Australian Government
Department of Health
Office of the Gene Technology Regulator

The Biology of *Sorghum bicolor* (L.) Moench subsp. *bicolor* (Sorghum)

Photo taken by R. R. Kowal, Department of Botany, University of Wisconsin-Madison

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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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ABBREVIATIONS

ABA	Abscisic acid
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Africa Biofortified Sorghum
ALUM	Australian Land Use and Management classification
Ca	Calcium
CGIAR	Consultative Group for International Agricultural Research
CMS	Cytoplasmic male sterility
cpDNA	Cytoplasmic DNA
DESA/UNSD	Department of Economic and Social Affairs, United Nations Statistics Division
DNA	Deoxyribonucleic acid
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization of the United Nations Statistics Division
Fe	Iron
GP1	Genepool 1 – primary genepool
GP2	Genepool 2 – secondary genepool
GP3	Genepool 3 – tertiary genepool
GRDC	Grains research and Development Corporation
GRIN	Germplasm Resources Information Network (USDA-ARS)
HCN	hydrocyanic acid (prussic acid)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IPM	Integrated pest management
m	metres
Mbp	Mega base pairs
mg	Milligrams
Mg	Magnesium
N	Nitrogen
Na	Sodium
NPV	nucleopolyherovirus
NSW	New South Wales
NSW DPI	New South Wales Department of Primary Industries
NT	Northern Territory
OECD	Organisation for Economic Co-operation and Development
OGTR	Office of the Gene Technology Regulator
P	Phosphorus
QAAFI	Queensland Alliance for Agriculture and Food Innovation
Qld	Queensland
QDAF	Queensland Department of Agriculture and Fisheries
t	Tonnes (metric)
the Regulator	the Gene Technology Regulator
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture Agricultural Research Service
WA	Western Australia
WA DA	Western Australia Department of Agriculture
WCSP	World Checklist of Selected Plants species (Kew Gardens, UK)
WRA	Weed risk assessment
Zn	Zinc

PREAMBLE

This document describes the biology of *Sorghum bicolor* (L.) Moench subsp. *bicolor,* with particular reference to its cultivation, uses and agroecology in the Australian environment. Information included relates to the taxonomy and origins of cultivated *Sorghum bicolor*, general descriptions of its morphology, reproductive biology, biochemistry, and biotic and abiotic interactions. The purpose of this document is to provide baseline information about the parent organism for use in risk assessments and risk management plans of genetically modified (GM) *Sorghum bicolor* that may be released into the Australian environment. The OECD and the Canadian Food Inspection Agency have also published biology documents about *Sorghum bicolor* that can be consulted. Common names of sorghum include wild grain, grain sorghum, broomcorn, milo, jowar, kafir corn, guinea corn and cholam, among many others (USDA ARS 2015). In this document 'cultivated sorghum' or 'sorghum' will be used to refer to *Sorghum bicolor* grown for grain in Australia.

Sorghum is a widely adaptable species that is cultivated as an annual cereal and forage crop in tropical, subtropical and temperate regions of the world. Sorghum grain is a staple human food in Africa and Asia, but is grown almost solely as a livestock feed in the western hemisphere. In Australia, sorghum is cultivated extensively in Qld and NSW where it is used almost exclusively for animal production in the beef, dairy, pig and poultry industries (QDAF 2012b).

Wherever possible, reference material discussing Australian examples is used, however much of the available information comes from other countries. Where differences may occur in the Australian context, or if it is unknown whether the information will be directly applicable to the Australian context, this will be highlighted.

SECTION 1 TAXONOMY

The genus *Sorghum* belongs to the grass family *Poaceae* (*Gramineae*), tribe *Andropogoneae*, subtribe *Sorghinae* (Clayton & Renvoize 1986). The *Andropogoneae* also contains important crops such as sugarcane (*Saccharum spp.*) and maize (*Zea mays*). The genus *Sorghum* is a very diverse group which has made the classification of domesticated and wild sorghums difficult (Wiersema & Dahlberg 2007). It consists of 25 recognised species that are classified morphologically into five subgenera: *Chaetosorghum*, *Heterosorghum*, *Parasorghum*, *Stiposorghum* and *Eusorghum* (Celarier 1958; Price et al. 2005a; USDA ARS 2015). Cultivated sorghum belongs to the subgenus *Eusorghum* (see below). Extensive lists of synonyms for *Sorghum* species can be found in the World Checklist of Selected Plant Species (WCSP 2013) and the USDA GRIN (USDA ARS 2015) databases. A list of the synonymous names for *Sorghum* species is given in Table A1, Appendix A.

The complexity of *Sorghum* is reflected in the chromosome number of the species belonging to the different subgenera (Figure 1). In *Parasorghum* and *Stiposorghum*, five is the lowest chromosome number and most polyploid species are autopolyploids in which chromosome number is built by units of ten (i.e. 2n=10, 20, 30). In *Eusorghum* the smallest chromosome number found is ten, the polyploid species are allopolyploids and chromosome number is built by units of twenty (i.e 2n=20, 40). Both *Chaetosorghum* and *Heterosorghum* are 2n=40 allopolyploids (Celarier, 1958).

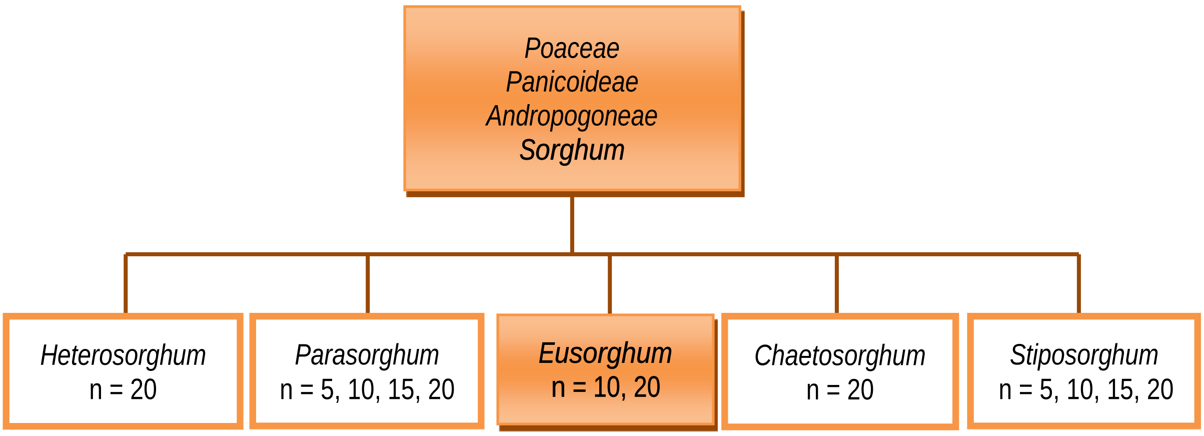

Figure 1. Subgenera of *Sorghum* (Ejeta & Grenier 2005).
n represents haploid chromosome number.

The five subgenera of *Sorghum* determined on morphological characteristics are not entirely concordant with molecular phylogenetic analysis and there are ongoing investigations to re-examine taxonomic classification. While one study indicated that *Sorghum* should be divided into three genera (Spangler 2003), another indicated that *Sorghum* should remain a single genus (Dillon et al. 2007a). The latter study suggested that the 25 *Sorghum* species form a distinct monophyletic group containing two strongly supported lineages. The authors proposed that *Eusorghum* together with *Heterosorghum* and *Chaetosorghum* formed one lineage, while *Parasorghum* and *Stiposorghum* formed a second strongly-supported lineage within the genus.

Subgenus *Eusorghum*

Eusorghum (sometimes referred to as *Sorghum* or *Eu-sorghum*) includes all cultivated sorghum races and their close wild relatives (Figure 2). The species and subspecies in this subgenus are inter-fertile and gene flow occurs from cultivated sorghum to wild relatives and *vice versa* (see section 9).

This subgenus contains three species: *S. halepense* commonly known as Johnson grass, a significant weed species; *S. propinquum*, and *S. bicolor* (de Wet 1978). The former two species are rhizomatous perennials while *S. bicolor* is a short-term perennial, lacks rhizomes and is usually cultivated as an annual (Ejeta & Grenier 2005).

Sorghum bicolor is further divided into three subspecies (Figure 2). *Sorghum bicolor* subsp. *bicolor* contains all the cultivated sorghums. *Sorghum bicolor* subsp. *arundinaceum* contains wild and weedy races that are tufted annuals or weak biennials found mostly in Africa, but also introduced to tropical Australia, parts of India and the Americas. *Sorghum bicolor* subsp. *drummondii* is the group of stabilised races that includes forage sudangrass and the weedy shattercanes (de Wet 1978; Dahlberg 2000).

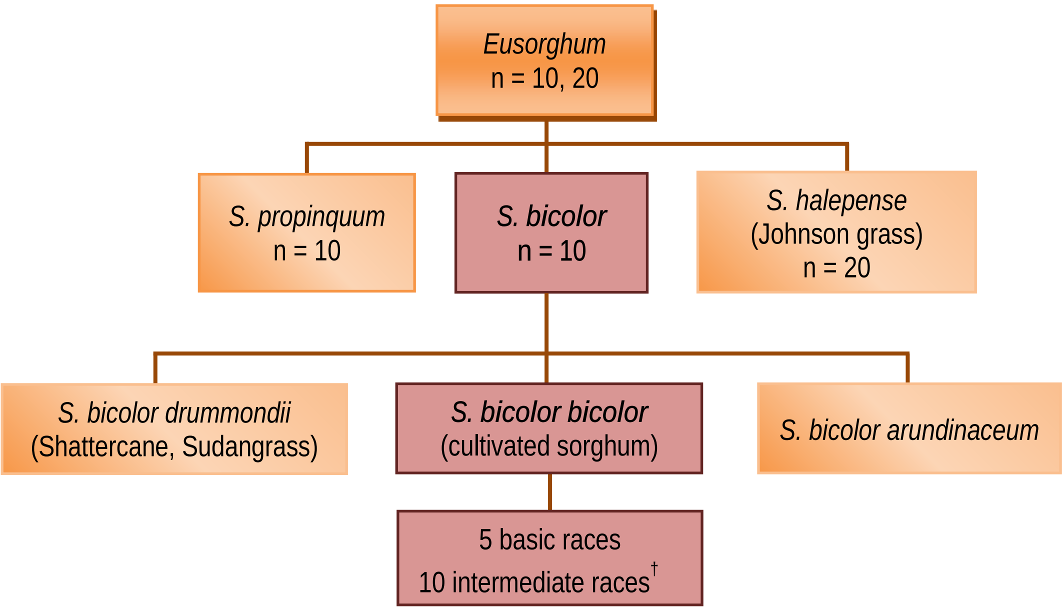

Figure 2. Species and subspecies of the subgenus *Eusorghum* (Ejeta & Grenier 2005).
†Harlan & de Wet (1972).

S. bicolor subsp. bicolor (this species will be referred as *S. bicolor* or sorghum in the biology document) includes five basic races and ten intermediate races which arise from combinations of the basic races (Table 1). They are recognisable by spikelet/panicle morphology alone, providing a simplified and workable system compared to earlier classifications (Harlan & de Wet 1972). These races can be linked back to their specific environments and the nomadic peoples that first cultivated them (Kimber 2000).

Table 1. Cultivated races of *Sorghum bicolor* subsp. *bicolor*.

Basic races		Intermediate races (combination of basic races)	
Race (1): bicolor	(B)	Race (6): guinea-bicolor	(GB)
Race (2): guinea	(G)	Race (7): kafir-bicolor	(KB)
Race (3): caudatum	(C)	Race (8): caudatum-bicolor	(CB)
Race (4): kafir	(K)	Race (9): durra-bicolor	(DB)
Race (5): durra	(D)	Race (10): guinea-caudatum	(GC)
		Race (11): guinea-kafir	(GK)
		Race (12): guinea-durra	(GD)
		Race (13): kafir-caudatum	(KC)
		Race (14): durra-caudatum	(DC)
		Race (15): kafir-durra	(KD)

Adapted from Harlan & de Wet (1972).

All *S. bicolor* races are genetically diverse diploids (2n = 2x = 20). The genome of *S. bicolor* (genotype BTx623) has been sequenced (Paterson et al. 2009). It is approximately 730 Mbp which is relatively small when compared to wheat and maize, but nearly 75% larger than rice, and contains 34,496 putative genes (Arumuganathan & Earle 1991; Paterson et al. 2009; ICRISAT 2015).

Other *Sorghum* subgenera present in Australia

Australian *Sorghum* species are mostly distributed in the monsoonal region of the NT. These species are a significant component of the understory of grassland, woodland and forest plant communities across the region. This area contains a high number of endemic taxa and is a centre of diversity for the Australian *Sorghum* species across four subgenera: *Chaetosorghum*, *Heterosorghum*, *Parasorghum* and *Stiposorghum* (Lazarides et al. 1991). Of the 25 species of the genus *Sorghum*, 17 are native to Australia and South East Asia, with 14 endemic to Australia. Details of the Australian *Sorghum* species are shown in Table 2 and distribution maps of endemic Australian *Sorghum* species are available in Appendix B (Figures B5, B6 and B7).

Table 2. Subgenera of the Australian *Sorghum*, their species, distribution and chromosome number.

Subgenus	Species	Chromosome number (2n)	Growth habit	Distribution
Chaetosorghum	*S. macrospermum*	40	Annuals	NT
Heterosorghum	*S. laxiflorum*	40	Annuals	Qld NT
Parasorghum	*S. grande*	30, 40	Mostly Perennials	NT
	S. leiocladum	20		NSW
	S. matarankense	10		NT
	S. nitidum	10, 20		Qld
	S. timorense	10, 20		NT , Qld, WA

Subgenus	Species	Chromosome number (2n)	Growth habit	Distribution
Stiposorghum	*S. amplum*	10	Mostly Annuals	WA
	S. angustum	10		Qld
	S. brachypodium	10		NT
	S. bulbosum	10		NT, WA
	S. ecarinatum	10		WA
	S. exstans	10		NT
	S. interjectum	30, 40		NT, Qld
	S. intrans	10		NT
	S. plumosum	10, 20, 30		NT, Qld, WA
	S. stipoideum	10		NT,WA

Adapted from Lazarides et al. (1991).

These Australian wild species of *Sorghum* do not hybridise with cultivated sorghum in the wild and only limited hybridisation events have been achieved under laboratory conditions (see section 9).

SECTION 2 ORIGIN AND CULTIVATION

2.1 Centre of diversity and domestication

The centre of origin and domestication for cultivated sorghum is considered to be the north-eastern part of Africa, most likely in the modern Ethiopia and Sudan regions where cultivation started approximately 4000 – 3000 BC (Dillon et al. 2007b). In his comprehensive review of literature on sorghum, Dogget (1988) states that "There can be no doubt that the cultivated sorghums of today arose from the wild *Sorghum bicolor* subsp. *arundinaceum*." Early domestication occurred by a process of disruptive selection where several traits advantageous for cultivation were favoured (Doggett 1988). In addition to disruptive selection, geographic isolation and recombination in different environments led to the creation of large number of types, varieties and races of sorghum. As a result three broad groups of *S. bicolor* were generated; cultivated and improved types, wild types and intermediate types (Kimber 2000). Cultivated sorghum developed with diverse morphological traits including height and inflorescence, and numerous uses including food, fodder, fibre and building material (Dillon et al. 2007b). Initially, selection efforts are likely to have concentrated on replacing the small-seeded, shattering, open panicles of wild types with the large seeded, non-shattering and compact panicles of domesticated lines (Doggett 1965). These changes contributed to improved yields over the original landrace varieties (Dillon et al. 2007b).

Although it is difficult to determine exactly when movements of sorghum to different regions occurred, these can be implied from known trade routes and trading relationships. Improved sorghum types were probably transported from north-eastern Africa to other parts of Africa (1500-1000 BC) through trade routes and human movements. From Africa it is believed to have spread through to the Middle East and India (900-700 BC) and Far East through shipping and trade routes. In China the crop was adapted to temperate conditions and varieties known as Kaoliangs were developed that are suited to cooler early season temperatures (Doggett 1988). Sorghum was first transported to America in the late 1800s in conjunction with the slave trade (Doggett 1988; FAO 1995).

2.2 Commercial uses

On a world scale sorghum is the fifth largest and most important cereal crop after wheat, maize, rice and barley (Doggett 1988; Ejeta & Grenier 2005; ICRISAT 2015). The annual production of sorghum is estimated at approximately 60 million tonnes globally (FAOSTAT 2013). Uses of sorghum are diverse and a number of in-depth reviews are available (Doggett 1988; FAO 1995; Taylor 2003). It is an important crop that serves as human staple and is a major livestock feed in intensive production systems. Sorghum may be seen as one of the crops best suited to future climate change due to its ability to adapt to conditions such as drought, salinity and high temperatures (ICRISAT 2015). Different races or cultivars of *S. bicolor* may be described as grain sorghum, fodder sorghum or sweet sorghum depending on their morphology or end use (Purseglove 1972). In some cases, sorghum is used as a dual purpose crop; after the grain is harvested, cattle are grazed on the stubble. Its potential as a biofuel crop has been identified and is gaining in importance (CGIAR 2015).

2.2.1 Food

Sorghum is an important dietary staple for more than 500 million people in 30 countries of Africa and Asia (ICRISAT 2015). In Africa, sorghum underpins food security due to its drought tolerance and its abilities to withstand periods of high temperatures and water logging. It is well suited to semi-arid and sub-tropical climatic conditions of much of Africa where intense rainfall often occurs in short periods (Doggett 1988). Cultivation in Africa is predominantly part of subsistence agriculture systems as opposed to the industrialised production methods in most other regions. Africa produces about one third of the world’s sorghum but has the lowest yields per hectare (FAO 1995; Taylor 2003). Worldwide over 50% of the sorghum produced is used for animal feed, however in some regions, particularly sub-Saharan Africa, the vast majority of sorghum production is for human food use (ICRISAT & FAO 1996).

Sorghum grains are prepared for a variety of food products including use as a boiled food similar to rice; roasting or popping like maize; threshing and grinding into flour to make breads, porridges, pancake, muffins, dumplings, breakfast cereals or couscous, as well as preparation of alcoholic and non-alcoholic beverages (Purseglove 1972; Doggett 1988; Taylor 2003; CGIAR 2015; ICRISAT 2015; FAO 2015). The stalks of sweet sorghum varieties with high sugar content are used to make sugar and syrup (CGIAR 2015).

There is increasing interest in developing the potential of sorghum for uses in human foods and beverages in western countries, in particular as a source of gluten-free food (O'Hara et al. 2013; Norwood 2015).

2.2.2 Feed

Both sorghum grain and plant biomass (leaves and stalks) are used as animal feed. It is a cheap alternative to maize and requires less water to produce similar yields due to its adaptability to dry conditions (FAO 2015). In Australia and other western countries, sorghum grain is primarily used as feed in the beef, dairy, pig and poultry industries (CGIAR 2015). Sorghum forage cultivars while inclusive of grain sorghum, are often distinct and include Sudangrass hybrids, sorghum x Sudangrass hybrids, sweet sorghum hybrids (*Sorghum bicolor*), open pollinated sweet sorghum and dual purpose sorghum grain hybrids (Cameron 2006). These are almost exclusively cultivated as forage and fodder crop. In Africa and Asia sorghum stalks are used as animal feed and are an important summer fodder (CGIAR 2015; ICRISAT 2015).

