Australian Government

Department of Health and Aged Care
Office of the Gene Technology Regulator

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

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

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ABBREVIATIONS

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ALUM	Australian Land Use and Management classification
CMS	cytoplasmic male sterility
cv.	cultivar
DNA	deoxyribonucleic acid
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization of the United Nations Statistics Division
GM	genetically modified
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)
h	hour
ha	hectare (10,000 m^2)
HCN	hydrogen cyanide/ 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
N	nitrogen
NPV	nuclear polyhedrosis virus
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
ppm	parts per million
QAAFI	Queensland Alliance for Agriculture and Food Innovation
Qld	Queensland
QDAF	Queensland Department of Agriculture and Fisheries
sp.	species
subsp.	subspecies
t	tonnes (metric)
USA	United States of America
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture Agricultural Research Service
Vic	Victoria
w	weight
WA	Western Australia
WCSP	World Checklist of Selected Plants species (Kew Gardens, UK)
WRA	weed risk assessment
Zn	zinc

GLOSSARY

Term	*Definition*
Allelopathy	A biological phenomenon by which an organism produces one or more molecules that influence the growth, survival and reproduction of other organisms.
Allopolyploid	Polyploid produced from a hybrid between two or more different species and therefore possessing two or more unlike sets of chromosomes.
Amphidiploids	Tetraploids containing the diploid chromosome set of both parents.
Anthesis	The period over which a flower is open.
Autopolyploid	An organism having more than two sets of homologous chromosomes, all derived from the same species.
C_3 and C_4 plants	These terms refer to the different pathways that plants use to capture carbon dioxide during photosynthesis. The first product of carbon fixation in C_3 plants involves a 3-carbon molecule, whilst C_4 plants initially produce a 4-carbon molecule that then enters the C_3 cycle. C_4 plants are more adapted to warm or hot seasonal conditions under moist or dry environments.
Cytoplasmic Male Sterile (CMS) system	CMS is total or partial male sterility in plants as a result of specific nuclear and mitochondrial genetic interactions. Male sterility is the failure of plants to produce functional anthers, pollen, or male gametes. The presence of genes for CMS in cultivated sorghum is an important factor in the commercial production of hybrid sorghum seed. The basic system for producing such hybrids uses three parental lines – A, B and R (restorer) lines. To produce commercial seed for sorghum, an A line (male sterile) is crossed with the corresponding B line (identical male fertile line), producing sterile seed plants (more A line), as cytoplasm is maternally-inherited. This progeny is then crossed with an R line which restores male fertility, to produce a F_1 hybrid line, which is male fertile and is sold as commercial seed (Oliveira et al., 2019).
Diploid	An organism made up of cells containing 2 sets of chromosomes (2N). Most species whose cells have nuclei (eukaryotes) are diploid, meaning many of their cells have 2 sets of chromosomes—one set inherited from each parent.
Disruptive selection	A mode of selection in which extreme values for a trait are favoured over intermediate values.
Environmental weeds	Naturalised, non-native species that have invaded non-agricultural areas of natural vegetation and are presumed to impact negatively on native species diversity or ecosystem function.
F_1 hybrid	Progeny of a cross between two different species or two different varieties from the same species. F_1 hybrids often display hybrid vigour and show better agronomic characteristics than the parental lines.
Grain filling	Period during seed maturation in which the seed accumulates nutrient reserves.
Haploid	Cells or organisms having a single set of chromosomes (1N), such as the gametes of higher plants.
Homologous	Having the same structure, relation or relative position, or evolution (Greek *homo* – the same). Homologous genes may have a similar, but not the same function.

