak and soil-borne diseases (McLeod et al. 1999). More recently sugarcane smut has become a serious threat to the industry, in 2006 it was detected on the east coast of Australia and is a notifiable disease under the Queensland Plant Protection regulations (Anon 2006). Overall pests and diseases result in net loss of less than 1%, which is low compared to other countries where it can be 10-15%. It is therefore important to maintain the low level of effects from these pests through the implementation of strict control and quarantine guidelines and the development of a response strategy in the event of an incursion. For more information refer to the National Sugar Industry Biosecurity Plan (Plant Health Australia 2004).

7.2.1 Pests

There are many insect and animal pests of sugarcane and some insects such as plant hoppers (*Perkinsiella saccharicida*), are also known vectors of diseases (Croft et al. 2000; Allsopp et al. 2003).

The cane grub (melolonthine white grubs, larvae of the endemic melolonthine beetle) are a major pest affecting the sugarcane industry. They collectively cost the industry over \$15 million a year in production loss and control costs. Several avenues are being pursued for the control of these insects. The application of the insecticide chlorpyrifos or the biological control agent *Metarhizium anisopliae* (a fungus that attacks the larvae) soon after planting, control the species for 2-3 years. Other insecticides such as granular cadusafos and liquid imidacloprid, applied after harvest or applied to the ratoon stubble also are of use but they require irrigation or rain to make them effective. All these applications are complicated by factors such as: stability in different soil types, long term nature and inaccessibility of the crop, difficulties associated with soil dwelling insects, and differences in life-cycle duration of the species (Robertson et al. 1998; Allsopp et al. 2003). The development of resistant cane varieties has been investigated with some success (Allsopp et al. 2003).

Recently, genetic engineering of sugarcane for resistance to cane grub has been initiated. This has created plants expressing compounds toxic to the cane grub such as snowdrop lectin, avidin or compounds obtained from the fungus *Metarhizium anisopliae*, which is also used as a bio-control agent (BSES 2005, (CRC SIIB 2006).

There are numerous vertebrate pests including ground rats (*Rattus sordidus*), climbing rats (*Melomys burtoni*), wallabies, striped possums (*Dactylopsila trivirgata*), the eastern swampen (*Porphyrio porphyrio*), cockatoos (*Cacatua galerita*), foxes and feral pigs. All these except for the fox and feral pig are native to Australia and consequently are protected. Permits for control of native animals in cane fields must be obtained from the relevant Cane Protection and Productivity Board. Rodents are the most serious pest to the sugarcane industry after the cane grub. They destroyed 825,000 tonnes of sugarcane valued at \$25 million during the 1999 and 2000 seasons (Dyer 2005). In addition, rats are known to be carriers of the bacterium *Leptospira* which can result in Leptosperosis disease in humans. The disease can be spread through soil, mud and water that have been contaminated with urine from infected animals (Anon 2003).

Integrated pest management is now widely employed to discourage and control economically damaging pests. Strategies such as controlling crop weeds have been shown to significantly reduce juvenile rat numbers by 50% and reduce crop damage by 60% (Allsopp et al. 2000;

Dyer 2005). A detailed risk analysis of potential pests and diseases affecting the sugarcane industry has been developed (Plant Health Australia 2004). Table 3 gives an overview of these insect pests.

7.2.2 Pathogens

Various biological agents including bacteria, fungi and viruses cause diseases of sugarcane. Diseases of sugarcane that have been identified in Australia are listed in Table 3.

Disease control in sugarcane is based on an integration of legislative control, resistant varieties, and other management procedures. Long-term disease management in Australia focuses on the development of disease resistant cultivars (McLeod et al. 1999). 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 et al. 2000). Machine harvesters can also transmit disease.

Many sugarcane diseases are also managed through the use of disease-free planting material supplied through Cane Protection and Productivity Boards. To obtain such planting material hot-water treatments are used to disinfect planting material. Long hot-water treatment (3 hours at 50°C) 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 (50°C for 30 minutes) is used to control chlorotic streak and some insect pests (Croft et al. 2000). Allsopp *et al* (2000) found that minimising cultivation can encourage healthy microbial communities and reduce disease-causing organisms (Allsopp et al. 2000).