2.2.3 Biofuel

Biofuels are being developed to replace fossil sources of transport fuels in response to concerns about climate change. The biofuel industry produces ethanol from the sugars accumulated in the stalks of sweet sorghum varieties and from the starch in the seeds of grain sorghum (Almodares & Hadi 2009; O'Hara et al. 2013). In Australia, sorghum grain is the main source for bioethanol production in the Dalby Bio-refinery, one of the three ethanol producing plants in Australia (Biofuels Association of Australia 2012). It buys around 200,000 tonnes of sorghum grain a year from local growers, from which it produces 76 million litres of fuel-grade ethanol (Dalby Bio-refinery 2011). The high starch content of sorghum grain (70% per grain weight) and the ability of sorghum to withstand hot dry conditions makes it suitable as a feedstock for ethanol production (Wylie 2008; Almodares & Hadi 2009). The ethanol production process from sorghum also generates two co-products, the 'Wet cake' and syrup that are high-protein, high value animal feed (RIRDC 2013).

2.3 Cultivation in Australia

Grain sorghum was first grown in Qld in 1938 and in NSW in 1940 using dwarf varieties introduced from the US. Hybrid varieties were first grown in Australia in 1962 and Australian production rapidly shifted to these varieties. In Australia, grain sorghum is primarily produced for stockfeed, however use for ethanol production is increasing (Spenceley et al. 2005).

2.3.1 Commercial propagation

Sorghum is propagated by seed. Sorghum planted in the field for commercial seed production has restrictions on how it can be grown, depending on the classification. Sorghum is considered to be predominantly a self-pollinated crop but high levels of outcrossing can also occur (see sections 4.2 and 9). The isolation distances for producing basic seed and certified seed of sorghum are 400 m and 200 m, respectively, from any source of contaminating pollen (OECD 2015). For production of hybrid seed lines the recommended isolation distances are 300 m for basic seeds and 200 m for certified seeds (OECD 2015). An isolation distance of 400 m from Johnson grass or other weedy sorghums is recommended (Gupta 1999). It has even been suggested that seed crops should be separated from one another by a distance of 1000 m due to their ability to cross-pollinate (FAO 2015). Seed companies undertake seed production in north Qld, the Ord River (WA) and the Murrumbidgee Irrigation Area on the NSW-Vic border.

2.3.2 Scale of cultivation

An average of 600,000-700,000 ha are under cultivation to sorghum annually across Australia (QDAF 2012b; ABARES 2015). Sorghum is one of the most important summer crops in Australia. In the 2014-15 season, the planting area of sorghum was 600,000 ha, or 60% of the one million hectares of summer crop plantings (ABARES 2015). Table 3 shows the recent Australian sorghum planting and yield data.

Table 3. Grain sorghum growing areas and production in Australia[a]

State	Scope[b]	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16[d]
NSW	A	164	197	221	214	175	184	180
	P	581	748	814	747	419	586	585

State	Scope[b]	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16[d]
Qld	A	333	435	436	431	356	547	500
	P	926	1183	1416	1475	860	1618	1450
WA	A	1	1	1	1	1	1	1
	P	0	1	2	1	2	4	2
Total[c]	A	498	633	659	647	532	732	681
	P	1508	1935	2239	2229	1282	2209	2037

[a] ABARES (2012; 2013; 2014; 2015; 2016)
[b] A - Area planted ('000 ha); P - Production (kt)
[c] Calculated from ABARES data above
[d] ABARES estimate

Over the last seven growing seasons, approximately 66% of sorghum was grown in central and southern Qld and 34% in NSW, with mean area planted of approximately 625,000 ha and a mean national production of 1.92 million tonnes annually (ABARES 2012; 2013; 2014; 2015; 2016). Small areas are cultivated in the NT and in Kununurra in the north of WA, where most of the hybrid seed is produced (Spenceley et al. 2005). Most grain sorghum production occurs as part of dryland farming systems except in NSW where it is frequently an irrigated crop (Spenceley et al. 2005). Figure 3 shows the main grain sorghum production areas of NSW and Qld.

The scale of grain sorghum cropping varies from season to season, largely in response to weather conditions. For example, from 2012 to 2014, production fell by approximately 40%, from approximately 2.2 million tonnes to 1.3 million tonnes due to unfavourable seasonal conditions (Table 3), which also affected grain quality (ABARES 2014). In the 2014-15 season production returned to approximately 2.2 million tonnes, reflecting rises in both planting scale and in average crop yields (ABARES 2016).

While yields are dependent on several factors, local climatic conditions are important. For example, yields are highest in cool growing areas such as Quirindi and Warwick (south eastern Qld), with average yields of 6 t/ha. Yield potential declines in hotter, drier south-west areas of Qld such as Roma, where target yields of 3.3 t/ha are more likely (Wylie 2008).

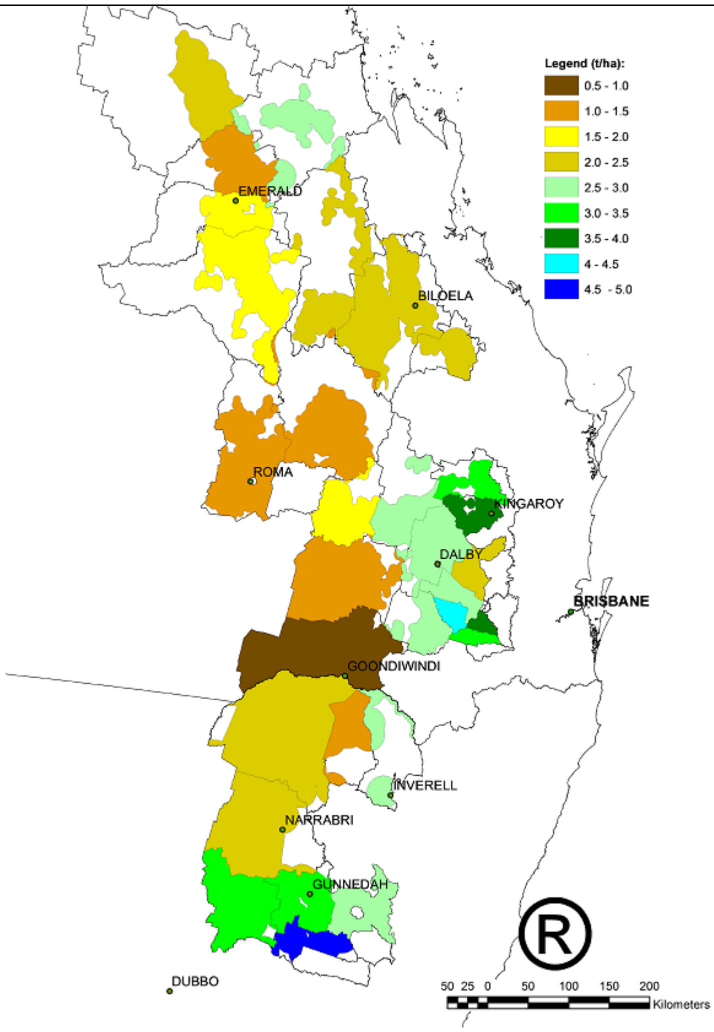

Figure 3. Grain sorghum production areas in northern NSW and Qld (reproduced with permission from QAAFI 2015).

A proportion of the Australian grain sorghum crop is sold on international markets annually, although the amount varies from season to season (Table 4). Over 95% of the Australian sorghum grain sold in the export market was sold to China each year since 2013 (UN Comtrade 2016). Australian sorghum is sought in China for its bright colour and other characteristics that provide similar performance to the Chinese crop when used in the production of baijiu, a traditional Chinese toasting drink (Norwood 2015)

Table 4. Australian sorghum export volume and value for the period 2011 to 2015 (UN Comtrade 2016).

Year	Quantity (t)[†]	Value ($US)
2011	115,989	$34,646,246
2012	205,133	$52,818,786
2013	798,798	$267,293,910
2014	358,613	$107,719,874
2015	1,513,668	$412,311,789

[†] Quantity rounded to the nearest whole number.

2.3.3 Cultivation practices

Grain sorghum

Sorghum is a versatile crop that can be cultivated in diverse physical and climatic situations but attention to cultivation practice is critical for optimising yield (Purseglove 1972; Cothren et al. 2000). Information about the practical aspects of sorghum cultivation can be found in literature provided online or in reports from the GRDC, NSW DPI and QDAF (QDAF2011d; QDAF 2012b; GRDC 2014). Additional information on sorghum growth requirements can be found in Section 6 of this document.

In selecting a suitable sorghum hybrid for planting, yield potential is important, but other characteristics such as lodging, maturity characteristics for the area of production, drought tolerance and insect and disease resistance are also critical (Vanderlip 1993; Cothren et al. 2000; Pacific Seeds 2008; Wylie 2008). As no single hybrid will be optimal under all conditions, the selection of two or more hybrid varieties is recommended to reduce the susceptibility to poor environmental conditions (Cothren et al. 2000; Moore et al. 2014). Hybrid lines commercially available in Australia are rated by seed companies for characteristics such as maturity, height, standability, organophosphate reaction and midge resistance (QDAF 2011d; Moore et al. 2014).

Temperature requirements

Sorghum is a C_4 species that is very water efficient (Spenceley et al. 2005; ICRISAT 2015). It requires a warm, summer growing period of 4 – 5 months. A temperature of 27°C to 30°C is required for optimum growth and development (Downes 1972; FAO 2015). The temperature can be as low as 21°C and as high as 36°C without a dramatic effect on growth and yield (Downes 1972). Night time temperature affects sorghum development. High night temperatures of around 31°C reduce yield (Downes 1972). Night time temperatures of 13°C or below can severely reduce grain production and frost can kill the plant. Seed set is highly susceptible to cold temperature. Constant low temperatures throughout the life cycle delay flowering (Tiryaki & Andrews 2001), induce male sterility (Downes & Marshall 1971) and result in the scarcity or total lack of seeds in panicles (Brooking 1976).

Water and soil requirements

Rainfall of 450 to 800 mm is sufficient for sorghum production (QDAF 2012b; FAO 2015). Sorghum can be susceptible to drought, which can result in yield losses due to reduced grain number and size, as well as lodging (QDAF 2012b).

Sorghum may be grown as an irrigated crop, mainly via flood (furrow or bay systems) or overhead irrigation. Furrow irrigation must avoid prolonged waterlogging which can cause major crop losses (Pacific Seeds 2008).

Sorghum is capable of growing in a wide range of soils from light loams to heavy clays but it thrives in light sandy soils (Kimber 2000). It is capable of tolerating a range of soil acidity from pH 5.0 to 8.5 and has a moderate tolerance to salinity (Doggett 1988; Kimber 2000; Cothren et al. 2000).

Planting practices

Sorghum is used in no-till or minimum till farming systems, planted directly into stubble from the previous crop (Cothren et al. 2000; Spenceley et al. 2005; QDAF 2011d; Moore et al.

2014). These systems are valuable in conserving moisture and in preventing or minimising erosion in crops (Cothren et al. 2000; Spenceley et al. 2005). Where seed bed cultivation is undertaken, particularly in irrigated areas, careful seed-bed preparation is required to ensure good germination (Doggett 1988; Spenceley et al. 2005; Pacific Seeds 2008).

Seeds are planted at a depth of 50-75 mm in moist soil (Spenceley et al. 2005; QDAF 2011d). Planting times differ in different regions. In most of Qld and northern NSW, the planting window goes from September to January (QDAF 2011d; QDAF 2012b). In the northern Qld Central Highlands, sorghum can be sown between late August and February (Pacific Seeds 2008). Hybrids that are considered quick-maturing flower within 60-65 days if planted early, and within 50-55 days if planted later with more favourable temperatures (QDAF 2011d). In Qld medium to late maturing hybrid lines generally yield higher under good moisture and nutrient conditions.

Optimum soil temperatures for planting are 21 to 33°C, although temperatures above 15°C are indicated as suitable (Pacific Seeds 2008; QDAF 2011d). Death of seedlings pre and post-germination associated with cold soil temperature is generally caused by either soil borne fungi or soil dwelling insects (Pacific Seeds 2008).

In Australia, planting densities are 30,000 – 150,000 plants/ha in dryland systems depending on rainfall and 150,000 to 250,000 plants/ha in irrigated systems (QDAF 2011d). Close row spacing is appropriate under favourable conditions when higher yields can be expected (QDAF 2011d).

Other cultivation practices

Although generally managed as an annual, many grain sorghum cultivars are short term perennials and keep growing after the maturity of the grain (Spenceley et al. 2005; QDAF 2011c). This trait is known as “staygreen”. It is thus necessary to perform chemical desiccation after grain fill to prevent tiller growth once the main heads are mature. This standard practice results in 100% plant death when done properly, facilitates harvesting and conserves water for the next crop. Sorghum should be harvested when grain moisture content has reached 13.5% or less, as delay will result in lodging of dead stalks (Spenceley et al. 2005) and grain with moisture above 12% may require drying before storage (House 1985).

Sorghum is a useful rotation crop in northern Australia (QDAF 2011d; GRDC 2014; Moore et al. 2014). A rotation cropping system provides substantial benefits including breaking disease and pest cycles, more effective use of resources, improving soil conditions, using residual soil nutrients and reduced development of herbicide resistance (Cothren et al. 2000; GRDC 2014; Moore et al. 2014). In Australia, sorghum has been grown in rotation with cereals, legumes, pastures, fallow, oilseeds and cover crops (WA DA 2001; GRDC 2014).

Information on sorghum pests and diseases and their management is provided in Section 7.

Forage Sorghum

Forage sorghum may be *S. bicolor* hybrid lines developed for forage production, *S. bicolor* subsp. *drummondii* lines (sudangrass) or *S. bicolor* x *S. bicolor* subsp*. drumondii* hybrids (Collett 2004; Cameron 2006). The general features of forage sorghum production have been described by Collet (2004) and Cameron (2006). Forage sorghum cultivation practices and temperature, water and soil requirements are the same as for grain sorghum, with the main

differences being grazing management and harvesting green matter for hay or silage production. Seeding rates are influenced by whether the primary focus is to provide material for stock grazing, green chop (freshly cut green stock feed), hay production or silage production. There is an optimal grazing window for forage sorghums, which will be during the vegetative growth phase when plants are 0.5 - 1.0 m tall. Forage sorghum will often be strip grazed then slashed to an even height post-grazing to facilitate more even regrowth. It may be cut for hay and silage at 0.8 – 1.3 m. Sweet sorghum with lower protein, but higher energy content is suitable for silage production.

In the NT, the *S. bicolor* hybrids and sudangrasses grown for forage are late flowering (Cameron 2006). Perennial sorghum (previously called 'Silk' sorghum) is also grown in this region. It is a hybrid of 'Krish' (*S. halepense x S. roxburghii*) with *S. bicolor subsp. arundinaceum* (Cameron 2014). Perennial sorghum has been used as short term pasture rotation, pasture mix with a legume, as a pioneer species and for weed control where dense plantings will out-compete weed species. It can be grazed from about 0.8 m (Cameron 2014).

Although generally lower in prussic acid than grain sorghums, care is needed when grazing stock on forage sorghum to avoid cyanide poisoning (see section 5.1.1).

2.4 Crop Improvement

Improvements in the adaptability of sorghum to modern farming methods are continuing worldwide and several biotic and abiotic factors have been identified as breeding targets for improved commercial outcomes.

2.4.1 Breeding

Gene pools for breeding

Breeding and cultivar improvement has relied principally on the diversity present in the *S. bicolor* biotypes, however the undomesticated *Sorghum* species including those endemic to Australia offer untapped novel traits and breeding effort is becoming more focused on overcoming technical reproduction constraints to allow use of this material (Dillon et al. 2007b). *Sorghum bicolor* has primary (GP1), secondary (GP2) and tertiary (GP3) gene pools, based on the ability of the crossing species to produce fertile offspring and this dictates whether genes or traits can be readily transferred (Harlan & de Wet 1971; see section 9). *Sorghum* races have considerable genetic diversity regarding photoperiod, seed quality and other agronomic traits that could be incredibly useful but had been poorly exploited for crop improvement (Kayodé et al. 2006; Dillon et al. 2007b). Conserving these germplasm reserves is crucial as they may be exploited to produce sorghum hybrids with a range of valuable traits (House 1985; Rooney & Smith 2000; Kayodé et al. 2006; Dillon et al. 2007b).

Mutations, whether naturally occurring or artificially induced, are an alternative source of genetic diversity. Gamma irradiation and chemical mutagen (ethyl-methane-sulphanate) protocols have been optimised for selected *S. bicolor* biotypes to generate random changes in the genome (Dillon et al. 2007b).

Development of hybrid varieties

Natural hybrids were selected by farmers/breeders to provide new cultivars that were drought tolerant and chick bug resistant or suitable for mechanical harvest. This was followed by deliberate hybridisation of biotypes to generate new hybrids in the 1920s,

continuing into the 1950s. The discovery of a cytoplasmic male sterile (CMS) system in sorghum led to the development of commercial sorghum hybrids that had high yields and disease and insect resistance (Stephens & Holland 1954). Early breeding programs in the US that developed commercial sorghum hybrids resulted in yield increases of 300% from 1950 to 1990 (Rooney & Smith 2000).

All commercial grain and forage sorghum varieties grown in Australia are F_1 hybrids produced utilising CMS (Cruickshank & Jordan 2012). A wide range of sorghum hybrids is available for commercial planting which address maturity, lodging or standability, tillering, disease and pest management, grain production characteristics, photoperiod sensitivity, drought tolerance and "Staygreen" characters among others (WA DA 2001; Spenceley et al. 2005; Pacific Seeds 2008; QDAF 2011a; QDAF 2011c; QDAF 2011d; Cruickshank & Jordan 2012; QDAF 2012a; GRDC 2014; Moore et al. 2014).

Breeding outcomes

As sorghum originated in northeast Africa, the landraces were photoperiod sensitive, requiring a day length shorter than 12 h to flower. Growing these lines as a summer crop in temperate regions where day length is longer than 13 h was difficult (Reddy et al. 2006). In addition, although plant height has been correlated with higher yield, taller plants are prone to lodging and are not suited to modern farming practices (Rao & Rana 1982). Thus, photoperiod-insensitive germplasm and short sorghum cultivars have been widely used in breeding programs (Rai et al. 1999; Rosenow & Dahlberg 2000; Rooney & Smith 2000; Reddy et al. 2006).

Two forms of drought tolerance have been identified in *sorghum*: pre-anthesis tolerance when plants are stressed prior to panicle differentiation; post-anthesis tolerance when stress occurs during grain filling (Rosenow et al. 1983; Rosenow & Clark 1995). Post-anthesis tolerance is referred to as staygreen, with plants maintaining green leaf area and photosynthetic capability under severe stress and resulting in higher grain yields than cultivars without this attribute (Borrell et al. 2000). The physiological components of staygreen are independently inherited and may be combined through breeding (van Oosterom et al. 1996). In some cases drought resistance has been a secondary selection consideration where primary selection is made for other traits such as yield or pest resistance under favourable water conditions, then selected genotypes are screened for drought tolerance (Rosenow et al. 1983). Sorghum lines selected for drought tolerance and lodging resistance have also shown other desirable characters including disease resistance and other positive stalk characteristics (Rosenow & Clark 1995).