Homologous chromosomes	Chromosomes with the same or allelic genes with genetic loci usually arranged in the same order.
Interspecific	Existing, arising or occurring between species.
Introgression	The transfer of genetic information from one species to another as a result of hybridisation between them and repeated backcrossing of the hybrid with the parent species receiving the genetic information.
LD_{50}	LD_{50} refers to an estimate of the amount of poison that, under control conditions, will be a lethal dose (LD) to 50% of a large number of test animals of a particular species.
Lodging	The condition of a plant, especially a cereal, that has been flattened in the field or damaged so that it cannot stand upright, e.g. as a result of weather conditions or because the stem is not strong enough to support the plant.
Naturalised	Non-native species that have been introduced and become established, and that reproduce naturally in the wild.
Panicle	A loose branching cluster of flowers, e.g. as in oats, or sorghum.
Parthenogenesis	The spontaneous development of an embryo from an unfertilised egg cell: parthenos = virgin, genesis = creation.
Photoperiod sensitivity	Ability of a plant to detect and respond to seasonal changes in the duration of daytime compared to night time. A plant that has lost photoperiod sensitivity will flower independently of day length while plants sensitive to photoperiod will flower only when days become shorter or longer.
Phylogenetics	The study of the evolutionary history and relationships among individuals or groups of organisms.
Polyploid	Cells or organisms containing more than 2 paired (homologous) sets of chromosomes. Polyploids (see below) are labelled according to the number of chromosome sets in the nucleus, with the letter N used to represent the number of chromosomes in a single set. Thus, a diploid would have 2N chromosomes, a tetraploid 4N and so on.
Progenitor	An ancestor or parent of an organism.
Promoter	DNA regulatory sequence adjacent to a gene that controls where in the plant, when, for how long and at what level this gene is expressed.
Ratoon	A new shoot or sprout growing from the base of a crop plant after it has been harvested by cutting (cropping).
Silique	2-celled elongated seed capsules (pods).
Sodicity	The amount of sodium held in a soil. A sodic soil is defined as a soil containing sufficient sodium to negatively impact crop production and soil structure.
Syntenic genes	Group of genes that lie in the same order in the same chromosome in different species.
Sympatric	Animals or plant species or populations occurring within the same or overlapping geographical areas.
Tetraploid	An organism made up of cells containing 4 sets of chromosomes (4N).
Tillering	The formation of aboveground shoots from a node located at the base of the principal shoot in grasses and some other plants.

Variety	A group of cultivated plants of significance in agriculture, forestry or horticulture, which have distinct and heritable characteristics. Often used interchangeably with *cultivar*.
Volunteers	Unwanted plants in succeeding crops emerging from the soil seedbank.
Wide crosses	Mating between individuals of different species or genera that do not normally sexually reproduce with each other.

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, forage sorghum, sweet sorghum, broom millet, broomcorn, milo, jowar, kafir corn, guinea corn and cholam, among many others (USDA ARS, 2022). In this document, ‘cultivated sorghum’ or ‘sorghum’ will be used to refer to *Sorghum bicolor* subsp. *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 predominantly grown as a livestock feed in other regions. 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 (GRDC, 2017).

Reference material discussing International and Australian examples was used for the writing of this document. When there was uncertainty about the applicability of overseas information in the Australian context, this was highlighted.

SECTION 1 TAXONOMY

The genus *Sorghum* belongs to the grass family *Poaceae* (*Gramineae*), subfamily Panicoideae, tribe *Andropogoneae*, subtribe *Sorghinae* (Clayton and 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 and Dahlberg, 2007). It consists of 27 recognised species that are classified morphologically into 5 subgenera (or 4 according to USDA ARS, 2024): *Chaetosorghum*, *Heterosorghum*, *Parasorghum*, *Stiposorghum* and *Eusorghum* (Price et al., 2005a; Ananda et al., 2020; USDA ARS, 2022). *Parasorghum* and *Stiposorghum* are considered to be in the same subgenera in some taxonomic classifications. 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, 2022) and the USDA GRIN (USDA ARS, 2022) databases. A list of selected synonymous names for *Sorghum* species is given in Table A1, Appendix A.