Bacterial diseases

Ratoon stunting disease (RSD) is a highly infectious disease caused by *Clavibacter xyli subsp xyli* which infects vascular tissues of sugarcane. The ratoon stunting disease of sugarcane is probably the most important disease of sugarcane. In Australia, the estimated loss from this disease was \$6.3m/year (McLeod et al. 1999). The symptoms are poor growth and stunted shoots, which might not be obvious if most plants in the field are infected. The visual symptoms of red-orange dots in the vascular tissues can be seen only when the stalks are cut and sliced (Croft et al. 2000). The disease is transmitted through 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 (Anon. 2005a).

Table 3 Insect pests of sugarcane (summarised from Agnew 1997 (Agnew 1997)).

Common Name	Species	Affected Plant Part	Control
Cane grubs	19 native species of beetle larvae	Roots – significant root damage destabilises stool leading to lodging	primarily insecticide sprays
Soldier fly	<i>Inopus rubriceps</i> and <i>I. flavus</i> larvae	Roots – poor germination	no chemical control, plough out and leave bare fallow for a season, replant late
Ground pearls (bugs)	<i>Eumargarodes laingi</i> and <i>Promargarodes australis</i> nymphs	Roots – form cysts in soil (pearl) and feed on sap	no chemical control, tolerant varieties, plough out and leave bare fallow for a season
Cicadas	3 species, nymphs	Roots – sap feeding	no chemical control, plough out and leave bare fallow for a season
Funnel ants	<i>Aphaenogaster pythia</i>	Roots – weakens stools	no chemical control, plough out
Symphylans	<i>Hanseniella</i> spp.	Roots – poor crop establishment	encourage rapid germination, insecticides
Nematodes	several	Roots – interfere with water and nutrient absorption	nematicides
Wireworms (click beetle larvae)	<i>Agrypnus variabilis</i> and <i>Heteroderes</i> spp.	Shoots – bore into the buds of setts or the growing point	insecticides in plant crops (none for ratoon crops)
Black beetles	<i>Heteronychus arator</i> and <i>Metanastes vulgivagus</i>	Shoots – chew into young shoots causing death of the shoot	no chemical control, plough out and leave bare fallow for a season, insecticides registered for <i>H. arator</i> control in NSW only
Rhyparida beetles	<i>Rhyparida morosa</i> and <i>R. dimidiata</i>	Shoots – chew into young shoots causing death of the shoot	none available
Butt weevil		Shoots – bore into setts and ratoons (occurs rarely)	none available
Stenocorynus weevil	<i>Stenocorynus</i> spp.	Shoots – chew roots of germinating setts, weakening growth (occurs rarely)	none available
Whitefringed weevil	<i>Naupactus leucoloma</i>	Shoots – chews leaves (occurs rarely)	none available
Large moth borer	<i>Bathytricha truncata</i>	Shoots – chew into young shoots causing death of the shoot (minor pest)	none available
Ratoon shoot borer	<i>Ephysteris promptella</i>	Shoots – chew into young shoots causing death of the shoot	no chemical control, damage only severe under drought conditions
Bud moth	<i>Opogona glycyphaga</i>	Shoots – chew buds preventing germination (occurs rarely)	none available
Field crickets	<i>Teleogryllus oceanicus</i> and <i>T. commodus</i>	Shoots – chew buds preventing germination (occurs rarely)	none available
Mole cricket	<i>Gryllotalpa</i> sp.	Shoots – chew buds and young shoots	none available
Wart eye	unidentified mites	Shoots – buds fail to germinate	none available
Sugarcane weevil borer	<i>Rhabdoscelus obscurus</i>	Stem – bore into stems allowing other diseases in	no chemical control, quarantine between growing areas of sugarcane and palms
Termites	several species	Stem – hollow out stems	no chemical control, remove dead wood from cane fields
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	<i>Perkinsiella saccharicida</i>	Leaf and stem – sap feeding, vector for Fiji disease	Fiji disease resistant varieties
Linear bug	<i>Phaenacantha australiae</i>	Leaf and stem – sap feeding, damaged leaves more susceptible to fungal diseases	natural enemies
Mealybug	<i>Saccharicoccus sacchari</i>	Leaf and stem – sap feeding	natural enemies
Aphids	3 species	Leaf and stem – sap feeding	natural enemies
Scale insect	<i>Aulacaspis madiunensis</i>	Leaf and stem – sap feeding	disease free planting material