Sorghum is affected by several pests and diseases and there has been mixed success in incorporating resistance through breeding programs. An area of success has been midge resistance where high levels of immunity have been incorporated from Indian, American and Australian biotypes into superior cultivars. In Australia over 80% of planted area in 1995 utilised cultivars with some midge resistance (Jordan et al. 1998). Resistance to diseases, grain mould and anthracnose has also been incorporated into commercial varieties (Reddy et al. 2006).

2.4.2 Genetic modification

Conventional breeding for improved grain and forage production has resulted in significant improvements in the productivity of sorghum. However, a range of biotic and abiotic factors

continue to limit the potential of the crop which have proven difficult to overcome using conventional breeding (Girijashankar & Swathisree 2009). This is due to a shortage of genes for desirable traits such as disease and pest resistance and drought tolerance, and to the difficulty in making wide crosses due to sexual incompatibility (Girijashankar & Swathisree 2009). Beneficial genes may be incorporated through genetic transformation technology coupled with *in vitro* techniques to regenerate GM plants.

Completion of the whole genome sequencing will increase the genomic data available and support the genetic improvement for domesticated sorghum. Initial analysis of the 730 Mb sorghum genome placed 98% of genes in their chromosomal context using whole-genome shotgun sequence validated by genetic, physical and syntenic information (Paterson et al. 2009). Its relatively small genome makes it an attractive model for functional genomics of other C_4 grasses in addition to providing information for the potential improvement of sorghum lines (Paterson et al. 2009).

One limitation to genetic modification is that sorghum cells are hard to grow in tissue culture. This is mainly due to the large amount of phenolic substances secreted into the culture by sorghum cells (Casas et al. 1993). Other issues for sorghum transformation are its inherent tolerance to antibiotics and the difficulty in choice of promoters (Muthukrishnan et al. 2004). Nevertheless, GM sorghum plants have been obtained using biolistic as well as agrobacterium-mediated transformation methods (Howe et al. 2006). A range of genes have been introduced into sorghum including the *bar* gene for herbicide tolerance (Casas et al. 1993; Casas et al. 1997), the chitinase gene *G11* against anthracnose disease and other stalk rot causing fungi (Krishnaveni et al. 2001) and the *Cry1Ac* gene that confers insect resistance (Girijashankar et al. 2005).

The Africa Biofortified Sorghum (ABS) (Biosorghum.org 2010) project aims to develop nutritionally enhanced GM sorghum varieties with increased levels of the amino acid lysine, vitamins A and E and more available iron and zinc (Wambugu 2007). GM sorghum developed through the ABS project has been reported to contain elevated levels of pro-vitamin A, reduced phytate and an improved protein profile with increased levels of tryptophan, lysine and threonine (Biosorghum.org 2010).

Some GM sorghum field trials have been undertaken with USDA approval in the US. The trialled GM sorghum plants displayed traits such as herbicide resistance, grain protein quality, nitrogen use efficiency, altered fertility, enhanced biomass, modified levels of soluble sugars and disease resistance. Field trials of GM sorghum for improved human nutrition (pro-vitamin A, zinc and iron biofortification) have been approved by the National Biosafety Authority in Kenya and Nigeria.

SECTION 3 MORPHOLOGY

3.1 Plant morphology

Sorghum is a cane-like grass with stout and erect stems (culms), 0.5 – 6 m tall. Most types used in grain production have a terminal compact or semi compact head (Kimber 2000; Figure 4). Cultivated sorghum is generally treated as an annual crop, but may be maintained over several seasons under suitable conditions and has been described as annual or weakly perennial (House 1985; Doggett 1988; Kimber 2000). Descriptions of sorghum plant morphology are available in the literature (Purseglove 1972; House 1985; Doggett 1988).

Figure 4. Sorghum plants showing upright stalk growth and alternate leaf pattern. Photo taken by R. R. Kowal, Department of Botany, University of Wisconsin-Madison.

3.1.1 Root system

The sorghum root system is highly organised and develops in two stages, the seminal roots and the adventitious crown roots. In early stages of growth, seminal roots develop from the single radicle of the germinating seedling. These have a limited functional life of approximately three weeks. Adventitious crown roots emerge from the coleoptile (first) node and potentially from several leaf nodes above the coleoptile node. These roots form the extensive secondary root system which branches freely, both laterally and down into the soil. Sorghum plants have a fibrous root system, characteristic of grasses, which can reach a depth of up to 1.5 to 2.4 m (Kimber 2000). An extensive root system and the ability to become dormant during water stress contribute to the drought resistance of sorghum that makes it notable as an adaptable crop in marginal dryland farming systems (Whiteman & Wilson 1965).

3.1.2 Stem (Culm)

The stem can be slender to very stocky, with thickness varying from 5 to 50 mm in diameter, tapering at the upper end. It is solid with a hard cortex and softer inner pith that may be sweet or insipid, juicy or dry (House 1985). Each stem node contains root bands and above them there are growth rings that can produce new stems if the upper part of the stem is damaged. The lowest nodes in the stem contain buds that can give rise to axillary tillers while basal tillers will form at the first node (House 1985; Doggett 1988).

3.1.3 Leaf

Sorghum leaves are concentrated near the base in some sorghum varieties while in others they are evenly distributed along the stem. Leaves are broad and coarse, linear to lanceolate in shape and look like maize leaves. They measure up to 90 - 100 cm in length and approximately 10 - 12 cm in width. Leaves are usually shorter and smaller at the top and the top leaf is called the flag leaf. Leaves alternate in two ranks on opposite sides of the stem and 14-18 leaves have been recorded on a plant at flowering. Leaf sheaths encircle the stem and there is a short membranous ligule at the junction of the leaf blade and the sheath (House 1985; Doggett 1988).

Under very dry conditions leaves curl inwards, reducing transpiration and moisture loss by decreasing the surface area. Irregular shaped silica deposits found in the leaves have been linked to drought tolerance and shoot-fly resistance (Doggett 1988).

3.1.4 Tillering

Sorghum cultivars show great variation in tillering capacity. Some varieties tiller early, while others tiller after flowering. The number of tillers is dictated by genetics, carbon supply and night temperatures (Pacific Seeds 2008). It is thought that temperature and day length affect tillering, high temperatures and short days repressing it. Tillering makes a valuable contribution to grain yield by compensating for poor establishment or in favourable growing seasons when greater plant growth can be supported (Pacific Seeds 2008).

Sorghum is generally cropped as an annual, but a ratoon crop can develop from the base of old plants (House 1985; Doggett 1988).

3.2 Reproductive morphology

The inflorescence of sorghum is a determinate panicle which may be compact or open but is usually compact in cultivated lines (Figure 5). It measures up to 50 - 60 cm in length and 30 cm in width (Doggett 1988). The panicle is made up of primary and secondary branches that carry the spikelets (Figure 6).

Figure 5. Close up photo of a compact sorghum panicle (reproduced with permission from QDAF Sorghum Overview).

The spikelets contain the flowers. The number of flowers *per* panicle varies from 1600 – 4000 (Stephens & Quinby 1934; Doggett 1988). Spikelets are pedicellate and lance shaped, 3 - 10 mm in length, 2 – 5 mm wide (Purseglove 1972; Doggett 1988). Spikelets usually occur in pairs. The sessile spikelet is bisexual and ovoid in shape whereas the other spikelet is sterile and only contains stamens. The sessile spikelet has two glumes, a lemma, a palea, two lodicules, three stamens and an ovary with two long styles that end in a plumose stigma (Doggett 1988).

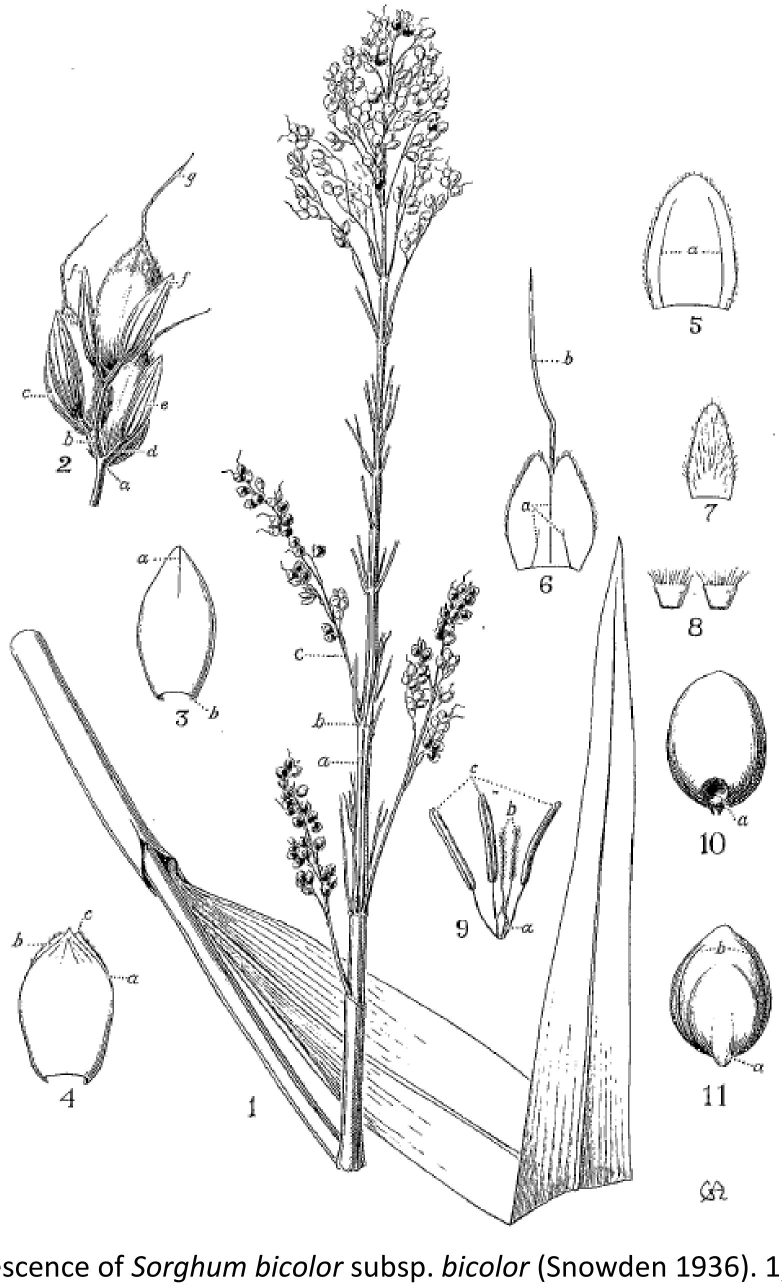

Figure 6. Inflorescence of *Sorghum bicolor* subsp. *bicolor* (Snowden 1936). 1, part of panicle: a, internode of rachis; b, node with branches; c, branch with several racemes. 2, raceme; a, node; b, internode; c, sessile spikelet; d, pedicel; e, pedicelled spikelet; f, terminal pedicellled spikelets; g, awn. 3, upper glume: a, keel; b, incurved margin. 4, lower glume: a, keel; b, keel wing; c, minute tooth terminating keel. 5, lower lemma: a, nerves. 6, upper lemma: a, nerves; b, awn. 7, palea. 8, lodicules. 9, flower: a, ovary; b, stigmas; c, anthers. 10, grain: a, hilum. 11, grain: a, embryonic mark; b, lateral lines.

SECTION 4 DEVELOPMENT

4.1 Reproduction

4.1.1 Asexual reproduction

Sorghum cannot reproduce vegetatively, but it can be propagated vegetatively from stem cuttings as root primordia are present at nodes (Thomas & Venkatraman 1930; Purseglove 1972; Schertz & Dalton 1980). Sorghum is non-rhizomatous or weakly rhizomatous (House 1985). Forage sorghums produce short rhizomes which may be involved in local spread of plants (Parsons & Cuthbertson 2001a; Parsons & Cuthbertson 2001c).

4.1.2 Sexual reproduction

Sorghum reproduces sexually via seeds. Modern cultivars are photoperiod insensitive and flowering occurs approximately 60 – 70 days after seedling emergence depending on sorghum varieties and growing conditions (Spenceley et al. 2005). When planting from mid-October to mid-January in southern Qld, plants flower between mid-December and mid-March. Flowering occurs within three days of panicle emergence from the flag leaf. Optimum flowering temperatures are 21 - 35°C. Outside this range, flowering may be delayed (Schertz & Dalton 1980).

Flowering lasts typically one week but may vary from two to fifteen days. Stigmas are receptive for 48 hours before anthesis and can remain in a receptive state for 5 - 16 days, depending on the cultivar (Stephens & Quinby 1934). The optimal time for pollination is reported to be within three days of blooming (Doggett 1988). As not all heads in a crop flower at the same time, pollen is usually available for four to five days (House 1985). Pollen is reported to require light and only germinates on the stigma after daybreak (Artschwager & McGuire 1949). Once the viable pollen reaches the receptive stigma, it germinates and fertilisation occurs within two hours, usually at dawn when temperatures are low (Artschwager & McGuire 1949; Schertz & Dalton 1980; Doggett 1988).

4.2 Pollination and pollen dispersal

4.2.1 Pollen

Pollen is short-lived and very sensitive to drying. Sorghum panicles may produce up to 24 million grains of pollen which remains viable for only three to six hours (Stephens & Quinby 1934; Karper & Quinby 1947; Doggett 1988; Lansac et al. 1994). Weather conditions including temperature and humidity may affect pollen viability (Schertz & Dalton 1980). It has been reported that pollen stored at 4°C and 75% relative humidity under controlled conditions could remain viable for up to 94 hours, while in the field pollen stored in the shade in pollination bags could remain viable for over 20 hours (Sanchez & Smeltzer 1965).

4.2.2 Pollination

Sorghum pollination is driven by three primary mechanisms: self-pollination, wind pollination and insect pollination. Sorghum is predominantly a self-compatible and self-pollinating crop species (Schertz & Dalton 1980). Under natural circumstances, fully-fertile plants are approximately 70 - 95% self-pollinated (Ellstrand & Foster 1983; Pedersen et al. 1998; 2000; Djè et al. 2004). However, outcrossing pollination by wind and insects do occur.

There is indirect evidence of insect pollination based on observations of honey bees and wild bees in sorghum trials (Schertz & Dalton 1980; Schmidt & Bothma 2005; Schmidt & Bothma

2006). Examination of insects collected from a trial sorghum crop found sorghum pollen grains on all the individuals collected, although there was no demonstration that pollination occurred via this means (Schmidt & Bothma 2005; Schmidt & Bothma 2006). These researchers reported that insects did collect pollen and moved between flowers in a crop, but they were not able to separate insect pollination from wind pollination in that trial (Schmidt & Bothma 2005). Pollen dispersal by bees may extend up to five kilometres as opposed to few hundred metres by wind dispersal (Arriola 1995; Schmidt & Bothma 2005). The role of bees or other animal species in sorghum pollination in Australia is currently unknown.

4.2.3 Outcrossing

Outcrossing rates in cultivated sorghum are estimated at 5 - 30% based upon multiple methods of calculation (Schertz & Dalton 1980; House 1985; Doggett 1988; Rai et al. 1999). In the field, the level of outcrossing varies according to the panicle type of the cultivar and wind direction (Schertz & Dalton 1980; Doggett 1988). The outcrossing rate of the race Durra, which is commonly used in commercial production and has compact panicles, is around 7% (Djè et al. 2004). Under controlled conditions, self-pollination can be ensured by bagging the panicles prior to opening of florets (Schertz & Dalton 1980).

In a study investigating crop-to-crop gene flow in race Kafir, Schmidt and Bothma (2006) observed that outcrossing rates among pollen receptors decreased as their distance increased from pollen donors. The experiment was laid out with the pollen donors (male-fertile B-line 'Redlan') grown in a 30 × 30-m block from which eight arms of the pollen receptors (male-sterile A-line 'Redlan') radiated out at distances ranging from 13 to 158 m. The average outcrossing rate, across directions, was 2.54% at 13 m, less than 1% at or beyond 26 m, and 0.06% at 158 m. Mathematical models estimated the maximum gene flow distance to be 200 to 700 m. These values were in agreement with observations by sorghum breeders, who use isolation distances of 100 m to achieve less than 1% gene flow from neighbouring fields. Distance and wind direction were found to be the primary factors determining the rate of gene flow. The authors suggested that outcrossing rates under natural conditions would be expected to be lower than what they observed because the use of male sterile receptors eliminated pollen competition and allowed the female flowers to remain receptive longer in the absence of pollination.

Information about sorghum outcrossing to compatible species can be found in section 9.

4.3 Seed development and dispersal

4.3.1 Seed morphology

Each sorghum panicle contains 800 – 6000 seeds. In intensive land use areas (such as the Liverpool Plains of NSW and the Eastern Downs of Qld) sorghum can produce 1 kg seed/m^2 when planted at a density of 100,000 per ha. This could be as many as 30,000 seeds/m^2 (assuming a 10 tonne/ha crop).

Sorghum grains can be variable in shape, size and colour. The seed is generally spherical, but may be flattened on one side. Sorghum grain contains the embryo, the endosperm and the testa and is surrounded by the pericarp (Figure 7). The testa and pericarp form the seed coat. Seed colours range from white and cream to brown, red, purple and black depending on the colour of the pericarp and testa (see section 5.3.1). Seed size varies from 1 - 6 g per

100 seeds (Stephens & Quinby 1934; Whiteman & Wilson 1965; Purseglove 1972; House 1985; Doggett 1988; Vanderlip 1993; FAO 1995; Spenceley et al. 2005; Pacific Seeds 2008).

4.3.2 Seed development

Seed development begins within seven days following pollination (Schertz & Dalton 1980). Seeds reach physiological maturity when they achieve maximum weight and have developed a dark spot on the grain opposite the embryo (Spenceley et al. 2005). The time taken from flowering to physiological maturity varies with growing conditions and with cultivar and has been estimated to take from 25 to 55 days (Schertz & Dalton 1980; Doggett 1988; Spenceley et al. 2005).

4.3.3 Seed dispersal

Wild sorghums have a shattering seed head. This trait was eliminated during domestication of grain sorghum as non-shattering sorghum lines were selected to allow the efficient harvest of grains (Hoffman et al. 2002; Ejeta & Grenier 2005). Initial domestication of sorghum involved converting wild types with small shattering seeds and loose panicles to those with larger non-shattering seeds and compact panicles (Dillon et al. 2007b). Non-shattering sorghum seeds may be dispersed through wind, water and animals, but throughout the history of cultivated sorghum, dispersal has most importantly been via humans (Andersson & deVicente 2010). Humans can also accidentally disperse sorghum seeds on clothing, harvest machinery and vehicles (Andersson & deVicente 2010).