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

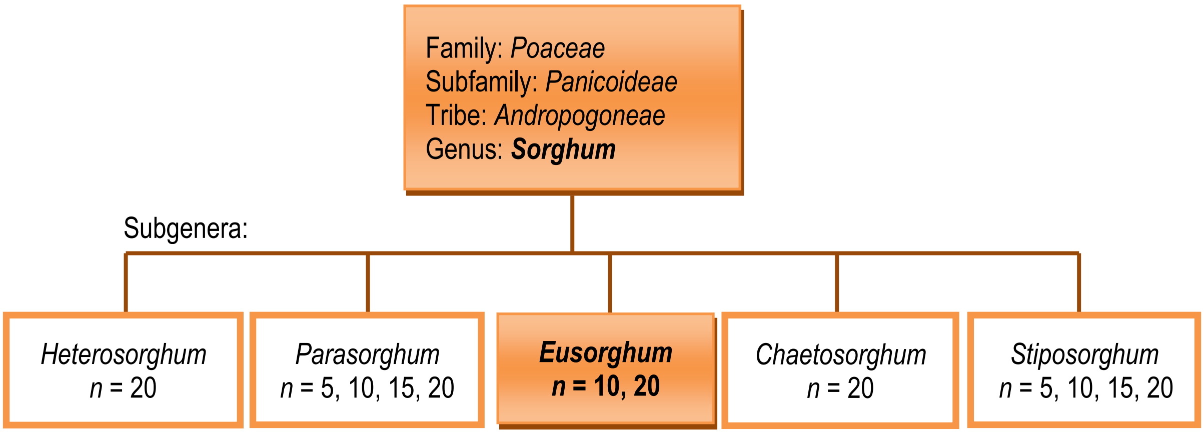

Figure 1 Subgenera of *Sorghum* as presented in Ejeta and Grenier (2005). *n* represents the haploid chromosome number. The genus and subgenus of Sorghum are highlighted as this subspecies is the focus of this document.

The taxonomy of the Sorghum species is still being debated. 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[1] 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.

[1] At the time of the Dillon et al. (2007a) publication, 25 *Sorghum* species, compared to the current 24 *Sorghum* species were recognised (Ananda et al., 2020).

1.1 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 can occur from cultivated sorghum to wild relatives and *vice versa* (see Section 9).

The subgenus *Eusorghum* 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 lived perennial that lacks rhizomes and is usually cultivated as an annual (Ejeta and Grenier, 2005).