Leaf scald is caused by the bacterium *Xanthomonas albilineans* which infects the vascular tissues of sugarcane. It is found in most sugarcane districts in Queensland (Croft et al. 2000). Leaf scald is characterised by the 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 (Anon. 2005c). Leaf scald can spread by wind-blown rain, plant material, and contaminated cutting equipment such as planters and harvesters (Croft et al. 2000). 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. Resistant cultivars are used to curb the spread of the disease and susceptible plants are not used in the breeding program (Anon. 2005c).

Fungal diseases

Orange rust is caused by *Puccinia kuehnii*. Disease symptoms are distinct from those of sugarcane rust caused by *P. melanocephala*. Pustules of the orange rust are orange while those of sugarcane rust are reddish brown. Leaf lesions tend to be grouped in clusters while those of sugarcane rust are distributed evenly on leaves. Pustules rupture the leaves and allow water to escape from the plant, leading to moisture stress. Rain favours the development of orange rust but inhibits the development of sugarcane rust (Croft et al. 2000).

In 1999-2000, sugarcane crops in Australia were affected by the outbreak of orange rust, which severely damaged the most widely grown commercial cultivar, Q124 (Apan et al. 2003). Subsequently, the high yielding and orange rust resistant cultivar, Q205 was developed (Courtney 2002). Highly susceptible parents are no longer used in any breeding programs. More recently, cultivars such as Q173 and Q182 have also been found to be affected by the disease (Anon. 2005a).

Table 4. Diseases of sugarcane that cause yield losses in Australia (Frison & Putter 1993; McLeod et al. 1999; Croft et al. 2000).

Common name	Causal agent	Control
Bacterial		
Leaf scald	<i>Xanthomonas albilineans</i>	Resistant varieties
Ratoon stunting disease (RSD)	<i>Clavibacter xyli</i> subsp. <i>xyli</i>	Disease free planting material
Red stripe (Top rot)	<i>Acidovorax avenae</i> subsp. <i>avenae</i>	Resistant varieties
Fungal		
Rusts	<i>Puccinia melanocephala</i> and <i>P. kuehnii</i>	Resistant varieties
Yellow spot	<i>Mycovellosiella koepkei</i>	Resistant varieties
<i>Pachymetra</i> root rot	<i>Pachymetra chaunorhiza</i>	Resistant varieties
Sugarcane smut	<i>Ustilago scitaminea</i>	Resistant variety, hot water treatment
Pineapple disease	<i>Ceratocytis paradoxa</i>	Fungicide applied to setts
Eye spot	<i>Bipolaris sacchari</i>	Resistant varieties
Red rot	<i>Glomerella tucumanensis</i>	Resistant varieties
Pokkah boeng ('tangle top')	<i>Fusarium moniliforme</i> (<i>Gibberella fujikuroi</i>) and <i>F. subglutinans</i> (<i>G. subglutinans</i>)	plants usually recover without need for disease control
Viral		
Chlorotic streak	Unknown, probably virus	Disease free planting material, good drainage
Fiji disease	Fiji disease phytoereovirus (FDV)	Resistant varieties
Mosaic diseases	Potviruses: Sugarcane mosaic virus (SCMV), Sorghum mosaic virus (SmMV), Maize dwarf mosaic virus (MDMV), Johnson grass mosaic virus (TGMV), striate mosaic associated virus.	Disease free planting material and resistant varieties

Sugarcane rust is caused by *Puccinia melanocephala*, an obligate parasitic fungus, which spreads by windblown spores. Transmission may occur over long distances and is favoured by cool conditions (Kishi 2002; Anon. 2005a). Symptoms begin as tiny, elongated spots, light green to yellow on leaves. These spots later enlarge and turn to reddish brown. Yield loss depends on environmental conditions and was estimated to be 10-20% in Australia and 20-40% in USA (Bernard 1980; University of Florida 2004). Estimated loss from sugarcane rust in Australia was \$3.5m (McLeod et al. 1999).