Sorghum seeds could potentially travel long distances when carried by water or in the excreta of birds and livestock, as it has been observed for its relative *S. halepense* (Holm et al. 1977; Warwick & Black 1983). Sorghum seeds are consumed by livestock, rodents, birds, and seed-eating ants (Andersson & deVicente 2010; see section 7.2.2). All of these could potentially disperse sorghum seeds with the distance travelled depending on the biology of each animal. Sorghum seeds have been shown to pass undamaged through the digestive tract of wild deer and to germinate on deer excreta in the US (Myers et al. 2004).

4.4 Seed dormancy and germination

Seed dormancy is another trait together with seed shattering that has been lost during sorghum domestication (Purseglove 1972; Dahlberg 1995; Cook et al. 2005a). Pre-harvest sprouting, the germination of seeds in the sorghum head prior to harvesting due to damp conditions, is a significant problem in sorghum production. It is due to the low dormancy of the seeds and results in grain deterioration (Steinbach et al. 1995; Steinbach et al. 1997). Considerable variation in dormancy and susceptibility to pre-harvest sprouting exists between varieties of sorghum (Steinbach et al. 1995; Steinbach et al. 1997; Rodríguez et al. 2011). However, dormancy is lost three months after harvest in all varieties (Gritton & Atkins 1963). A study found that few grain sorghum seeds were viable four months after burial regardless of burial depth and none were viable eight months after burial (Jacques et al. 1974).

Sorghum seeds can germinate from as early as seven days post-fertilisation to the full maturity of the seeds. Germination is impacted by abiotic factors such as soil water content, depth of sowing and temperature. Temperatures of 20 - 35°C are best to promote seed germination of most sorghum varieties (Franks et al. 2006). Low temperatures reduce the number of germinating seeds, germination speed and seedling growth, resulting in poor crop establishment. The percentage of germinated seeds gradually decreases with temperatures

below 20°C with the exception of sorghum cold tolerant varieties in which germination rates decrease below 16°C. For all varieties, seed germination is completely inhibited at 10°C (Franks et al. 2006). High temperatures of 40 - 48°C also inhibit sorghum germination (Peacock 1982). In Australia, a minimum temperature of 15°C at planting is recommended, with faster germination at higher temperatures (QDAF 2011d).

4.5 Sorghum life cycle

The developmental stages of sorghum's life cycle are shown in Table 5 (House 1985; Vanderlip 1993; Spenceley et al. 2005). Vegetative Phase includes three stages (0 – 2) and occurs from plant establishment to flower bud initiation; Floral Phase includes stages 3 - 5 from inflorescence development to commencement of flowering (anthesis); and Grain Filling Phase, stages 6 - 9, from flowering to physiological maturity. The timing and length of each stage within the crop growth cycle will vary depending on sorghum cultivar, location, planting times and seasonal conditions, but the cycle will generally take between 90 and 140 days to complete (House 1985; Vanderlip 1993; Spenceley et al. 2005).

Table 5. Developmental stages of Sorghum. Adapted from Vanderlip (1993).

Growth Stage	Days after germination*	Identifying characteristic
0	0	Emergence – coleoptile visible at soil surface
1	10	Collar of 3rd leaf visible
2	20	Collar of 5th leaf visible
3	30	Growing point differentiation at approximately the 8 leaf stage
4	40	Final leaf visible in a whorl
5	50	Boot stage – panicle extended into flag leaf sheath
6	60	Half-bloom – half of the plants flowered
7	70	Seed at Soft dough stage
8	85	Seed at Hard dough stage
9	95	Physiological maturity – maximum dry matter production

*These numbers are approximate, as they correspond to sorghum plants of the Hybrid RS610 cultivated in Kansas (US).

Emergence occurs when the coleoptile first breaks through the soil surface, generally 3 – 10 days after planting (House 1985; Vanderlip 1993; Spenceley et al. 2005). Leaf development occurs in a series of stages defined by the number of leaves produced on the stem (Table 5). When the third leaf is fully emerged the root system develops rapidly and the plant enters a fast period of growth with rapid accumulation of dry matter that continues until maturity (Vanderlip 1993; Spenceley et al. 2005).

Differentiation from vegetative to reproductive development occurs approximately 30 days after emergence when one third of the production cycle has elapsed (Vanderlip 1993). At this point the total number of leaves has been determined and all except the final three or four leaves are fully expanded with about 80% of total leaf area present. The lower first to third leaves may be lost. Stem growth rate is rapid following this point. Approximately one

fifth of the total growth has occurred at this time but a higher proportion of the total uptake of nutrients will have occurred (Vanderlip 1993).

At the Boot stage all leaves are fully expanded providing maximum leaf area and light interception. The panicle is nearly full size and is enclosed in the flag leaf sheath. Except for the peduncle, culm elongation is largely complete (Vanderlip 1993). During the grain filling phase (Soft dough, stage 7) the stem starts to lose weight and lower leaves are being lost with eight to twelve functional leaves remaining on the upper portion of the stem. Stem weight loss continues as the grain continues to mature and by maturity the remaining functional leaves may stay green or brown off and die (Vanderlip 1993).

SECTION 5 BIOCHEMISTRY

Sorghum foliage contains dhurrin and nitrates that are toxic at certain concentrations (Hulse et al. 1980; Yaremcio 1991; Ellis 2007; QDAF 2014). In addition, sorghum contains a number of anti-nutritional compounds that can have serious negative effects on human and animal nutrition (Hulse et al. 1980; Salunkhe et al. 1990; Smitha Patel et al. 2013).

A comprehensive review of literature on sorghum composition, effects on nutrition and protein digestibility can be found in Hulse et al. (1980) and Duodu et al. (2003).

5.1 Toxins

5.1.1 Dhurrin

Sorghum produces the cyanogenic glycoside dhurrin. Dhurrin concentrations vary in different above ground tissues and depending on environmental conditions (Doggett 1988). Dhurrin is hydrolysed to yield equal parts of hydrocyanic acid (HCN, cyanide or prussic acid) and p-hydroxylbenzaldehyde (Doggett 1988). Hydrolysis of dhurrin happens when plant tissues are disrupted, as dhurrin and hydrolytic enzymes are stored in different cell compartments (Kojima et al. 1979; Thayer & Conn 1981). The greatest risk of stock poisoning by cyanide is from young plants or new growth, particularly in stressed or damaged plants (Purseglove 1972; Doggett 1988; QDAF 2013). The risk of poisoning is low when animals feed on flowering and seeding plants or silage (QDAF 2013). Grain and sweet sorghums have higher levels of dhurrin than forage sorghums (QDAF 2013).

Sorghum seeds contain trace amounts of dhurrin (1 to 29 ppm), whereas sprouts of the same seeds grown for 3 days in the dark at 30˚C contain 258-1030 ppm of dry weight (Panasiuk & Bills 1984). Drying and grinding of sprouts to produce a meal does not reduce the potential HCN content and the amount of HCN obtained from sprouts grown from 100 g of seed (61.3 mg) exceeds the average fatal dose for an adult (Panasiuk & Bills 1984).

Farm workers have been overcome by cyanide fumes in large industrial scale sorghum silage operations. The LC_{50} in gaseous form is 100-300 µg/g, with death occurring in less than 1 h.

5.1.2 Nitrate Poisoning

In ruminant animals plant nitrates can be metabolised into toxic nitrites. In monogastric animals the risk of nitrate poisoning is lower because conversion to nitrites occurs closer to the end of the digestive tract (Yaremcio 1991). In Australian conditions levels of nitrate above 1.5% KNO_3 per feed dry weight are considered dangerous (QDAF 2014). Ruminants can tolerate nitrate containing feed if introduced gradually, so the rumen bacterial population can adapt to the diet. However, high levels of nitrate should never be fed to

hungry stock (QDAF 2014). Sorghum has the capacity to accumulate nitrates when soil nitrate content is high (QDAF 2014).

5.1.3 Mycotoxins

Mycotoxins are produced by various fungi growing on grains, grain legumes and oilseeds (Hulse et al. 1980). Two groups of fungal toxins that reduce the nutritional and feed quality are associated with sorghum grain. One group is the ergot 'alkaloids' produced by *Claviceps africana* and the other group is the 'aflatoxins' produced by *Aspergillus flavus* when sorghum grains are stored under high moisture content (QDAF 2010a). The effects of these diseases on the sorghum plant are discussed further in Section 7.2.

Ergot toxins

Ergot is a fungal disease of sorghum caused by *Claviceps africana* (QDAF 2010b). The fungus produces fungal sclerotes, a compact mass of hardened fungal mycelium that contains food reserves and variable levels of toxins, including the alkaloid dihydroergosine. Ergot contaminated grain causes toxicity in livestock. The legal limit for stockfeed in Australia is 0.3% sclerotes by weight for sorghum intended for stock other than feedlot cattle, where a 0.1% sclerotes by weight limit is imposed. Contaminated grain can be mixed with ergot-free grain to achieve sclerote levels below the limits set for each use.

Effects on different livestock species vary. Milk production in sows may be reduced or stopped, resulting in poor piglet growth or loss of litters. Milk production in dairy cows can also be affected, while growth of feedlot cattle is reduced. Chickens appear to be less susceptible to the effects of alkaloids (QDAF 2010b).

Aflatoxins

Alternaria alternata, *Aspergillus spp.* and *Fusarium spp.* can infect sorghum (QDAF 2010a). Toxins may be produced by fungi on weathered grain that has been exposed to high moisture before harvest. *Alternaria alternata* and *Fusarium* mycotoxins are strong but levels rarely reach concentrations of concern. Pigs and poultry are more susceptible than cattle (QDAF 2010a).

Aspergillus spp. on grain stored with high moisture content of 14 – 20% may produce levels of aflatoxins that can cause severe liver damage and reduced growth in pigs and other livestock. In Qld the permitted legal limit of aflatoxins in sorghum for stockfeed is 0.02 mg/kg but this limit is rarely reached (QDAF 2010a).

Mycotoxins can also pose a threat to human health and to food quality. Hepatotoxic, carcinogenic, mutagenic and teratogenic effects of aflatoxins are of concern (FAO 1995). Aflatoxin toxicity can occur as acute aflatoxicosis or as chronic exposure, particularly in developing countries and can induce a range of conditions, including liver cancers and immunosuppressive effects (Wild & Gong 2010). Approximately 4.5 billion people in developing countries are chronically exposed to uncontrolled levels of aflatoxins through consumption of a wide range of affected foods (Williams et al. 2004).

5.2 Allergens

Sorghum pollen has been found to induce allergic reactions in India (Davies 2014). In a study assessing the allergenic capacity of five tropical grasses, sorghum pollen caused the least severe reaction amongst the species tested. Sorghum pollen induced strong allergic

reactions in 16% of 133 patients suffering respiratory allergies, while pollen from the other four species produced these reactions in 22 – 52% of the patients (Sridhara et al. 1995). Five proteins in sorghum pollen are the main cause of the patients' allergic reaction but only one, called Sor b 1, has been identified so far (Sridhara et al. 2002; Davies 2014).

Pollen of tropical grasses are important air-borne allergens in subtropical Australia (Davies et al. 2012). *Sorghum halepense* is an important source of grass pollen allergens for patients with hay fever and allergic asthma in subtropical regions of the world (Lomas et al. 2012). Of 48 grass pollen-allergic patients from Qld, it was found that 77% showed a positive allergic reaction to pollen of *S. halepense* (Lomas et al. 2012). The proteins Sor h 1 and Sor h 13 have been identified as the main cause of the allergic reaction to *S. halepense* pollen (Lomas et al. 2012). It is not known which percentage of grass pollen-allergic patients in Australia is allergic to sorghum and whether there exists cross-sensitivity to pollen of sorghum and *S. halepense*.

5.3 Other undesirable phytochemicals and anti-nutritional factors

5.3.1 Tannins

Tannins, also known as condensed tannins or proanthocyanidins, are phenolic compounds. Tannins are widespread throughout the plant kingdom with diverse biological and biochemical functions, such as protection against predation from herbivorous animals and pathogenic attack from bacteria and fungi. They contribute the bitter flavour and astringency in fruits, vegetables, and certain beverages. Tannins are found in grains, such as sorghum with a pigmented testa layer, some finger millets and barley, but not in major cereal crops, such as rice, wheat, and maize (Dykes & Rooney 2007). Sorghum tannins have anti-nutritional effects that are discussed here but also beneficial ones that are described in Section 5.4.

Although almost all wild sorghums contain condensed tannins in their grains, both tannin and non-tannin types are present in cultivated sorghums. Tannin sorghums are often grown in hot, humid regions of Africa for their better resistance to grain mould and bird damage (Rooney & Miller 1982; Awika & Rooney 2004). Because tannins in sorghum grains have been shown to decrease protein digestibility and feed efficiency in humans and animals, grain sorghum production as a feedstock in the US has been almost entirely restricted to non-tannin types (Rooney & Miller 1982; Awika & Rooney 2004).

Tannin content in the grain is one of the most important factors affecting the feeding value of sorghum. In sorghum, tannin resides mainly in the pigmented testa. Sorghum cultivars may be divided into three categories, depending on their genotypes and tannin contents: type I sorghums do not have a pigmented testa and are tannin free; type II sorghums have a pigmented testa layer that contains condensed tannins; and type III sorghums contain tannin both in the testa and the pericarp (Rooney & Miller 1982). Dykes & Rooney (2006) recorded tannin concentrations of 0.28, 4.48 and 11.95 g/kg in type I, II and III sorghum categories, respectively. Generally, sorghums with more than 1% condensed tannins are considered high tannin varieties. Although tannin containing grains are coloured, not all coloured sorghum grains contain tannins, since pigmentation can result from other phenolic compounds that accumulate in the pericarp (Dykes & Rooney 2006).

The anti-nutritional properties of sorghum tannins have been extensively reviewed (Salunkhe et al. 1990; Chung et al. 1998; Hagerman et al. 1998). Tannins bind with high

affinity to the proline-rich storage proteins of sorghum and inhibit their digestion (Butler et al. 1984). Tannins decrease the activity of digestive enzymes and reduce protein and amino acid availabilities and mineral and vitamin uptake (Chung et al. 1998). As a result, tannins decrease growth rate and feed efficiency. They also damage the mucosal lining of the gastrointestinal tract, change the excretion rate of certain cations and increase the excretion of proteins and essential amino acids (Salunkhe et al. 1982; Mole et al. 1993).

Methods to remove or inactivate tannins prior to consumption include physical means such as milling or hulling, soaking grains, chemical removal, addition of tannin-complexing agents and amino acids, cooking, germination/sprouting, drying and plant breeding approaches (Salunkhe et al. 1990). The choice of the appropriate method(s) is dependent on a number of factors, including the ease of use in a domestic context (Salunkhe et al. 1990).

5.3.2 Phytic Acid

Phytic acid and/or phytate is a principal storage form of phosphate that is ubiquitous in plants, particularly in cereals and legumes. Phytic acid restricts the bioavailability of proteins, vitamins and minerals like calcium, iron, zinc and magnesium (Afify et al. 2011). Phytic acid forms insoluble or nearly insoluble compounds with the above mentioned minerals and the resulting phytate compounds are excreted in faeces (Hulse et al. 1980). Phytic acid is stored mainly in the aleurone layer of sorghum seeds as phytin bodies or aleurone grains, and to a smaller extent in the embryo. The bran of sorghum is reported to contain the highest levels of phytate with the ability to bind 50 - 88% of the iron, calcium and zinc present. This anti-nutrient is of particular importance to monogastric animals while ruminants possess digestive enzymes that degrade phytate and release the chelated minerals. Reducing phytate action is one objective of the ABS Project that aims to improve African human nutrition (Biosorghum.org 2010).

5.3.3 Enzyme inhibitors

Protease inhibitors present in sorghum grains are active against proteolytic enzymes such as serine proteases, trypsin and chymotrypsin. Inactivation of these enzymes can decrease digestibility of dietary proteins (Boisen 1983).

5.4 Beneficial phytochemicals

Sorghum grains have a horny and a floury endosperm and a large fat-rich germ (Figure 7). The endosperm (storage tissue) contains carbohydrates, some protein and minor quantities of fat and fibre (Hulse et al. 1980; Dicko et al. 2006).

Carbohydrate concentrations in the endosperm have been reported from 65 - 90 % (w/w), of which starch is the major component. Starch is the main source of stored energy for the embryo and in sorghum is resistant to degradation, which impairs its digestibility but makes it desirable for managing obesity and diabetes.

The protein content in the grain is 7 - 15% (w/w) and includes albumins, globulins, kafirins, cross-linked kafirins and glutelins (Dicko et al. 2006). Sorghum protein content, like that of other cereals, is deficient in the essential amino acid lysine and has a poor nutritional value because kafirins are protease resistant (Hulse et al. 1980; Dicko et al. 2006).

Grain sorghum is a good source of B vitamins including thiamine, riboflavin, niacin, pyridoxine, pantotenic acid, biotin and folic acid and other vitamins like A, D, E and K (Taylor 2003). Sorghum is also a good source of minerals like potassium, magnesium, iron, zinc and

copper but is low in calcium and sodium (Dicko et al. 2006). Availability of some of these nutrients may be affected by other compounds in the grain, such as phytate.

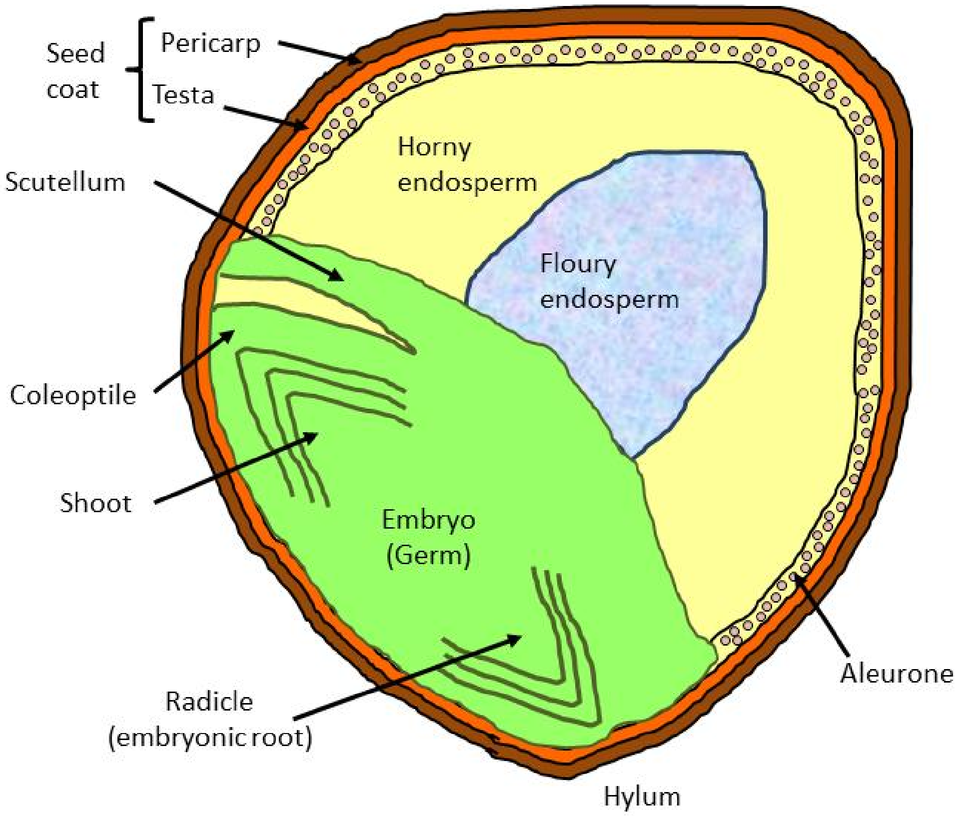

Figure 7. Illustration of a sorghum grain.