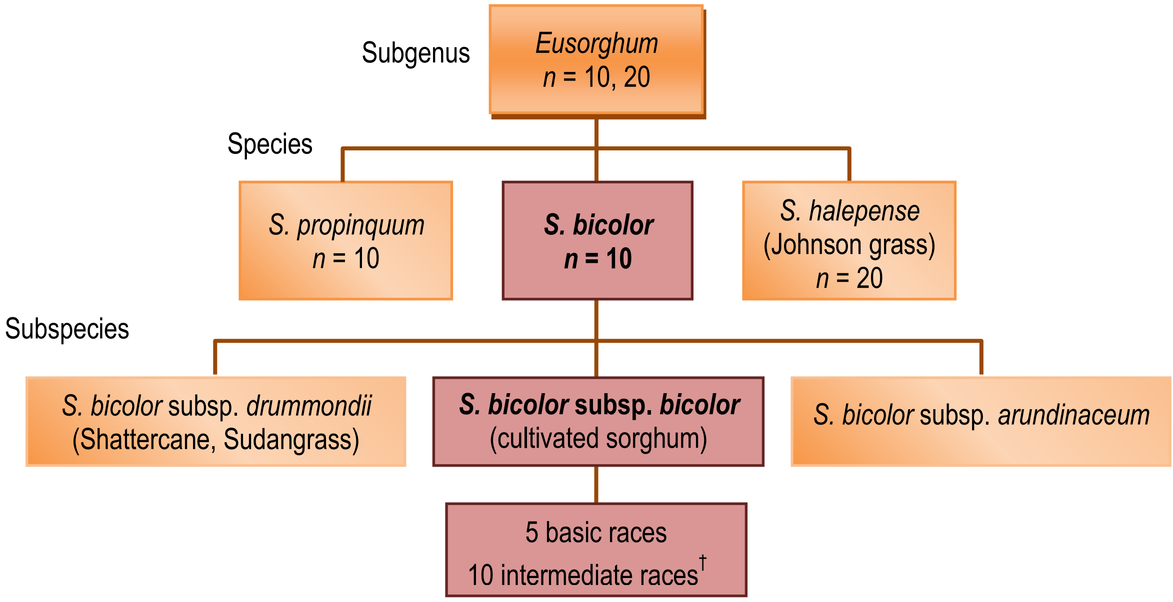

Figure 2 Species and subspecies of the subgenus *Eusorghum* as presented in Ejeta and Grenier (2005). † Intermediate races recognised by Harlan and de Wet (1972). *n* represents the haploid chromosome number. Being the focus of this document, the classifications of cultivated Sorghum are highlighted.

Sorghum is further divided into three subspecies (Wiersema and Dahlberg, 2007) (Figure 2). *S. bicolor* subsp. *bicolor* contains all the cultivated sorghums. *S. bicolor* subsp. *arundinaceum*[2] 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. *S. bicolor* subsp. *drummondii*[3] contains annual weedy derivatives arising from the hybridisation of domesticated sorghum and subspecies *arundinaceum* and includes forage Sudangrass and the weedy shattercanes (de Wet, 1978; Dahlberg, 2000). Alternative naming and classifications for these subspecies are available in Table A1 (Appendix A), including the scientific names accepted by The Australian Plant Census (APC).

Cultivated sorghum includes 5 basic races and 10 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 and de Wet, 1972). These races can be traced back to their specific environments and the nomadic peoples that first cultivated them (Kimber, 2000).

[2] The *S. bicolor* subsp. *arundinaceum* is currently known as *S. bicolor* subsp. *verticilliflorum* (Ananda et al., 2020). Given the recent change, and to be consistent with cited literature, this document will continue using subsp. *arundinaceum*.

[3] The *S. bicolor* subsp. *drummondii* is currently known as *S. bicolor* nothosubsp. *drummondii* (Ananda et al., 2020). To be consistent with cited literature, this document will continue using subsp. *drummondii*.

Table 1 Cultivated races of cultivated Sorghum, with genotype abbreviated in parentheses

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 and de Wet, 1972).

All cultivated Sorghum races are genetically diverse diploids ($2n = 2x = 20$). The genome of Sorghum (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 and Earle, 1991; Paterson et al., 2009; ICRISAT, 2015).

1.2 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 27 species of the genus Sorghum, 17 are native to Australia and South East Asia, with 13 endemic to Australia (Lazarides et al., 1991; Myrans et al., 2020; Myrans et al., 2024). 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 B6, B7 and B8). All members presented in Table 2 belong to the tertiary gene pool (GP3), see Figure 9.

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	Annual	NT
Heterosorghum	*S. laxiflorum*	40	Annual	Qld, NT
Parasorghum	*S. grande*	30, 40	Mostly Perennials	NT
	S. leiocladum	10, 20		NSW
	S. matarankense	10		NT
	S. nitidum	10, 20		Qld
	S. timorense	10, 20		NT, Qld, WA
Stiposorghum	*S. amplum*	10, 30	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, 40		NT, Qld, WA
	S. stipoideum	10		NT, WA

Adapted from Lazarides et al. (1991); Ananda et al. (2020).

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, USES 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 regions of modern Ethiopia and Sudan, where cultivation started approximately 4000 - 3000 CE (Dillon et al., 2007b). Cultivated sorghums of today arose from the wild *S. bicolor* subsp. *arundinaceum* (Doggett, 1988). Early domestication occurred via a process of disruptive selection where several traits advantageous to cultivation were favoured (Doggett, 1988). In addition to disruptive selection, geographic isolation and recombination in different environments led to the creation of a large number of sorghum types, varieties and races. As a result, three broad groups of sorghum were generated; cultivated and improved types; wild types; and intermediate types (Kimber, 2000). Cultivated sorghums developed with diverse morphological traits including height and inflorescence characters, and for numerous uses including food, fodder, fibre and as a 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 CE) through trade routes and human movements. It is believed that sorghum was taken from Africa to the Middle East and India (900 - 700 CE) and the 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