Pachymetra root rot caused by *Pachymetra chaunorhiza* is a disease only found in Australia in the Queensland and NSW sugarcane districts (Magarey & Bull 2003). The disease seems to favour high rainfall areas and spores generated by this fungus can survive up to 5 years in the soil (Anon. 2005a). In northern Queensland, surveys indicate that almost every field is infected with the disease. The disease is characterised by a soft rot of the primary and some secondary roots leading to poor root development. Yield loss caused by Pachymetra root rot was estimated to be up to 40% (Magarey 1994). Fungicides have not been effective at an economical rate and control is based on planting resistant cultivars (Anon. 2005a).

Sugarcane smut, caused by *Ustilago scitaminea*, is a serious disease of sugarcane that can reduce yields by 20-30%. The disease causes severe stunting and is characterised by black, whip-like structures that form at the growing points of sugarcane plants. These whips replace the spindle leaves and are formed in the shoots developing from infected cane cuttings (Frison & Putter 1993). There was an outbreak of smut in Australia in July 1998 in the Ord River area of Western Australia. This outbreak was controlled and the disease had not been detected in eastern Australia until 2006 when it first appeared in Childers in Qld. Since then it has spread to Mackay, Burdekin and other areas and is now seen as being widely spread and established (Watson 2007). The spread and occurrence of the disease is being controlled through planting of existing and new resistant varieties (Q177, Q200, Q208, KQ228 and QS94-2329), using uninfected canes and best farming practices. However the resistant varieties can have a lower yield than the non-resistant cultivars. Yield or resistance is also dependant on soil type in the region (Watson 2007).

In order to reduce the spread of sugarcane smut, the movement of sugarcane and sugarcane machinery is restricted in Queensland (Anon. 2002b). Provisions under the *Plant Protection Act 1989* (Qld) allow for inspectors to order the destruction of diseased cane and practical guidelines have been developed to control the spread of the disease (Anon. 2005b; Anon. 2005d; Anon 2006). An independent report was commissioned to assess the economic impact of sugarcane smut (Watson 2007). Some of the recommendations include; the development of a regional smut response plan prior to planting in spring 2007; an assessment of the risk of smut infestation on the region including a proposed course of action when smut is detected in each farm in that region; a program for reducing smut susceptibility and the rate of spread of smut in the region (minimising the inoculum pressure); the propagation and distribution of clean (smut-free) and smut-resistant planting material; reducing the probability of the spread of smut by mechanical means and the risks of the presence of abandoned cane; recommendations for changing the approved variety lists for planting and ratooning (Watson 2007).

Other fungal diseases of sugarcane are minor diseases (Table 4) and cause less impact on yield.

Viral diseases

Chlorotic streak is thought to be caused a virus. The disease occurs in sugarcane districts with wet and poorly drained fields. Lower incidence of the disease is generally found in drier regions (Croft et al. 2000). The symptoms are the yellow to white streaks on the leaf and on the midrib and leaf sheath. Older streaks change to yellow and are more visible than younger

streaks. Finally chlorosis starts to appear in the middle of the leaves. Internal vascular bundle tissues may be reddish in colour. Yield can be reduced by up to 70% (Croft et al. 2000). The disease is transmitted in the soil by water. It is common in areas with poor drainage and flood prone areas. Chlorotic streak can also be transmitted through cuttings. Infected cuttings show poor germination, slow growth and a reduction in stool number.

Fiji disease is caused by *Fiji disease virus* (FDV). The 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. The colour of the galls can vary from white to green and the surface of the gall is usually smooth. When the gall is old the epidermis may be ruptured and appear brown. At advance stage of infection, stem development slows down and successive leaves become smaller and stiffer, the whole top part of the stem develops a fan like appearance (Croft et al. 2000). Fiji disease can be transmitted by infected cuttings and plant hoppers (*Perkinsiella saccharicidae*) are a known vector for the disease. Significant yield loss was recorded in 1970s in Queensland (Croft et al. 2000). Due to the intensive management program put in place, there have been no reports of disease incidence since the 1980s.