Sorghum is a rich source of phytochemicals including tannins, phenolic acids, anthocyanins, phytosterols and poliosanols (Awika & Rooney 2004). While these compounds have detrimental effects as mentioned for tannins, there are also reports of potential positive impacts on human health such as cholesterol lowering properties, reduction of cancer risk and improvement of cardiovascular health (Awika & Rooney 2004; Soetan 2008). The ability of phenolic compounds to act as antioxidants has been recognised and extensively investigated (Salunkhe et al. 1990; Hagerman et al. 1998). Tannins have been reported to exhibit anticancer, anti-mutagenic, antimicrobial and other beneficial properties (Chung et al. 1998; Awika & Rooney 2004). These effects may be related to the anti-oxidative property of tannin which protects against cellular oxidative damage (Chung et al. 1998). However, the practical applications of tannins and other dietary polyphenols in relation to human health require further research (Awika & Rooney 2004).

Sorghum grain contains phytosterols that are cholesterol-like compounds and policosanols that are fatty alcohols. These compounds have been examined in relation to cardiovascular health, particularly their lowering cholesterol properties. It is yet to be determined whether sorghum will be a viable source in a commercial context (Awika & Rooney 2004).

SECTION 6 ABIOTIC INTERACTIONS

Sorghum exhibits tolerance to abiotic stress factors including high temperature and drought; it can become dormant in adverse conditions and resume growth when conditions improve (FAO 2015). These characteristics account for its success as a crop in semiarid regions of the world where prolonged periods of drought and temperature extremes are common (ICRISAT & FAO 1996; Spenceley et al. 2005; FAO 2015).

6.1 Nutrients

Adequate nutrition is necessary to meet the growth and yield potential of sorghum (Vanderlip 1993; Wylie 2008; Pacific Seeds 2008; QDAF 2011c). The two principal nutrients required for successful production of sorghum are nitrogen (N) and phosphorus (P) (Wylie 2008; Pacific Seeds 2008; QDAF 2011c). Other nutrients may be needed, but less frequently. These include zinc (Zn), sulphur (S) and potassium (K) based on testing of levels (Pacific Seeds 2008; QDAF 2011c). In Australia sorghum is often grown in rotation with other crops so nutrient requirements may vary depending on the other crops grown in the rotation (QDAF 2011c; GRDC 2014).

Application of N is necessary before floral initiation to increase yield (Vanderlip 1993). If N is applied at planting, seeds must be protected from the fertiliser (QDAF 2011c).

Sorghum is more tolerant to low soil P than wheat or barley (Moore et al. 2014) and deficiency is most likely to occur after long fallow, due to low levels of soil microbes (QDAF 2011c). Application of P needs to be carefully managed as it can induce Zn deficiency which in turn reduces N uptake (QDAF 2011c). P is best applied as a band at sowing (Pacific Seeds 2008).

Generous plant nutrition is vital at flowering as rapid plant growth and nutrient uptake occurs at this time. If there is a nutrient deficiency during this period it cannot be corrected during later stages (Vanderlip 1993).

6.2 Salinity and Sodicity

Sorghum is moderately tolerant to soil salinity, similar to wheat (Cothren et al. 2000). In Australia subsoil salinity is common in clay soils of northern NSW and sorghum growth has been affected by the soil salinity in this region (Moore et al. 2014).

Subsoil sodicity occurs when an excess of exchangeable sodium cations are attached to clay particles. Sodicity affects the physical characteristics of soils. It causes dispersion in clay soils which affects drainage by inducing hard setting and soil surface sealing. This can lead to surface waterlogging and restrict germination of sorghum (Moore et al. 2014).

6.3 Temperature

Temperature requirements for sorghum growth were described in section 2.3.3. High temperatures can be responsible for cellular dehydration with significant disorders in membrane structure, composition and function and can cause ‘leaf firing’ (leaf chlorosis starting at the tips and margins and progressing down the leaf blade). Sorghum lines show variable susceptibility to heat (Jordan & Sullivan 1982). Similarly, genetic diversity exists in sorghum for cold tolerance at adult plant stage and at germination. This may assist in expansion of sorghum into areas of higher elevation and temperate climate (Kimber 2000).

6.4 Water

While sorghum can tolerate periods of water deficit, it does respond well to rainfall and to soil moisture conservation (Rosenow et al. 1983; GRDC 2014; Moore et al. 2014). Even with inherent tolerance, extreme conditions are responsible for suboptimal grain yields and there has been considerable focus on the genetic basis of drought tolerance as part of breeding programs (GRDC 2014). A number of morphological and physiological features are important in sorghum drought resistance, particularly in comparison with maize:

- establishment of the root system occurs before rapid above ground growth
- the secondary root system is extensive
- silica deposits in the root endodermis help protect against root collapse under drought stress
- leaves have a waxy coating and can roll inwards in drought conditions
- lower evapotranspiration; it requires less water to produce the same amount of dry matter
- sorghum competes well with weeds once established
- the plant can remain dormant during drought conditions and resume growth when conditions improve

Waterlogging can also cause plant stress. Short-term waterlogging can increase the risk of seedling disease and may be involved in root rots and reductions in N uptake as well as N loss via soil leaching (Pacific Seeds 2008; Philp & Harris 2013; GRDC 2014; Moore et al. 2014). Water flow into furrows may carry herbicides applied at planting into furrows, concentrating them around the seed zone and may also carry soil into furrows, effectively increasing the seed depth, both of which may reduce seedling emergence (GRDC 2014). Waterlogging is more likely in irrigated crops or adverse soil conditions (Moore et al. 2014).

SECTION 7 BIOTIC INTERACTIONS

7.1 Weeds

The most severe weed competition with dryland sorghum occurs during crop establishment. Early in this phase, weeds compete with the developing sorghum seedlings for moisture, nutrients and space (Vanderlip 1993). Herbicide application is a common solution and pre-emergent herbicides are often applied, although seed protection treatments may be required (Spenceley et al. 2005; Pacific Seeds 2008). Delaying weeding one, two and three weeks compared to standard practices reduces sorghum yield 4%, 12% and 18%, respectively (Burnside & Wicks 1969). Weeds that germinate later than 30 days after sowing have little effect on yield (Burnside & Wicks 1969).

In a survey of weeds and weed management of dryland cropping areas of north-eastern Australia (northern NSW, southern and central Qld) the common major weeds were *Sonchus oleraceus*, *Rapistrum rugosum*, *Echinochloa* subsp. and *Urochloa panicoides* (Osten et al. 2007). This survey also found that few growers were using integrated weed management and that herbicide resistance had been and continued to be an issue in this region. The herbicides approved for use in sorghum cultivation in Australia are shown in Table 6 (Moore et al. 2014). Weed control needs to be targeted to ensure correct timing and application

rates. It must also consider any crops to be planted following sorghum to achieve optimal control without residual effects (Moore et al. 2014).

Glyphosate and mixes with glyphosate are commonly used for weed control in fallows, while atrazine and metolachlor are predominantly used for in-crop weed control.

Table 6. Herbicides registered for use in sorghum (Moore et al. 2014).

	Herbicide	Group	Sorghum use pattern			
			Pre-plant	Post-plant / pre-emergent	Post-emergent	Pre-harvest crop dessication
Residual activity – check plant backs	2,4-D amine	I	√			
	Atrazine	C	√	√	√	
	Dicamba	I	√		√	
	Dicamba + atrazine	I & C			√	
	Fluroxypyr	I	√		√	
	Fluroxypyr + Atrazine	I & C			√	
	S-metolachlor	K		√		
	S-metolachlor + Atrazine	K & C		√		
	Triclopyr	I			√	
	Tribenuron-methyl	B	√			
Knockdown activity	Glyphosate	M	√			√
	Amitrole + Paraquat	L & Q	√			
	Diquat	L	√			√
	Paraquat	L	√			
	Paraquat + Diquat	L	√			

7.2 Pests and diseases

7.2.1 Invertebrate Pests

In Australia insect pests will affect sorghum throughout its life cycle. The main pests of sorghum are the moth *Helicoverpa armigera* and the sorghum midge *Stenodiplosis sorghicola* (QDAF 2012a). Table 7 outlines the most common insect pests of sorghum including the type of damage caused and possible control strategies (Franzmann 2007). Both Qld and NSW state authorities provide an extensive summary of predator species for these pests, as well as information on control methods (Spenceley et al. 2005; QDAF 2012a; Moore et al. 2014).

Table 7. Details of sorghum pests in Australia (Franzmann 2007).

Plant stage[a]	Pest	Status in Australia	Damage	Control
Germination	Black field earwig (*Nala lividipes*)	Minor, widespread, regular	Germinating seed serves as food to nymphs and adults; most damage is recorded at early plant stage as they attack roots	Mainly chemical, germinating seed baits, insecticide seed dressings
	False wireworms: Southern false wireworm, (*Gonocephalum macleayi*) Large false wireworm (*Pterohelaeus alternatus*)	Major, widespread, irregular	Larvae feed on seeds, roots, growing tips of plants; adults feed on young plants by cutting off plant at the ground level	Integrated Pest Management (IPM)
	Cutworms *Agrotis spp.*	Minor, widespread, irregular	Larvae feed on leaves, stems of young plants leading to wilting and death	Chemical - pyrethroid sprays effective
Vegetative	Corn aphid (*Rhophalosiphum maidis*)	Minor, widespread, regular	Adults and nymphs suck sap and produce honeydew. Plants turn yellow when attacked by large numbers, heads produce sticky grain; loss of yield can occur under dryland conditions	Chemical
	Armyworms: Northern army worm (*Leucania separata*) Common armyworm *(Leucania convecta)* Dayfeeding	Minor, irregular	Larvae defoliate young plants; mature plants may outgrow damage but seed yield is reduced; signs include chewed leaf margins, faecal pellets	Chemical

Plant stage[a]	Pest	Status in Australia	Damage	Control
	armyworm (*Spodoptera exempta*)			
Flowering; seed	Corn earworm *(Helicoverpa armigera)*	Major, widespread, regular	Larvae feed on developing seeds	Biocidal; nucleopolyherovirus (NPV)
	Sorghum midge *(Stenodiplosis sorghicola)*	Major, widespread, irregular	Midge larvae destroy developing seed. Large populations may completely destroy the crop	IPM
	Sorghum head caterpillar *(Cryptoblabes adoceat)*	Minor, restricted, irregular	Larvae feed on developing seed; each larva can destroy 0.5 g of grain	Chemical
	Yellow peach moth *(Conogethes punctiferalis)*	Minor, restricted, irregular	Larvae feed on developing seed. Each larva can destroy up to 1 g of grain	Chemical

[a] Vegetative = Vegetative growth phase; Flowering; Seed = Flowering head and seed development

Management

Helicoverpa (*H. armigera*) can now be controlled using an IPM approach using nucleopolyherovirus (NPV) that is selective for *Helicoverpa*, while midge control is generally achieved by planting midge tolerant cultivars. These approaches eliminate impacts on natural predators that help to control these insect pests (Spenceley et al. 2005; QDAF 2012a).

Armyworms and soil insects are important pests during the early stage of crop development (Spenceley et al. 2005; Pacific Seeds 2008; QDAF 2012a). These pests are not often at levels requiring control, but may be a problem in cool conditions or in compacted soils (Spenceley et al. 2005; QDAF 2012a).

Aphids and rutherglen bugs are controlled by choosing sorghum hybrids with open panicles, since these insects prefer closed panicle types, which also make spray penetration more difficult (QDAF 2012a).

7.2.2 Vertebrate Pests

Feral pigs, kangaroos, mice and various birds, especially parrots, will eat sorghum grain once it is at or near maturity. Cattle, horse and sheep will all graze on sorghum. Native and introduced mice have been documented to collect and carry viable grain. Plague mice have been shown to reach numbers of up to 3,000 per hectare in sorghum crops (GRDC 2011).

Birds, particularly large parrots such as galahs (*Eolophus roseicapilla*), cockatoos and cockatiels (both members of the *Cacatuoidea*) are attracted to sorghum when is mature, especially to sorghum with white or yellow seed coats as these are more palatable than red or brown seeded types (Dogget, 1998). Sorghum is also a common component of native and introduced bird seed mixes for feeding.

7.2.3 Diseases

Most of the diseases under Australian conditions are caused by fungal pathogens including ergot, rusts, smuts, rots and blights; as well as Johnson grass mosaic virus. Much of the information available for Australian crops is available from the NSW DPI and QDAF websites.

Leaf diseases can reduce yield. Photosynthesis drives grain development and filling during the grain filling phase. Gains in these parameters are closely related to leaf area which is affected by these diseases (Pacific Seeds 2008). Planting hybrids with good disease resistance at the correct time will manage such disease problems (Spenceley et al. 2005).

Ergot

Ergot is a fungal disease caused by *Claviceps africana* (QDAF 2010b; GRDC 2014). Ergot was first recorded in Australia in 1996, is endemic to Qld and has been found in northern NSW (QDAF 2011a; Moore et al. 2014). The development of resistance to ergot infection is a major goal of sorghum breeding in Australia (QDAF 2015).

Ergot infects the unfertilised sorghum flower when fungal spores land and grow down to the developing ovary, which is rapidly replaced by the fungal mass, becoming a hard body known as the sclerote (QDAF 2010b). Ergot infection can occur at any time if suitable weather conditions occur. A constant temperature of 20°C and relative humidity close to 100% favours maximum infection under experimental conditions and in the field infections are associated with at least two days of rainy weather and temperatures below 28°C (QDAF 2010b). Factors which result in poor or uneven pollination such as rainy conditions increase susceptibility of grain sorghum, while for late tillers, forage sorghum and male sterile lines infection can occur under a broader range of conditions (QDAF 2010b). Ergot is readily identified by the honeydew oozing from sorghum flowers that dries up into a white powder that is often observed on the leaves and on the soil under affected plants (Figure 8).

Ergot reduces grain set and consequently yield. It also affects grain quality due to lower nutritional value and the presence of sclerotes (QDAF 2010b; Moore et al. 2014). Ergot can survive all year in honeydew on other hosts including *S. halepense*, Columbus grass (*Sorghum x almum)* and volunteer grain and forage sorghum, but it does not survive on sorghum stubble or as sclerotes in the soil. Spores are generally spread by wind, but also by insects, animals, humans and machinery (QDAF 2011c).

Sorghum rust or leaf rust

Rust is caused by *Puccinia purpurea* and is more serious in late-sown crops or susceptible hybrids in humid areas. Hybrids with resistance are usually selected for late planting. Early symptoms of the disease include small purple red or tan spots on leaves that widen and produce elongated raised pustules which break open to release a brown, powdery mass of spores (Spenceley et al. 2005; QDAF 2011a; Moore et al. 2014). If the disease is serious,

leaves are destroyed and pinching of the grain results, which promotes lodging and decreases yield, however this is rare (Spenceley et al. 2005; QDAF 2011a; Moore et al. 2014).

Figure 8. Honeydew oozing on a grain sorghum head infected with *Claviceps africana* (reproduced with permission from QDAF Sorghum disease management).

Fusarium stalk rot

The main causes of stalk rot in Qld are *Fusarium* species, mainly *F. thapsinum* and *F. andiyazi*, both of which survive in infected sorghum residues, infecting plants during the early stages of plant growth. Mild wet weather is conducive to rot infection which can lead to lodging (QDAF 2011b). This pathogen is difficult to control after planting and symptoms may not always be obvious (QDAF 2011b). The use of non-host crops in rotations and practices to minimise moisture stress are recommended (Moore et al. 2014).

Head smut

Smut is a soil-borne disease caused by *Sporisorium reilianum* (Spenceley et al. 2005; QDAF 2011a). Symptoms usually appear at the boot stage when the head is replaced by a mass of black spores covered in a white fungal membrane. This membrane breaks open on emergence of the head and disperses the spores. Heads that are partially affected become sterile. Disease may be seed borne and onset occurs with favourable cool weather conditions. Sowing resistant hybrids during cool weather conditions is an important control measure (Spenceley et al. 2005; QDAF 2011a).

Leaf blight

Leaf blight (*Exserohilum turcicum*) symptoms are elliptical spots up to 20 mm wide and 100 mm long, initially water soaked, drying to straw-coloured spots with red, purple or tan margins. Spores are produced on these spots during damp conditions and are dispersed by wind (QDAF 2011a). The fungus can survive on undecomposed sorghum residues, volunteer sorghum plants and *S. halepense*. If the disease is severe, pinched grains are formed, resulting in lower yields (QDAF 2011a). In the coastal areas, humid conditions favour the severity of the disease, especially on susceptible hybrids. Resistant hybrids are recommended where the disease is a problem (Spenceley et al. 2005; QDAF 2011d).

Johnson grass mosaic virus

Mosaic virus is an important sorghum disease that occurs in Qld. Common symptoms include light and dark-green lines on veins, red leaf (severe leaf reddening, followed by formation of red spots or large areas of dead tissue) and red stripe (red or tan stripes parallel to the veins). Severe infections can cause stunting and death in some plants. Aphids are the main vector which transmits and spreads the disease. Control is usually by planting resistant hybrids. However, a strain of the virus that occurs in South and Central Qld can infect resistant hybrids (Spenceley et al. 2005; QDAF 2011a).

SECTION 8 WEEDINESS

Cultivated sorghum has several characteristics common to weed species such as wind pollination (although it is mostly self-pollinating) and its ability to germinate and grow in a range of environmental conditions. However, the capacity to shatter and distribute seed has been lost through the domestication and breeding process (Dillon et al. 2007b), it is non-rhizomatous or weakly rhizomatous (House 1985) and the survival of seed in the soil is limited. Some well-known weeds are closely related to cultivated sorghum, such as *S. halepense* which is a rhizomatous perennial, or annual grasses occurring as hybrids between cultivated and wild sorghums within the *S. bicolor* species (Ejeta & Grenier 2005).

8.1 Weediness status on a global scale

Cultivated sorghum does not have a weed status although it can appear as volunteer plants after crop harvest. In the Global Compendium of Weeds (Randall 2012) there are only four references to *S. bicolor* listed, three in the US as casual alien, cultivation escape and naturalised, as well as one in Australia with the non-specific category of 'weed'.

8.2 Weediness status in Australia

Naturalised non-native plant species are defined as those that have been introduced and become established and that now reproduce naturally in the wild, without human intervention (Groves et al. 2003). Naturalised species are ranked according to their invasiveness in agricultural and natural ecosystems in the categories shown in Table 8 (Groves et al. 2003). The special category of 'noxious weed' is recognised throughout Australia, in that the category is enacted by legislation in each State or Territory for particular invasive plant species. A declaration of 'noxiousness' always implies the need for active management to reduce the impact of the particular plant species on human activities (Groves et al. 2003).

Cultivated sorghum is a naturalised species and a category 3 weed in agricultural systems according to Groves et al (2003), being a minor problem in Qld and NSW. Sorghum does not appear in the weed list of the Weeds in Australia database (accessed in February 2017).