Sorghum is the fifth largest and most important cereal crop in the world after wheat, maize, rice and barley (Doggett, 1988; Ejeta and Grenier, 2005; Adebo, 2020). Annual global production of sorghum is estimated at approximately 60 million tonnes (FAOSTAT, accessed October 2024) and is predicted to increase (Tan et al., 2024). Uses of sorghum are diverse and a number of in-depth reviews are available (Doggett, 1988; FAO, 1995; Taylor, 2003; Tan et al., 2024). Sorghum 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 (Heuzé et al., 2015; ICRISAT, 2015; Chaturvedi et al., 2022). Different races or cultivars of sorghum 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, where cattle are grazed on the stubble after the grain is harvested. Its potential as a biofuel crop has been identified and is gaining in importance (Byrt et al., 2016).

2.2.1 Food

Sorghum is an important food grain for more than 750 million people in the semi-arid tropical regions of Asia, Africa, and Latin America (Liedtke et al., 2020). 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 the semi-arid and subtropical 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 used in most other regions of the world. Africa produces about one third of the world’s sorghum but has the lowest yields per hectare (Pereira and Hawkes, 2022). 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 and FAO, 1996; Adebo, 2020).

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; FAO, 1999; Taylor, 2003; McCann et al., 2015). The stalks of sweet sorghum varieties with high sugar content are used to make sugar (jaggery) and syrup, and the sugars can also be fermented to produce ethanol (Mathur et al., 2017).

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; Baxter, 2019; GRDC, 2020). Human food uses in Australia are minor and include in gluten-free beer, breakfast cereals, baked products and biofuels (McCann et al., 2015; GoodFood, 2018; Arnott's, 2022; Ducksbury and Stefoska-Needham, 2022; de Almeida Moreira et al., 2024).

2.2.2 Feed

Both sorghum grain and plant biomass (leaves and stalks) are used as animal feed. It is a cheaper alternative to maize, and due to its adaptability to dry conditions, requires less water to produce similar yields (Skerman and Riveros, 1990). In Australia, sorghum grain is primarily used as feed in the beef, dairy, pig and poultry industries (GRDC, 2017). Sorghum forage cultivars while inclusive of grain sorghum, are often distinct and include Sudangrass hybrids, sorghum × Sudangrass hybrids, sweet sorghum hybrids, 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 panicles are cut from the standing stalk and the stalks are left for animals to graze. The stalks can also be cut and stored for dry season animal fodder (FAO, 1999).

2.2.3 Biofuel

Sorghum can be used to produce ethanol from the sugars accumulated in the stalks of sweet sorghum varieties and as a biomass feedstock for fuel pellets (Almodares and Hadi, 2009; O'Hara et al., 2013; de Almeida Moreira et al., 2024). 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 (Grain Growers, 2021). That refinery buys around 200,000 tonnes of sorghum grain each year from local growers, from which it produces 76 million litres of fuel-grade ethanol (The Ecoefficiency Group, 2017). The high starch content of sorghum grain (70% per grain weight) and the ability of sorghum to withstand hot dry cultivation conditions makes it suitable as a feedstock for ethanol production (Wylie, 2008; Almodares and 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 (The Ecoefficiency Group, 2017). Sorghum straw has an estimated energy density of 3.7 giga joules per cubic meter that can be amplified by pelleting to contribute to bioelectric potential (de Almeida Moreira et al., 2024).

2.3 Cultivation in Australia

Dwarf varieties of grain sorghum introduced from the USA were first grown in Qld in 1938 and in NSW in 1940. 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; Section 2.2.3). As sorghum is naturally gluten-free and possesses potential health benefits, there are also opportunities for higher-value markets for Australian grown sorghum (Fox, 2018; GRDC, 2020).