Sugarcane mosaic is caused by a number of potyviruses such as the *Sugarcane mosaic virus* (SCMV). The mosaic symptom pattern appears in young growing leaves. Once the leaves are older, infected leaves may appear relatively normal as the mosaic become green. Yield loss caused by sugarcane mosaic was 40% in some fields in Australia (Croft et al. 2000). Aphids are the vector for transmission of the disease and seed produced by infected cane can also transmit the disease.

For a summary of viral diseases of sugarcane see Table 4.

SECTION 8 WEEDINESS

In Australia sugarcane occurs almost exclusively in managed cultivation. In sugarcane growing districts, transient sugarcane plants may occur along roadsides or railways where it can establish after displacement during transport, but there is no indication that these form self-perpetuating populations.

Because of higher genetic variability of polyploid species, *S. spontaneum* has variable morphology and physiology, enabling it to develop higher phenotypic plasticity and effectively compete in disturbance prone and changeable habitats. *S. spontaneum*'s competitive advantage is due to its diverse reproductive abilities, it can reproduce by both vegetative propagation (layering, root and stem cutting) and seed. It invades aggressively both underground and above ground by extending rhizomes, tillers (secondary shoots) and tertiary shoots, which together form thick stools or clumps (Pursglove 1972). The dense root mat of *S. spontaneum* makes it impossible for young seedlings to penetrate and emerge. *S. spontaneum* tolerates a broad range of soil types and moisture contents, is shade tolerant and produces many small wind dispersed seed (Pursglove 1972). These weedy like traits have not been incorporated into commercial *S. spontaneum* hybrids.

There are a number of species within genus *Saccharum* which are recognised as weeds elsewhere such as *Saccharum arundinaceum*, *S. bengalense*, *S. floridulum*, *S. narenga*, *S. procerum* and *S. ravennae* (Randall 2002). There are no records of these species in Australia (Hnatiuk 1990; Randall 2002).

8.1 Weediness status on a global scale

Commercial cultivars of sugarcane are hybrids of *S. officinarum* and *S. spontaneum*, these hybrids are not recognised as weeds anywhere in the world (Holm et al. 1997).

S. spontaneum, considered the most primitive species, 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 subtropical regions, most commonly found in central and south-eastern Asia (Holm et al. 1997). It is classified as a noxious weed in 42 states of the USA (USDA 2004) and is present as a sporadic weed in Europe, Africa and the tropical New World (Holm et al. 1997). *S. spontaneum* is a serious agricultural weed in Thailand, the Philippines, India and Indonesia 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 (Holm et al. 1997; Hammond 1999).

S. officinarum has escaped the agricultural area and naturalised in some areas but has not been recorded as a major weed (Hnatiuk 1990; Holm et al. 1997; USDA 2004).

Other species in the *Miscanthus* and *Erianthus* genera are listed in 'A Global Compendium of Weeds' as weeds of agriculture in Asia (Randall 2002).

8.2 Weediness status in Australia

Commercial cultivars of sugarcane are hybrids of *S. officinarum* and *S. spontaneum*. These hybrids are not recognised as weeds in Australia. They have lost many of the critical weedy attributes that were present in the parental species from which the cultivated sugarcane hybrids were derived (Holm et al. 1997). Most commercial cultivars of sugarcane are routinely harvested before flowering as the process of flowering leads to reduction in stem sugar content (Moore & Nuss 1987). As discussed above, when allowed to flower, sugarcane flowering is erratic and variable and sugarcane seed is short-lived. Even if seed is produced, the chance of it germinating, surviving to reproductive maturity and spreading is low (Rao 1980; Bakker 1999).

8.3 Weediness in Agricultural systems

The potential for *Saccharum spp.* hybrids to become weeds in Australia is low because canes are harvested before they flower as mentioned above. Unaided dispersal of the sugarcane vegetative materials is unlikely due to the size and weight of the stem sections. Animal pests such as feral pigs have the strength to remove plant material and take them elsewhere, but there are no reports of feral pigs or other animal pests of sugarcane having done so. Establishment and spread of volunteers are unlikely as the seedlings of modern cultivars are highly susceptible to pests and weeds and therefore unlikely to establish and spread without human intervention. Un-germinated stem cuttings tend not to survive for long as they are rapidly degraded by soil micro-organisms due to their high sugar content. In addition, they have specific requirements for factors such as soil type, sun light and temperature (Bakker 1999; Hogarth & Allsopp 2000).