Table 8. Weediness categories used in Groves et al. (2003).

Category	Explanation
0	Reported as naturalised but only known naturalised population now removed or thought to be removed
1	Naturalised and may be a minor problem but not considered important enough to warrant control at any location

Category	Explanation
2	Naturalised and known to be a minor problem warranting control at 3 or fewer locations within a State or Territory
3	Naturalised and known to be a minor problem warranting control at 4 or more locations within a State or Territory
4	Naturalised and known to be a major problem at 3 or fewer locations within a State or Territory
5	Naturalised and known to be a major problem at 4 or more locations within a State or Territory
+	Present in a State or Territory but not given a rating as an agricultural weed, either because it was not considered a problem or because it was not known to occur in agricultural areas at present.

8.3 Weediness in natural and agricultural ecosystems

Cultivated sorghum is not present in natural environments. In agricultural ecosystems, sorghum volunteers are commonly found along road sides, around sheds, silos and intensive animal feeding enterprises in the areas of cultivation. These are usually as a result of spillage during transport. There are few reports of cultivated sorghum volunteers in cropping systems. In a study monitoring weeds in four cropping regions of subtropical Australia, sorghum, along with a number of other crop species, was reported as a volunteer (Rew et al. 2005). It has been noted as difficult to eradicate from subsequent grain crops (Cook et al. 2005a).

8.4 Control measures

In cultivated areas sorghum is commonly controlled by herbicide, most frequently glyphosate (Allen 1985). Cultivation can also be used.

8.5 Weed risk assessment

The weed risk potential of sorghum has been assessed using methodology based on the Australia/New Zealand Standards HB 294:2006 National Post-Border Weed Risk Management Protocol. This Protocol rates the weed risk potential of plants according to properties that strongly correlate with weediness (Virtue et al. 2008). These properties relate to invasiveness, impacts and potential distribution. The distribution of sorghum is driven by economics, as well as factors such as climate and soil suitability.

In summary, as a volunteer (rather than a crop) sorghum is considered to:

- have a low ability to establish amongst existing plants
- have a low tolerance to average weed management practices in cropping and intensive land uses
- have a short time to seeding (less than one year)
- have a low ability for volunteers to establish in any land use
- rarely reproduce by vegetative means
- be unlikely to undergo long distance spread by natural means

- be commonly spread long distances from dryland and irrigated cropping areas by human activities
- have a limited ability to reduce the establishment or yield of desired plants
- have a low ability to reduce the quality of products or services obtained from all land use areas
- have a low potential to restrict the physical movement of people, animals, vehicles, machinery and/or water
- have a low potential to negatively affect the health of animals and/or people
- may act as a reservoir for a range of pests and pathogens
- have a low effect upon soil nutrients, salinity, stability and the water table.

This is consistent with previous assessments of sorghum in Australia summarised in Section 8.2, and provides a baseline for the assessment of GM sorghum.

8.6 Weediness of other *Sorghum* species

Five *Sorghum* species that belong to the gene pool groups GP1 and GP2 and therefore are able to outcross with cultivated sorghum (see section 9) are naturalised in Australia (Table 9). Of these, three species have been declared noxious in different states (Parsons & Cuthbertson 2001b). *S. halepense* is declared noxious in 88 councils of NSW and in NT; *Sorghum* subsp. hybrid cv. Silk is declared noxious in 40 councils of NSW and *Sorghum x almum* is declared noxious in 85 councils of NSW. *S. halepense* and *S. bicolor* subsp. *drummondii* are the primary weedy relatives of interest to agriculture due to their invasiveness and propensity to evolve resistance to herbicides (Holm et al., 1977; Heap 2012).

Table 9. Sorghum species listed as weedy in agricultural systems in Australia.

Species	Alternate name (s)	Category[1]	Gene Pool
S. x almum[1,3]	Columbus grass	5	GP2
S. halepense[1,3]	Johnson grass	5	GP2
S. spp. hybrid cv. Silk[1,3]	Silk forage sorghum	n/a	GP1-2?
S. *bicolor* subsp. *drummondii*[1,2]	Shattercane, Sudangrass	+	GP1
S. bicolor subsp. *arundinaceum*[1,2]	*S. bicolor* subsp. *verticilliflorum*	5	GP1

[1] Source: Groves et al. (2003)
[2] Source: Parsons and Cuthbertson (2001b)
[3] Source: Weeds in Australia database (Department of the Environment 2015)

8.6.1 Sorghum halepense (Johnson grass)

The most widely recognised noxious weed is *S. halepense*, commonly known as Johnson grass. The origin of Johnson grass is unclear, but it may be a natural allotetraploid hybrid between the cultivated *S. bicolor* and wild rhizomatous species *S. propinquum* native to Southeast Asia, Indonesia, and the Philippines (Paterson et al. 1995).

S. halepense was probably introduced as a potential fodder grass in the mid-nineteenth century and is now widespread in arable areas of NSW and Qld. It causes severe crop losses from competition, allelopathic action and via acting as a host for crop pests and diseases. Its

pollen also induces allergic reactions in people with hay fever and allergic asthma in tropical regions (see section 5.2).

S. halepense has been cited as one of the ten worst weeds in the world. It is an aggressive perennial grass posing a threat as a serious weed in agricultural systems of many countries from the Mediterranean through the Middle East to India, Australia, central South America and the US (Holm et al. 1977). There are over three hundred references considering *S. halepense* a weed that may be declared noxious, invasive and subject to quarantine restrictions (Randall 2012).

Seeds from *S. halepense* disperse by shattering and also by wind, animals and humans (Parsons & Cuthbertson 2001b). Its seed does not survive long in shallow soil depths, but large seed banks can be accumulated in the upper layer of soil by frequent seed input each year. *S. halepense* seeds survive longer at depths greater than 22 cm in undisturbed soil, meaning persistent seed banks can accumulate at greater depths (Leguizamón 1986). Seeds of *S. halepense* have a hard coat which enables survival in harsh conditions (Hill 1983). While *S. halepense* primarily reproduces through seed, its invasiveness is due to its ability to persist and to spread through rhizomatous vegetative reproduction (Parsons & Cuthbertson 2001b). Rhizomes from this species are extensive and can regenerate after cutting during cultivation (Warwick & Black 1983). *S. halepense* occurs sympatrically with grain sorghum, has overlapping flowering times permitting a high likelihood for genetic exchange and hybridisation has been observed in field trials in the US (Arriola & Ellstrand 1996; Arriola & Ellstrand 1997; Ejeta & Grenier 2005).

S. halepense is also considered to be a major problem in the natural environment. *S. halepense* is listed as occurring in wet areas in particular along field borders, roadsides, creeks and canal banks, readily invading cultivated and irrigated paddocks from these areas (Parsons & Cuthbertson 2001b).

S. halepense readily invades arable areas in high rainfall regions. In lower rainfall areas it appears to be more restricted to road sides, waste areas and fence lines. It produces dhurrin and nitrate (see section 5) and is a risk to livestock when occurring in pasture. Up to 50% of cattle may die rapidly upon feeding on it (Parsons & Cuthbertson 2001b).

Control measures used for *S. halepense* are difficult because of the regeneration from rhizomes (Parsons & Cuthbertson 2001b). Rhizomes can be limited in *S. halepense* if plants are kept small by mowing, especially in conjunction with competition from other forage species. Repeated mowing and out-competition by paspalum has been successful in the Darling Downs (Parsons & Cuthbertson 2001b). Cultivation of fallow ground to expose rhizomes to adverse surface conditions has been also used (Hill 1983). Repeated cultivation every three or four weeks is useful but not reliable. Integrated control measures in which crop rotation with competing crops, cultivation, and herbicides are combined give the best results (Parsons & Cuthbertson 2001b).

8.6.2 ***Sorghum x almum*** **(Columbus grass)**

Another aggressive weedy species is *S. x almum* also called Columbus grass, a hybrid between S. *bicolor* and S. *halepense.* This annual grass has been cultivated as forage sorghum in Australia. *S. x almum* appears mostly along roadsides, fence lines and in natural environments but is considered to be less problematic than *S. halepense* (Parsons & Cuthbertson 2001b). It is dispersed by seed which floats and can stick to wool and fur of

animals. Seeds can pass through the digestive tract of animals and remain viable so the plant can be spread widely by travelling animals. Columbus grass has the capacity to harbour diseases and insect pests of sorghum, to contaminate grain sorghum seed and poison stock with high levels of dhurrin and occasionally toxic amounts of nitrate (Parsons & Cuthbertson 2001b).

Columbus grass is not readily controlled by cultivation, although repeated cultivations at short intervals can be effective. This practice must be offset by managing an increased erosion risk. Similarly, repeated mowing and slashing reduces vigour but does not eradicate the plant. Chemical control with certain herbicides can be effective. Best results are obtained by slashing or burning in December and spraying the regrowth at early flowering (Parsons & Cuthbertson 2001a).

8.6.3 *Sorghum bicolor* **subsp.** *drummondii* **(Shattercane and sudangrass)**

S. bicolor subsp*. drummondii* is an annual grassy weed that either is an "off-type" of cultivated sorghum which has naturalised or potentially a cross between cultivated sorghum and the wild progenitor *S. bicolor subsp. arundinaceum*. *S. bicolor* subsp. *drummondii* includes forage sudangrass and the weedy shattercanes (Defelice 2006).

Shattercanes have a very efficient type of shattering caused by an abscission layer that forms at the base of the spikelet (Defelice 2006). The abscission layer forms at the approximate time of seed maturity, and all of the seeds are readily dropped from the plant with only a light breeze. The seeds typically mature and drop before the cultivated crop is harvested, leaving the seeds in the field. In highly mechanised cultivation systems their spread may not be controlled (Ejeta & Grenier 2005). Seeds may be spread by wind and water, on animal coats, through ingestion by birds and cattle, and in contaminated seed stock and feeds (Burnside et al. 1977). In studies comparing cultivated sorghum and shattercane seed survival in soil, sorghum seeds showed limited germination after four months and none at eight, whereas some shattercane seeds still germinated after three years (Jacques et al. 1974). Shattercane also exhibits seed resistance to deterioration compared to cultivated sorghum, possibly due to physical and compositional barriers to microbial infection (Fellows & Roeth 1992). There are reports from North America indicating that shattercane seed may survive for up to 13 years in soil, making control of this weed difficult (Burnside et al. 1977).

S. bicolor subsp. *drummondii* is an important agricultural weed in the US (USDA 2015) but in Australia is classified as a category 3 weed in natural ecosystems and category + in agricultural ones (see Table 8; Groves et al. 2003). Likewise it has been listed as naturalised in disturbed sites in Australia (Richardson et al. 2011) but it is not listed as weed in the Weeds in Australia database (Department of the Environment 2015).

8.6.4 *Other sorghum species*

S. bicolor subsp. *arundinaceum* is classified as a category 5 weed in Groves et al. (2003) being a problem in agricultural ecosystems in Qld. However it is not classified as noxious or a controlled weed in the Weeds in Australia database.

Perennial ('Silk') sorghum cultivated in the NT as forage sorghum is declared noxious in parts of NSW, however concerns about weediness of this hybrid have not been realised in the NT. This forage sorghum can be ploughed out after use, seedlings and young plants can be controlled by herbicides and the crop can be eradicated by heavy grazing, particularly in the dry season (Cameron 2014). However, caution is recommended in ensuring seeds and plant

material are not transferred to other properties or roadsides due to their weedy potential (Cameron 2014). Perennial sorghum can be spread via seed dropping onto arable land and seed sale has been restricted due to fears of reversion to the *S. halepense* parent or of contamination with *S. halpense* seed which is similar to perennial sorghum seed (Cook et al. 2005b).

SECTION 9 POTENTIAL FOR VERTICAL GENE TRANSFER

Vertical gene transfer is the transfer of genetic information from an organism to its progeny by conventional heredity mechanisms, both asexual and sexual. In flowering plants pollen dispersal is the main mode of gene flow. For cultivated crops, gene flow could occur via successful crosspollination between the crop and neighbouring crops, related weeds or taxonomically related native species.

For hybridisation to occur through crosspollination at least five factors must be satisfied, as summarised below (Conner et al. 2003; Mutegi 2009):

- the two taxa must be situated close enough for pollen exchange to occur
- the populations must overlap at least partially in flowering time to allow pollen from one population to reach a receptive plant in the other
- they must share a pollen vector
- the two taxa must be reproductively compatible
- the resultant F_1 hybrid must be viable and at least partially fertile to allow for the introgression of alleles from one taxa to another through backcrossing

The likelihood of gene flow from crops to wild or weedy relatives will depend on a number of important factors. Key considerations include the nature of the allele(s) transferred; beneficial, neutral or detrimental to the wild or weedy species, noting that this may vary with time or environment; the gene flow pressure and the relative sizes of the crop and of the wild or weedy population (Ellstrand et al. 1999; Stewart et al. 2003; Ellstrand 2003; Ejeta & Grenier 2005; Andersson & deVicente 2010).

Sorghum gene pools

Sorghum is a well-documented example of the sympatric association and interaction of a crop with wild and weedy relatives within an agro-ecosystem (Arriola & Ellstrand 1996; Arriola & Ellstrand 1997; Ejeta & Grenier 2005). The *Sorghum* genus has been divided into three distinct gene pools based on the degree of cross compatibility (Harlan & de Wet 1971).

The primary gene pool (GP1) of sorghum contains members of the subgenus *Eusorghum* that are sexually compatible (Figure 10). It includes cultivated sorghum, *S. propinquum*, *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *arundinaceum*. These species are fully inter-fertile and the high level of compatibility permits spontaneous hybridization, outcrossing and introgression (Ejeta & Grenier 2005; Dillon et al. 2007b). For this reason, they have provided the base for breeding efforts until recent times.

The secondary gene pool (GP2) is comprised of the tetraploid relatives including *S. x almum* and *S. halepense.* Members of GP2 and GP1 (including cultivated sorghum) have the potential to hybridise with each other despite ploidy level differences, to produce either sterile triploids or partially fertile tetraploids (Arriola & Ellstrand 1996; Arriola & Ellstrand 1997).

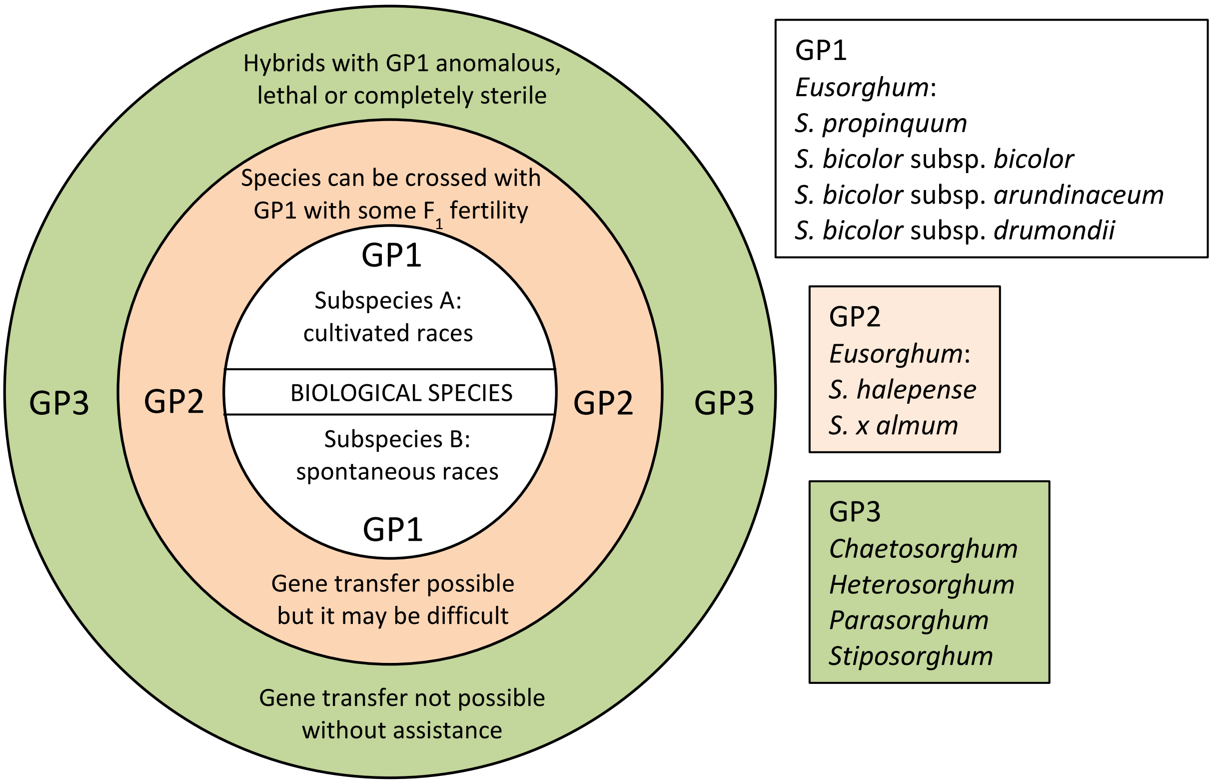

Figure 10. The sorghum gene pools. Adapted from Harlan & de Wet (1971) and Ejeta & Grenier (2005)

The tertiary gene pool (GP3) consists of the wild sorghum relatives from other subgenera of *Sorghum – Chaetosorghum, Heterosorghum, Parasorghum and Stiposorghum.* These species are not known to be capable of outcrossing or introgressing with GP1 and GP2 in nature. Wild Australian species form the majority of the tertiary gene pool, comprised of 19 divergent *Sorghum* species (Lazarides et al. 1991). The species in GP3 constitute an untapped gene pool for breeding. However, outcrossing of cultivated sorghum with this group is difficult even under laboratory conditions (see below).

9.1 Crosses within GP1

The outcrossing rates of modern cultivated sorghum vary widely depending on cultivar and environmental conditions, but an average of less than 10% is cited (House 1985). For weedy taxa with open grass-like panicles such as *S. bicolor* subsp. *drummondii*, crosspollination ranged widely from 0 to nearly 100% for individual plants, whereas outcrossing between cultivated lines in the same study ranged from 0 to 13 % (Pedersen et al. 1998).

The capacity for sexual compatibility between cultivated sorghum and its wild and weedy relatives of GP1 resulting in introgression and hybrids is well documented. Compatibility between domesticated and wild taxa in areas with sympatric occurrence has often resulted in wild relative/weedy/domesticated hybrid complexes, including intraspecific and interspecific crosses (Ellstrand et al. 1999). Weedy or wild species of sorghum are commonly found together in cultivated environments and have hybridised successfully. For example, *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *arundinaceum* are annual weeds found in cultivated grain sorghum crops (Ejeta & Grenier 2005; Andersson & deVicente 2010).

Analysis of progeny segregation showed that crop-specific alleles are present in wild *S. bicolor* when it occurs with the crop in Africa (Ejeta & Grenier 2005).