Narenga porphyrocoma has been collected from a single site in Queensland within commercial sugarcane growing areas (Australia's Virtual Herbarium 2004).

8.4 Weediness in Natural ecosystems

Volunteer sugarcane seedlings of modern cultivars are non-invasive in natural habitats and are likely to be controlled by natural herbivores during early stages of growth or be out-competed by other weeds. Sugarcane does not appear to be problem as a volunteer weed (Berville et al. 2005).

Australia's Virtual Herbarium has records of *S. spontaneum* collected in the Northern Territory, Queensland and northern New South Wales (Australia's Virtual Herbarium 2007). Naturalised population of *S. spontaneum* have been found in Northern Australia, further

research is being undertaken into the fertility of this species (Bonnett et al. 2007). Evidence suggests that currently *S. spontaneum* is not a serious weed in Australia, because surviving uncultivated populations have established in the Northern Territory for at least 50 years without further spread. Stools of the commercial *S. spontaneum* cultivars can be seen around the planted fields however these do not appear to spread. None of five recognised *Saccharum* species (*S. spontaneum*, *S. robustum*, *S. barberi*, *S. sinensis* and *S. officinarum*) are native to Australia. Some of these species are maintained within Australian sugarcane research stations as germplasm. Only two parental species of modern cultivars, *S. spontaneum* and *S. officinarum*, are recorded naturalised in Australia, (Hnatiuk 1990).

S. officinarum has escaped the agricultural area and become naturalised in some areas but has not been recorded as a major weed in Australia (Hnatiuk 1990; Holm et al. 1997; USDA 2004). Lazarides et al (1997) recorded it as a minor weed found naturalised in some Tropical and Mediterranean climates in Australia. *S. officinarum* has also been recorded as a minor weed and/or a quarantine species in some countries because it may pose a risk of quarantine disease transmission (Randall 2002).

As a result of many years of cultivation, *S. officinarum* has essentially lost the capacity to invade in uncultivated habitats. Recent molecular studies have shown *S. officinarum* to have low levels of genetic diversity compared to other *Saccharum* species (Nair 1999; Janno et al. 1999; Coto et al. 2002). Generally this species has less capacity to compete in the natural environment than *S. spontaneum*. However, due to its perennial nature, some populations escape from cultivation and can persist as long as there is sufficient moisture in the root zone. A few populations of *S. officinarum* have established outside agricultural areas in southern Queensland for 30-40 years. These populations consist of only a few stools and do not result in further spread (Randall 2002).

Miscanthus sinensis has been recorded in southern Western Australia, the central coast of New South Wales, southern South Australia, southern Victoria and in two locations in Tasmania (Australia's Virtual Herbarium 2004) and locally is considered weedy (Hnatiuk 1990; Lazarides et al. 1997). *S. robustum* is thought to have arisen from a spontaneous hybridisation event between *Miscanthus floridulus* and *S. spontaneum*. *Miscanthus floridulus* is a noxious weed overseas, it has been found naturalised in Australia but has not been recorded as a weed (Australia's Virtual Herbarium 2004). *Miscanthus nepalensis* is recorded as locally invasive in New Zealand and Brazil (Randall 2002).

Some accessions of the *Saccharum* complex, such as *Erianthus* and *Miscanthus* are maintained in many sugarcane research station germplasm collections for sugarcane breeding in Australia.

8.5 Control measures

Remaining stands of sugarcane are removed through treatment with herbicides such as glyphosate rather than by tillage. This in turn reduces soil compaction and improves soil structure (Willcox et al. 2000).

SECTION 9 POTENTIAL FOR VERTICAL GENE TRANSFER

Sugarcane is closely related to the genera *Erianthus*, *Narenga*, *Miscanthus* and *Sclerostachya*. These genera including *Saccharum* are collectively known as the *Saccharum* complex and are expected to be sexually compatible at some levels (Bull & Glasziou 1979; Grassl 1980; Daniels & Roach 1987).

9.1 Intraspecific crossing

As indicated above, sugarcane flowering is variable in the field and the crop is exclusively vegetatively propagated. Sugarcane is a largely cross-pollinated species with a low frequency

of selfing and pollen is dispersed by wind (McIntyre & Jackson 2001). No insect or animal vectors for sugarcane pollen are known. Pollen viability is low under natural environmental conditions (Moore 1976). Sugarcane pollen rapidly desiccates after dehiscence, having a half life of only 12 minutes and no viability after 35 minutes at 26.5°C and 67% relative humidity (Moore 1976). Even under artificial conditions, storage of sugarcane pollen is difficult and has been the subject of intensive investigations by sugarcane breeders, who would like to store valuable pollen for desirable crosses.

Different varieties of sugarcane produce different amounts of pollen. Crossing and selfing therefore varies greatly. Analysis of seed derived from crossing studies show seed set varied between 3.1-22.7% reflecting the poor viability of sugarcane pollen (Grassl 1980; Rao 1980). In some case seed were uniform in size but up to 30% were smaller or shrivelled, however, most of them germinated (Rao 1980). Molecular methods have indicated that 0-17% of progeny from apparent hybrid crosses are actually the result of selfing (flower being fertilised by its own pollen (McIntyre & Jackson 2001). Selfing frequencies were found to vary dramatically between 0-18% to 0-80% (Hogarth 1980; McIntyre & Jackson 2001).

Viable pollen of sugarcane would not be expected to disperse very far. Accordingly, cross-pollination would only be expected to occur to flowering sugarcane plants growing in close proximity. In addition, a very low rate of successful crosses would be expected due to the rapid loss of pollen viability.

The fertility of the commercial sugarcane cultivars is currently poorly understood. This is mainly a result of the fact that the seeds produced as a result of flowering are not the primary product of this crop. In fact the plant are not grown to the flowering stage and are harvested prior to the onset of flowering as to optimise sugar content in the plants.

Bonnett et al. (2007) have undertaken a study to determine the pollen viability of the three cultivars Q117^A, Q183^A and Tellus^A. This included the recording of presence of flowers with subsequent sub-sampling of pollen for viability tests. Variation in the propensity to flower, seed viability and germination rates were observed among the cultivars. Fertile seed was produced by all three cultivars but they differed in the germination success. It is important to know which cultivars may show overlapping flowering times, and thus the potential for cross pollination. The proportion that would have viable seeds as a result of cross fertilisation needs to be determined. These studies, as well as the impact on the environment of any successful cross fertilisations are currently being undertaken.

In addition, due to the planting of smut resistant varieties, such as Q177, Q200, Q208, KQ228, large numbers of new hybrid cultivars are now being cultivated and the flowering properties of these are currently poorly understood (Bonnett et al. 2007). These relatively new varieties are likely to be the target for the future development of transgenic varieties thus having a more detailed understanding of their flowering and reproductive properties will be essential.

9.2 Interspecific crossing

It has been reported that species within the genus *Saccharum* can hybridise with other closely related species (Grassl 1980; Daniels & Roach 1987). However, such reports of hybridisation do not generally refer to modern sugarcane varieties (complex hybrids).

Gene flow between *Saccharum spp.* hybrids to other *Saccharum* species is likely to be low, because plants are likely to be harvested before flowering. In case of commercial sugarcane cultivars if seed set happens, seedling survival is poor, and field management methods would limit survival of any volunteer plants.

None of five recognised *Saccharum* species (*S. spontaneum*, *S. officinarum*, *S. robustum*, *S. barberi* and *S. sinensis*) are native to Australia. These species are maintained within sugarcane research stations as germplasm stocks. These species have been used in breeding programs to produce new varieties. Of these species only *S. officinarum* and *S. spontaneum* are recorded as naturalised in Australia. There are no records of native or endangered species having sexual compatibility with sugarcane in Australia (Daniels & Roach 1987).