Field-based gene transfer studies in the US demonstrated that based on a number of vegetative and reproductive characteristics, sorghum/shattercane F_1 hybrids showed similar levels of fitness to the shattercane parent suggesting that transferred crop genes would persist in the population within agroecosystems, if they are neutral or beneficial to the progeny (Morrell et al. 2005). In a study about hybridisation between shattercane and grain sorghum, a pollen donor source of grain sorghum was grown surrounded by shattercane plants that radiated outwards to a maximum distance of 200 m (Schmidt et al. 2013). Hybrid offspring occurred in 12% and 41% of shattercane panicles at 200 m, depending on the year of the experiment (Schmidt et al. 2013). This work demonstrates that if flowering time overlaps, hybridisation between sorghum and shattercane occurs at least at 200 m.

9.2 Crosses between sorghum and GP2 species

The most widely recognised noxious weed amongst the *Sorghum* species is *S. halepense* (Johnson grass) which is a serious problem both in Australia and overseas (see section 8). Molecular evidence of genetic introgression between cultivated sorghum and *S. halepense* has been obtained in the US (Arriola & Ellstrand 1996). Plants of *S. halepense* were placed at increasing distances from a plot of sorghum to allow spontaneous crosspollination and production of hybrid seed, and hybrids were detected 100 m from the crop, leading to the conclusion that interspecific hybridisation can and does occur at a substantial and measurable rate (Arriola & Ellstrand 1996). Crop to weed gene flow was reported to be highly dependent on the weed's distance from the cultivated crop, the location of the experimental site and the abiotic and biotic factors prevalent during the study year (Arriola & Ellstrand 1996). This may be attributed to the abundance of pollen availability near the crop increasing the likelihood of hybrid formation (Arriola & Ellstrand 1996).

Molecular evidence strongly suggests that introgression has occurred and persisted between cultivated sorghum and *S. halepense*. Morrell et al. (2005) surveyed allelic diversity in 16 commercial sorghum cultivars and 13 samples of *S. halepense* and *S. x almum* from various locations worldwide, including *S. halepense* samples from across the US with differing exposure to cultivated sorghum. The presence of 77 cultivar-specific alleles in the US samples of *S. halepense,* but absent from worldwide samples of weedy sorghum relatives, suggested that introgression had occurred. Within the US a higher frequency of cultivar-specific alleles was found in *S. halepense* from areas with higher exposure to crop sorghum than those more distant from the crop, suggesting a relationship between levels of exposure and introgression (Morrell et al. 2005). Both recent and older introgression of crop genes was implied in this study based on the number of alleles and timing of exposure, with the persistence of older introgression suggesting a lasting impact of cultivated sorghum on the genetic composition of *S. halepense* populations (Morrell et al. 2005).

An example of natural hybridisation between diploid *S. bicolor* and tetraploid *S. halepense* has been implicated in the origin of the weedy *S. x almum* (2n=40), a perennial rhizomatous noxious weed commonly referred to as Columbus grass (Doggett 1988). Restriction fragment length polymorphism (RFLP) analysis revealed that both *S. x almum* and *S. halepense* contain a combination of alleles specific to their putative parent species (Paterson et al. 1995).

In Australia the distribution of cultivated sorghum overlaps with that of weedy sorghums such as *S. halepense*, *S. x almum* and Perennial (Silk) forage sorghum. Distribution maps for these species are shown in the Appendix B (Figures B1, B2, B3, B4).

9.3 Crosses between sorghum and GP3 species

Cultivated sorghum does not hybridise naturally with the wild Australian species due to pollen-pistil incompatibility (Hodnett et al. 2005). The pollen of undomesticated species behaves abnormally in the pistils of *S. bicolor* and pollen rarely grows beyond the stigma not resulting in embryo formation. However, incompatibility may be overcome for breeding purposes under laboratory conditions. A sorghum accession homozygous for a recessive allele that permits exogenous pollen growth in its pistils has been identified (Laurie & Bennett 1989). This overrides pollen-pistil incompatibility, making possible hybridisation between *S. bicolor* and undomesticated *Sorghum* species (Price et al. 2005b; Price et al. 2006). Hybrids between *S. bicolor x S. macrospermum*, *S. bicolor* x *S. angustum* and *S. bicolor* x *S. nitidim* have been produced, although hybrids had to be recovered by embryo rescue and tissue culture in some instances (Price et al. 2005b; Price et al. 2006; Kuhlman et al. 2010). Thus genomic introgression from wild germplasm into sorghum can occur and it is now technically possible to accelerate the incorporation of novel genes into future cultivars (Price et al. 2006; Kuhlman et al. 2010).

9.4 Intergeneric crossing

Saccharum and *Sorghum* are considered to be the closest crop relatives in the *Poaceae*. Hybrids between sorghum and sugarcane (*Saccharum officinarum* or *Saccharum* hybrids) have been obtained under artificial conditions for breeding purposes (Thomas & Venkatraman 1930; Nair 1999; Hodnett et al. 2005). Sorghum has been used both as female and male parent and many flowers had to be crosspollinated in order to generate a few hybrids (Thomas & Venkatraman 1930; Nair 1999). Most of the hybrids obtained were not vigorous and lacked valuable agronomic traits. Although these experiments demonstrate that sugarcane and sorghum are partially sexually compatible, hybridisation in the wild has not been reported.

Hybridisation experiments have been also attempted between *Zea mays* and sorghum and even though the maize pollen tube grew through the sorghum ovary, the recovery of sorghum-maize hybrids was not successful (Laurie & Bennett 1989).

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APPENDIX A

Table A1: Selected synonyms for Sorghum species[a]

Name Used	Synonyms*
S. bicolor subsp. *bicolor*[†]	*S. basutorum*
	S. bicolor var. *arduinii*
	S. bicolor var. *subglobosum*
	S. bicolor var. *technicum*
	S. cafforum
	S. cafforum var. *brunneolum*
	S. cafforum var. *lasiorachis*
	S. caudatum
	S. cernuum
	S. cernuum var.*agricolarum*
	S. cernuum var. *orbiculatum*
	S. conspicuum
	S. conspicuum var. *pilosum*
	S. conspicuum var.*rubicundum*
	S. coriaceum
	S. coriaceum var.*subinvolutum*
	S. dochna
	S. dochna var. technicum
	S. durra
	S. elegans
	S. gambicum
	S. guineense
	S. japonicum
	S. margaritiferum
	S. melaleucum
	S. membranaceum
	S. membranaceum var. *ehrenbergianum*
	S. miliiforme
	S. nervosum
	S. nigricans
	S. notabile
	S. roxburghii
	S. roxburghii var. *hians*
	S. saccharatum
	S. simulans
	S. splendidum
	S. subglabrescens
	S. subglabrescens var. *compactum*
	S. subglabrescens var. *compactum*
	S. subglabrescens var. *oviforme*
	S. subglabrescens var. *rubidum*
	S. technicum
	S. vulgare
	S. vulgare var. *caffrorum*
	S. vulgare var. *durra*
	S. vulgare var. *roxburghii*
	S. vulgare var. *saccharatum*
	S. vulgare var. *technicum*
S. bicolor subsp. *drummondii*[†]	*S. bicolor* var. *drumondii*
	S. x *drumondii*
	S. hewisonii
	S. niloticum

Name Used	Synonyms*
	S. sudanense *S. vulgare* var. *drumondii* *S. vulgare* var. *sudanense*
S. bicolor subsp. *arundinaceum*[†]	*S. aethiopicum* *S. bicolor* subsp. *verticilliflorum* *S. brevicarinatum* *S. lanceolatum* *S. macrochaeta* *S. pugionifolium* *S. stapfii* *S. usambarense* *S. verticilliflorum* *S. virgatum* *S. vogelianum*
S. x *almum*	(= *S. bicolor* x *S. halepense*)
S. amplum	
S. angustum	*Sarga angusta*
S. brachypodum	
S. bulbosum	
S. ecarinatum	
S. exstans	
S. grande	
S. halepense	*S. controversum*[†] *S. miliaceum* *S. miliaceum* var. *parvispicula*
S. interjectum	
S. intrans	*Sarga intrans*
S. laxiflorum	*Vacocarpus laxiflorum*
S. leiocladum	*Andropogon australis* subsp. *leiocladua* *Sarga leioclada*
S. macrospermum	*Vaciocarpus macrosperma*
S. matarankense	
S. nitidum	*S. fulvum* *Andropogon serratus* *Holcus fulvus* *Holcus nitidus*
S, plumosum	*Andropogon australia* *Holcus plumosus* *Sarga plumosa*
S. propinquum	*Andropogon propinquus*
S. purpureosericeum	*S. dimidiatum* *Andropogon purpurosericeus* *Sarga purpurosericea*
S. stipoideum	*Sarga stipoidea*
S. timorense	*S. australiense* *S. brevicallosum* *Andropogon tropicus* var. *timorense* *Sarga timorensis*
S. versicolor	*Sarga versicolor*

[a] Source: (USDA ARS 2015)

[†] Due to the large number of synonyms for *S. bicolor* subspecies and for *S. halepense*, only those with the genus name "Sorghum" are provided. Others (including *Andropogon* and *Holcus* synonyms) may be found on the USDA-ARS GRIN website.

APPENDIX B

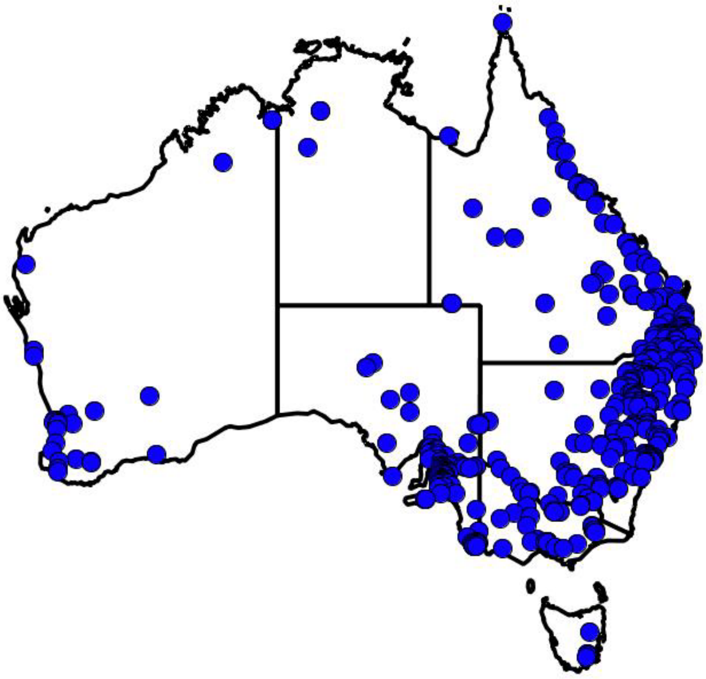

Figure B1: Distribution map of *S. halepense* (Johnson grass) in Australia (ALA 2010) (ALA Johnson grass).

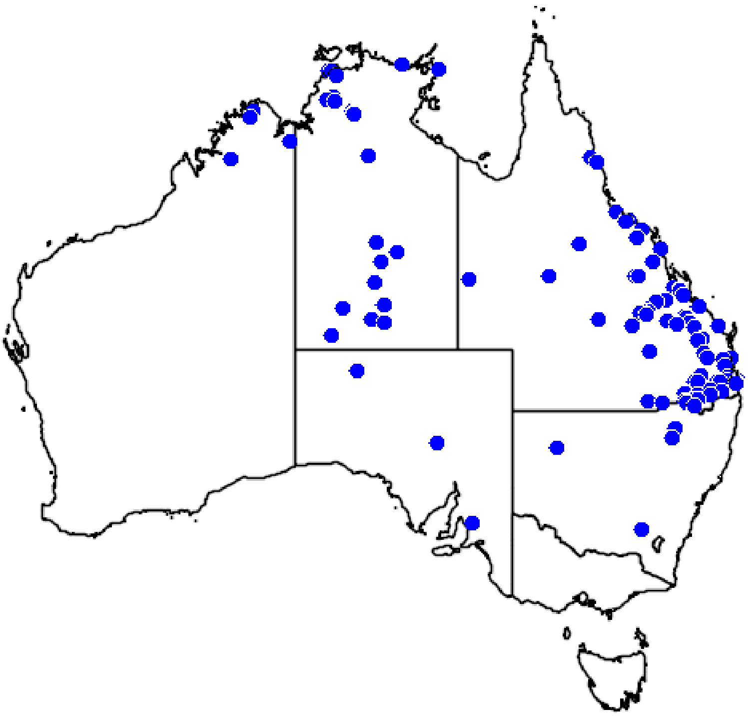

Figure B2: Distribution map of *S. x almum* Parodi in Australia (ALA 2010). (ALA Sorghum x almum).

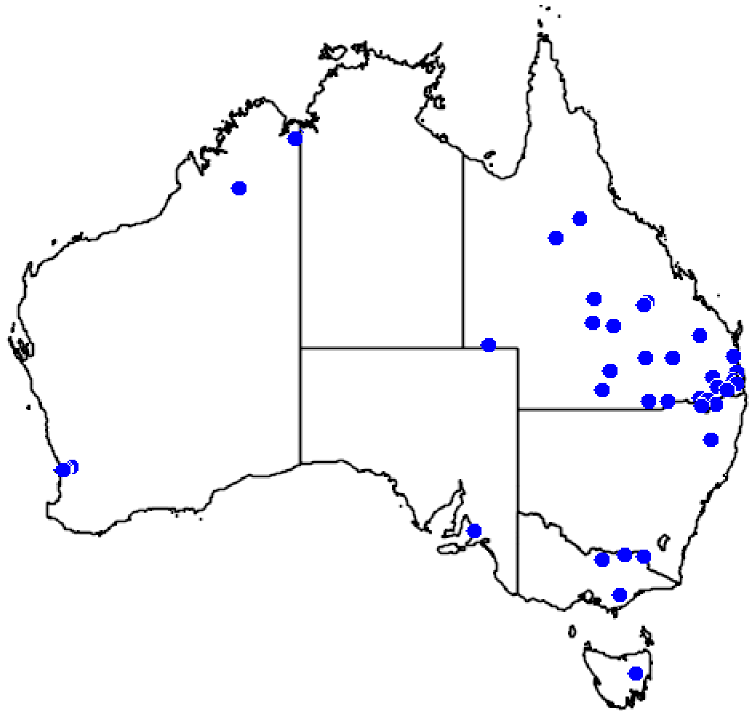

Figure B3: Distribution map of *S. bicolor* subsp. *drummondii* (Sudangrass & shattercane) in Australia (ALA 2010) (ALA S. bicolor subsp. drumondii).

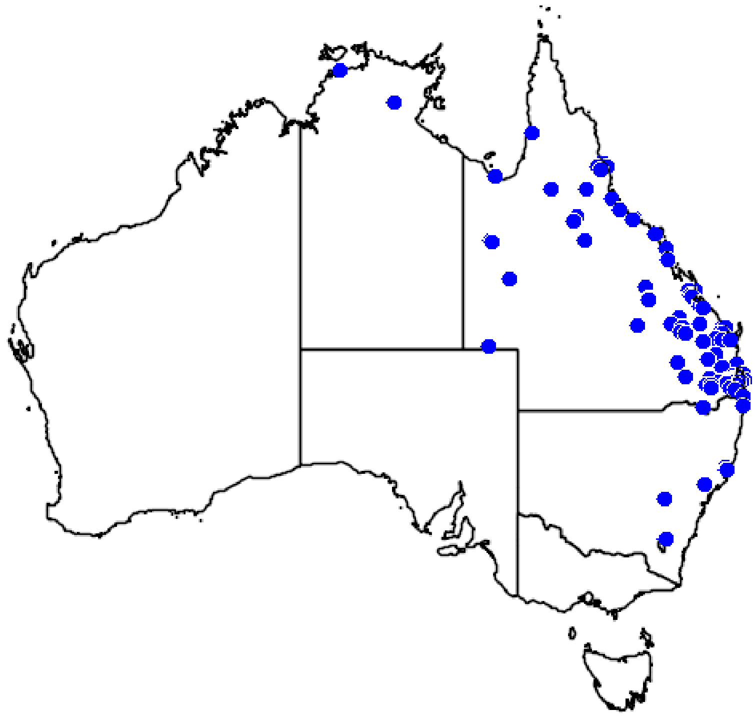

Figure B4: Distribution map of *S. bicolor* subsp. *arundinaceum* in Australia (ALA 2010) (ALA S. bicolor subsp. arundinaceum).

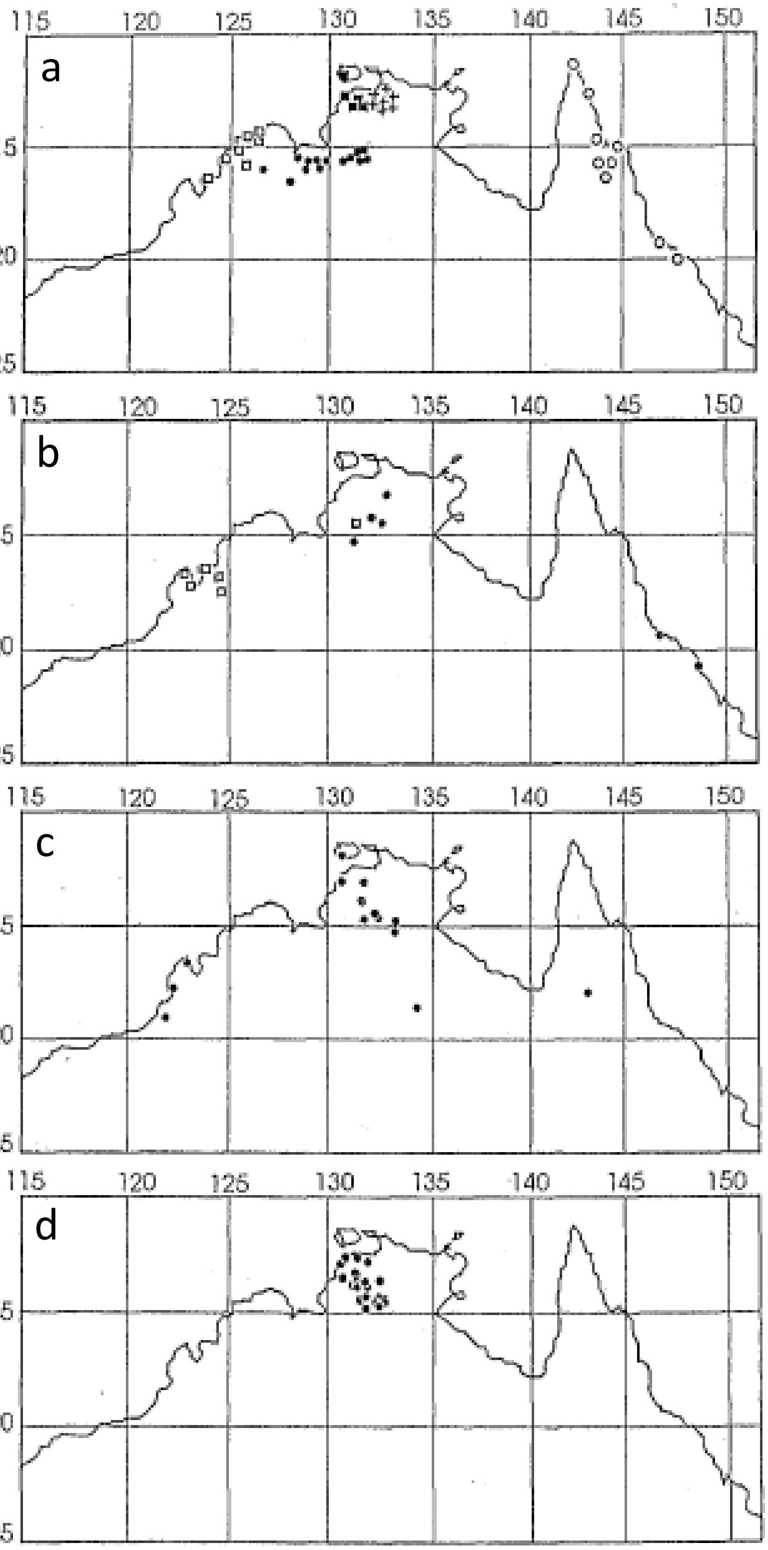

Figure B5: Distribution from collections of endemic *Sorghum* species in Australia: (a) ☐*S. amplum,* ○*S. angustum,* ●*S. bulbosum,* +*S. brachypodum,* ■*S. exstans*; (b) ☐*S. ecarinatum* and ●*S. grande*; (c) ●*S. interjectum* (d) ●*S. intrans* (Lazarides et al. 1991) (see CSIRO publication)