There are a number of species within the *Saccharum* genus which are recognised as weeds elsewhere, such as *Saccharum arundinaceum*, *S. bengalense*, *S. floridulum*, *S. narenga*, *S. procerum*, *S. ravennae* (Randall 2002). These species have potential to outcross successfully with hybrid sugarcane but as mentioned above there have been no records of these species in Australia (Hnatiuk 1990; Australia's Virtual Herbarium 2007).

9.2.1 *Natural interspecific crossing*

As indicated above, sugarcane is closely related to the genera *Erianthus*, *Narenga*, *Miscanthus* and *Sclerostachya*. These five genera (including *Saccharum*) are collectively known as the *Saccharum* complex and are expected to be sexually compatible at some levels. It is unlikely that sugarcane will hybridise naturally with *E. arundinaceus*. In addition, similar to *S. officinarum*, resulting hybrids are likely to lack vigour and fertility due to chromosome elimination (Bull & Glasziou 1979; Grassl 1980; Daniels & Roach 1987).

9.2.2 *Crossing under experimental conditions*

Although many attempts to cross between these species may have been attempted in sugarcane research stations, limited publications are available. Of 96 crosses made at BSES in Queensland between *Erianthus arundinaceus* and *S. officinarum* or hybrid *Saccharum* spp., 26 were fertile producing over 1000 seedlings. Only 19 of the putative hybrids survived, all were derived from *S. officinarum* as a female parent and *E. arundinaceus* as a male parent (Piperidis et al. 2000). Genuine hybrids were produced at a frequency of 2.8% however all of these hybrids had poor vigour and were sterile (Piperidis et al. 2000). Chromosome elimination has been observed in all these hybrids. Molecular studies have demonstrated that *E. arundinaceus* is genetically quite distant from *Saccharum* (Nair 1999; Alix et al. 1999).

Nonetheless Cai et al. (2005) have successfully produced a fertile intergeneric cross between *E. arundinaceus* and *S. officinarum* thus potentially opening opportunities for breeders to utilise the beneficial traits of *E. arundinaceus*, such as good ratooning ability, drought and/or water logging tolerance and disease resistance, in breeding programs.

Hybridisation with *Saccharum* has also been attempted with some distantly related genera belonging to tribe Andropogoneae such as *Imperata* (blady grass), *Sorghum* (sorghum) and *Bambusa* (bamboo) (Thomas & Venkatraman 1930; Janakiammal 1938; Rao et al. 1967; Nair 1999). These claims for intergeneric hybrids are based on anatomical morphological and cytological studies but have never been verified by molecular analysis. A few of these putative intergeneric hybrids could not be accepted as true hybrids (Rao et al. 1967; Grassl 1980; Nair 1999).

Histological analysis of crosses between *S. officinarum*, *S. robustum*, *S. spontaneum* plus seven *Saccharum* hybrids and *Bambusa* indicated that hybrid embryos aborted during the early embryogenic stage (Rao et al. 1967). Four mature seeds were obtained from 960 crosses using *Bambusa* as a female parent, all putative hybrid seeds were either from *S. spontaneum* or *S. robustum* as male parents. These putative hybrids either failed to germinate from seed or died at seedling stage (Rao et al. 1967).

Sorghum species have been artificially crossed with *Saccharum* hybrids and *S. officinarum* (Grassl 1980; Nair 1999). Wild *Sorghum* species are among the weeds of Australian sugarcane crops and are widespread in Australia (Hnatiuk 1990; McMahon et al. 2000). Generally, the putative hybrid offspring have been of low vigour and fertility, but back crossing to both parents have been achieved (Grassl 1980; Sreenivasan et al. 1987). However, Grassl (1980) recorded that after the 4th to 5th generation of backcrossing to sorghum, the sugarcane chromosomes had been eliminated from the intergeneric hybrids (Grassl 1980).

There is one report of experimental cross between *I. cylindrica*, a common weed in sugarcane growing districts in Queensland and a *Saccharum* hybrid, producing triploid progeny resembling sugarcane, which could apparently self-fertilise to produce F2 progeny (Daniels & Roach 1987; Sreenivasan et al. 1987). 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 artificial hybrids have not been observed in the wild.

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