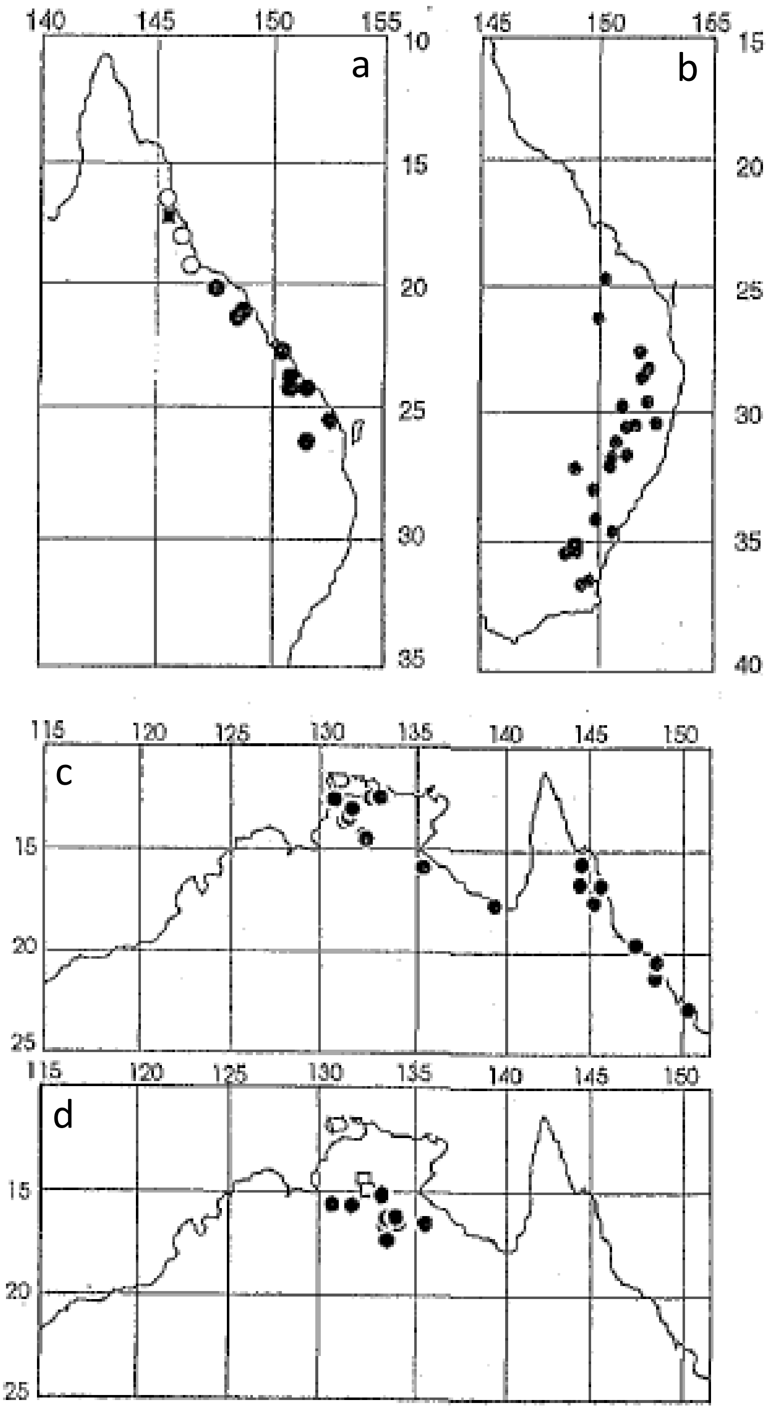

Figure B6: Distributions of endemic *Sorghum* species in Australia: (a) *S. nitidum*: ●awned, ○awnless, ■intermediate forms;(b) ●*S. leiocladum;* (c) ●*S. laxiflorum;* (d) □*S. macrospermum,* ●*S. matarankense* (Lazarides et al. 1991) (see CSIRO publication*)*

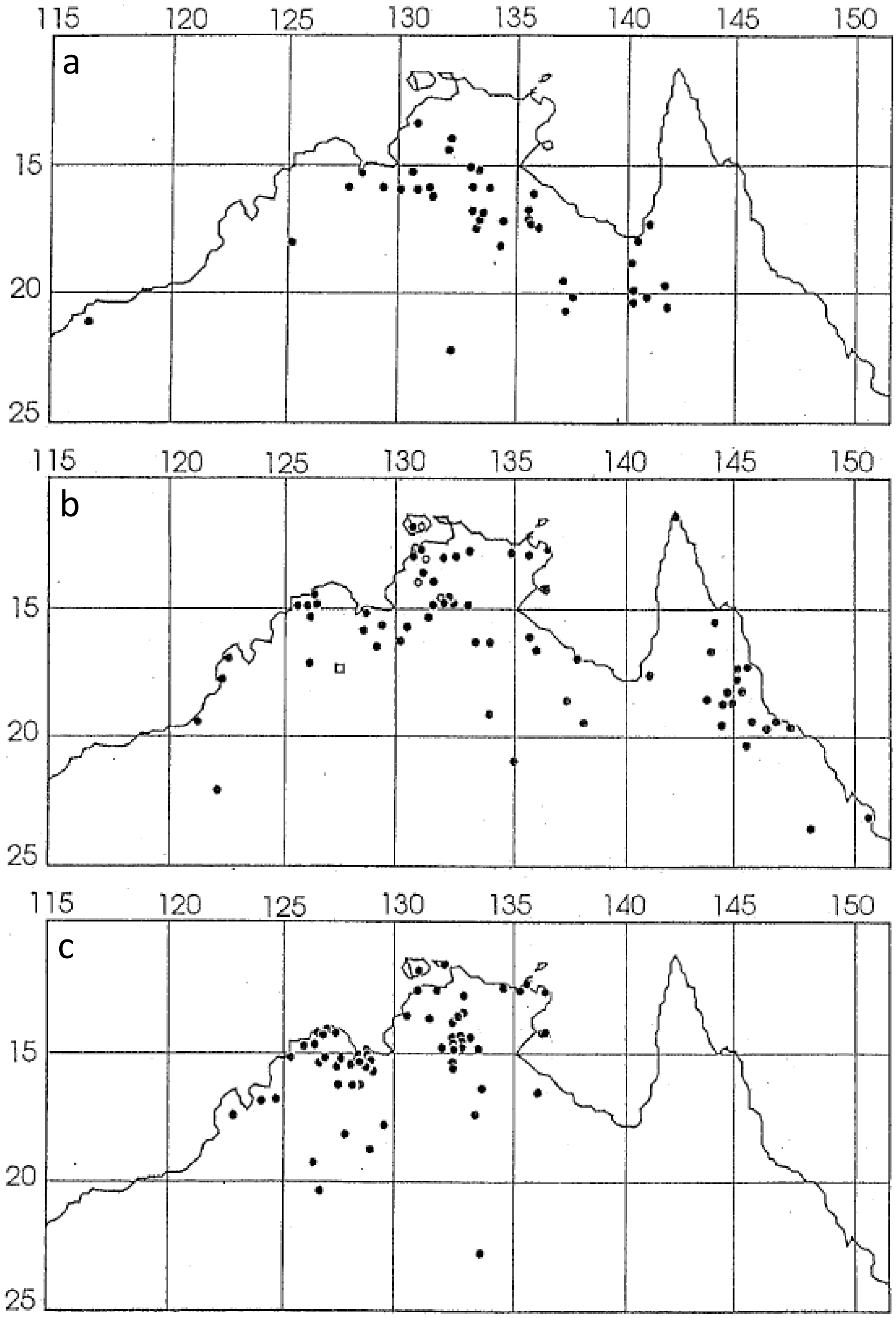

Figure B7: Distributions of endemic Australian *Sorghum* species; (a) ●*S. timorense*; (b) *S. plumosum*, ●*var. plumosum*, and ☐*var. teretifolium*, O unknown hybrid, probably *S. plumosum* x *S. intrans;* (c) ●*S. stipoideum* (Lazarides et al. 1991) (see CSIRO publication)

APPENDIX C WEED RISK ASSESSMENT

Species: *Sorghum bicolor* subsp*. bicolor* (grain sorghum)

Relevant land uses (according to ALUM[1]):

1. Production from dryland agriculture (ALUM classification 3.3.1 Cereals)

2. Production from irrigated agriculture (ALUM classification 4.3.1 – Irrigated cereals)

3. Grazing dryland modified pastures (ALUM classification 3.2.5 – Sown grasses)

4. Grazing irrigated modified pastures (ALUM classification 4.2.4 – Sown grasses)

5. Intensive uses (ALUM classification 5. It includes: 5.2 – Intensive animal production; 5.3.2 – Food processing factory; 5.7.2 – Roads and surrounding land use)

Background: The Weed Risk Assessment (WRA) methodology is adapted from the Australian/New Zealand Standards HB 294:2006 National Post-Border Weed Risk Management Protocol. The questions and ratings (see table) used in this assessment are based on the South Australian Weed Risk Management Guide (Virtue 2004). The terminology is modified to encompass all plants, including crop plants.

Grain sorghum is mainly grown in NSW and Qld, and is listed as an agricultural and ruderal weed species which are the first to establish in disturbed areas (Groves et al. 2003). It is mentioned as a minor problem in Australia, warranting control in four or more locations of NSW and WA (Groves et al. 2003).

Information in this WRA was sourced from the sorghum biology document and the references within this document.

[1] Australian Land Use and Management classification system version 8 published October 2016 (ABARES ALUM classification system).

Invasiveness questions	**Sorghum**
1. What is sorghum's ability to establish amongst existing plants?	**Rating: Medium in all relevant land uses** Although sorghum has been used in no-till systems, being sown directly onto previous crop stubble, establishment of sorghum seedlings is hampered by weed competition. Therefore, sorghum seedlings may establish in disturbed land but they are unlikely to progress within dense vegetation.
2. What is sorghum's tolerance to average weed management practices in the land use?	**Rating: Low in all relevant land uses** Limited reports are available, but sorghum volunteers in cropping areas have been listed as being controlled by standard herbicide applications. It is also a standard practice to chemically desiccate sorghum plants at the final stages of the life cycle to avoid tiller growth. When done properly, this results in 100% plant mortality.
3. Reproductive ability of sorghum in the land use:	
3a. What is the time to seeding in the land uses?	**Rating: < 1 year** Time to seeding is approximately four months from planting.
3b. What is the annual seed production in the land use per square metre?	**Rating: low (< 1000 seeds/m^2) in all relevant land uses** A sorghum panicle can bear from 800 to 6000 seeds, so a single sorghum volunteer can produce more than 1000 seeds. Sorghum volunteers are common in regions where sorghum is cultivated. However, when weed populations are managed effectively, the density of sorghum volunteers is low. In wheat and sorghum growing regions of subtropical Australia, sorghum volunteers appeared in 54.4% of the paddocks surveyed in a study about weeds, however their density was 0.35 plants/m^2 or less (Rew et al. 2005). According to this, when sorghum volunteers are controlled, they produce less than 1000 seeds/m^2.
3c. Can sorghum reproduce vegetatively?	**Rating: No in all relevant land uses** Sorghum does not reproduce vegetatively. There are reports of plants growing from cuttings and ratoons may develop at the base of the plant.

4. Long distance seed dispersal (more than 100 m) by natural means in land uses	
4a. Are viable plant parts dispersed by flying animals (birds and bats)?	**Rating: Do not know in all relevant land uses** Birds, particularly large parrots such as galahs (*Eolophus roseicapilla*), cockatoos and cockatiels (both members of the *Cacatuoidea*) will eat sorghum grain. Sorghum seeds could potentially travel long distances in the excreta of birds, however there are no records of this in the literature.
4b. Are viable plant parts dispersed by wild land based animals?	**Rating: Do not know in all relevant land uses** Sorghum seeds are consumed by livestock, rodents and seed-eating ants. All of these animals could potentially disperse sorghum seeds with the distance travelled depending on the biology of each animal. Sorghum seeds have been shown to pass undamaged through the digestive tract of wild deer and to germinate on deer excreta in the US.
4c. Are viable plant parts dispersed by water?	**Rating: Occasional in irrigated cropping land use and in intensive (roadsides) land uses/Unlikely in all other relevant uses** Sorghum seeds can be transported by water potentially over long distances after heavy rain or irrigation.
4d. Are viable parts dispersed by wind?	**Rating: Highly unlikely in all land uses** There are no reports of seeds being transported by wind so it is unlikely that sorghum would be spread in this manner.

5. Long distance seed dispersal (more than 100 m) by human means in land uses:	
5a. How likely is deliberate spread via people?	**Rating: Occasional** Sorghum is a crop species that is purposely cultivated for the production of grain that is transported to intensive land use areas for processing and use in feedlots and dairy farms. Human deliberate spread of volunteer sorghum plants is probably very rare.
5b. How likely is accidental spread via people, machinery and vehicles?	**Rating: Common in all relevant land use areas** Sorghum volunteers are commonly found along road sides, around sheds, silos and intensive animal feeding enterprises in the areas of cultivation. These are usually as a result of spillage during transport.
5c. How likely is spread via contaminated produce?	**Rating: Unlikely in/from all relevant land use areas** Sorghum farming in dryland and irrigated cropping areas is often characterised by rotation with other crops. The amount of sorghum seed left in the field prior to planting of a rotation crop would depend upon the efficiency of the harvesting of the grain, cleaning of the machinery and general weed management procedures. Growth of sorghum volunteers within a rotation crop would depend upon the weed management procedures of the latter crop. Since sorghum volunteers are easily managed, there is a low risk of contaminating the harvest of subsequent crops. Long distance dispersal via contaminated hay and forage may also occur in or from intensive use areas. This could occur from areas purposely producing hay/forage or if roadside vegetation were cut for this purpose.
5d. How likely is spread via domestic/farm animals?	**Rating: Do not know in all relevant land use areas** Sorghum seeds could be spread in mud on animal hooves if animals are moved from one paddock to another or from feedlots. In addition, livestock animal feeding on sorghum may be able to spread seeds in their excreta, although there is no evidence about this in the literature.

Impact questions	**Sorghum**
6. Does sorghum reduce the establishment of desired plants?	**Rating: < 10% reduction in all relevant land use areas** No reports were found to indicate that the levels of volunteer plants would be high enough to reduce the establishment of desired plants in cropping or pasture situations. Volunteer plants should be easy to detect in subsequent crops commonly used in rotations and intensive use areas like roadsides. Control of sorghum is relatively simple.
7. Does sorghum reduce the yield or amount of desired plants?	**Rating: < 10% reduction in all relevant land uses** Sorghum is a minor weed in Australia, and is not considered to threaten agricultural productivity or native biodiversity. The density of sorghum volunteers is likely to be low in all relevant plant uses and hence there would be a low reduction of yield or amounts of other plants.
8. Does sorghum reduce the quality of products or services obtained from the land use?	**Rating: Low in all relevant land uses** Sorghum has a low impact on both the establishment and yield/amount of desired species and thus there is no expectation that it would reduce the quality or characteristics of products, diversity or services available from the relevant land use areas.
9. What is the potential of sorghum to restrict the physical movement of people, animals, vehicles, machinery and/or water?	**Rating: Low in all relevant land uses** Sorghum may grow as volunteers in cropping areas but due to low volunteer numbers and the relative ease of control it is not likely to restrict movement of people, animals, vehicles, machinery or water.
10. What is the potential of sorghum to negatively affect the health of animals and/or people?	**Rating: Low in all relevant land uses** Sorghum produces dhurrin which is metabolised to hydrogen cyanide (HCN), potentially causing cyanide poisoning in livestock. Sorghum can also contain high levels of nitrates which can lead to nitrate poisoning. In addition, sorghum pollen may cause respiratory allergies in some people. Since the density of sorghum volunteers is expected to be low, exposure of people and animals

Impact questions	**Sorghum**
	would also be low. Therefore the risk of these negative effects is negligible.
11. Major positive and negative effects of sorghum on environmental health in the land use	
11a. Does sorghum provide food and/or shelter for pathogens, pests and/or diseases in the land use?	**Rating: Minor to Major in all relevant land use areas** Volunteer sorghum is a refuge for insect pests and diseases that affect cultivated sorghum and other crop species like sugarcane (Groves et al. 2003; Cook et al. 2005a; Cook et al. 2005b). Volunteer sorghum is susceptible to conventional weed management practice, so the risk of sorghum acting as a pest reservoir would be minor if it is actively managed. However, if volunteer sorghum is not controlled, then the risk of harbouring pests that may affect crops is major (Andersson & deVicente 2010).
11b. Does sorghum change the fire regime in the land use?	**Rating: Minor or no effect in all relevant land use areas** It is unlikely that growth of sorghum volunteers would be dense enough or occur in habitats that are fire prone (such as forest understorey), to increase the risk of fire.
11c. Does sorghum change the nutrient levels in the land use?	**Rating: Minor or no effect in all relevant land use areas** Sorghum may remove soil nutrients as a crop, which may be a problem for subsequent crops. However, due to the expected low frequency of volunteer plants it is unlikely in any other context.
11d. Does sorghum affect the degree of soil salinity in the land use?	**Rating: Minor or no effect in all relevant land use areas** Sorghum is largely grown in Australia as a dryland crop, so is unlikely to affect salinity. Likewise, the density of plants growing as volunteers or in weedy situations is unlikely to have any effect on salinity.
11e. Does sorghum affect the soil stability in the land use?	**Rating: Minor or no effect in all relevant land use areas** Sorghum has an extensive root system so it would be expected to stabilise soil.

11f. Does sorghum affect the soil water table in the land use	**Rating: Minor or no effect in all relevant land uses** The number and density of sorghum volunteers is expected to be low for all relevant land uses, and would not be expected to affect the soil water table.
11g. Does sorghum alter the structure of nature conservation by adding a new strata level?	**Rating: Minor or no effect in all relevant land uses** The number and density of sorghum volunteers is expected to be low for all relevant land uses, and would not be expected to add a new strata level.