2.3.1 Commercial propagation

Sorghum is propagated by seed. While sorghum is considered to be a predominantly self-pollinated crop, high levels of outcrossing can also occur (see Section 4.2 and Section 9). Hence, isolation distances for producing basic seed[4] is 400 m, and certified sorghum and its hybrid seed is 200 m from any other pollen source. In areas where cross-pollination with *S. halepense* or *S. sudanense* is a possibility, the isolation distance is increased and should not be less than 800 m and 400 m, respectively (OECD, 2021).

Major providers of sorghum seed undertake seed production in the Ord River (WA) and the Macquarie, Lachlan and Murrumbidgee valleys in NSW (North Queensland Register; FarmOnline). Sorghum seed production is also undertaken in South-east, Central and North Qld. In addition, all major seed companies carry out variety testing and breeding activities in South-east Qld, Central Qld and the Lockyer Valley.

2.3.2 Scale of cultivation

Sorghum is one of the most important summer crops in Australia. In recent years, it was cultivated at an average of 550,000 - 620,000 ha annually (GRDC, 2017; ABARES, 2021, 2024). In the 2018-19 season, the planting area of sorghum was ~550,000 ha, or ~50% of the 1,130,000 ha of summer crop plantings (ABARES, 2021). Recent Australian sorghum planting and yield data are shown (Table 3).

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

State	Scope[b]	2017-18	2018-19	2019-20	2020-21[d]	2021-22[e]	2022-23	2023-24
NSW	A	108.3	152.3	44.4	130.0	160.0	195 195	175
	P	279.0	222.1	78.9	494.0	576.0	819 819	710
Qld	A	352.4	393.6	159.0	380.0	425.0	490	415
	P	974.5	926.3	313.2	1000.0	1385.5	1813	1500
WA	A	0.6	2.4	0.3	0.8	0.9	1.0	1.1
	P	1.3	9.2	1.8	2.0	2.9	3.4	2.4
Vic	A	0.9	2.0	0.4	0.0	0.4	1.0	1.0
	P	2.5	2.6	3.6	0.0	1.7	2.0	2.6
Total[c]	A	462.2	550.2	204.1	510.8	586.3	687	592.1
	P	1257.2	1160.2	397.5	1496.0	1966.2	2637.4	2215.0

[a] Data sourced from ABARES (2021); (ABARES, 2024).
[b] A - Area planted ('000 ha); P - Production (kt).
[c] Calculated from ABARES data above.
[d] ABARES estimate.
[e] ABARES forecast.

Over the last 5 growing seasons (2018-23), approximately 67% of sorghum was grown in Qld and 32% in NSW, with a national annual mean production and planting area of 1.9 million tonnes and approximately 535,000 ha, respectively. Most grain sorghum production occurs as part of dryland farming systems except in NSW where it is frequently produced as an irrigated crop (Spenceley et al., 2005). The main grain sorghum production areas of NSW and Qld are illustrated in Figure 3.

The scale of grain sorghum cropping varies from season to season, largely in response to rainfall pattern and price outlook (Spenceley et al., 2005). For example, total production was approximately 2.2 million tonnes in the 2014-15 season (ABARES, 2016) but severe drought in the NSW and Qld growing regions

[4] Basic and certified seed: Seed producers need to follow standard practices that assure the quality and purity of their varietal seeds. These standard practices are prescribed by the OECD Seed Scheme and isolation distances ensure that the level of cross-contamination with pollen from related plants is minimal. In crops to produce Basic seed of parental lines, the minimum varietal purity will be 99.9% (OECD, 2021). In crops to produce Certified seed, the minimum varietal purity of plants of the seed-bearing parent will be 99.7% (OECD, 2021).

severely affected production during the five years to 2019/20, with the 2019/20 NSW crop of being just 7% of the long-term average production for that state (Grain Growers, 2021).

While yields are dependent on several factors, local climatic conditions are important. For example, yields are highest in cool growing areas such as Quirindi (NSW) 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).

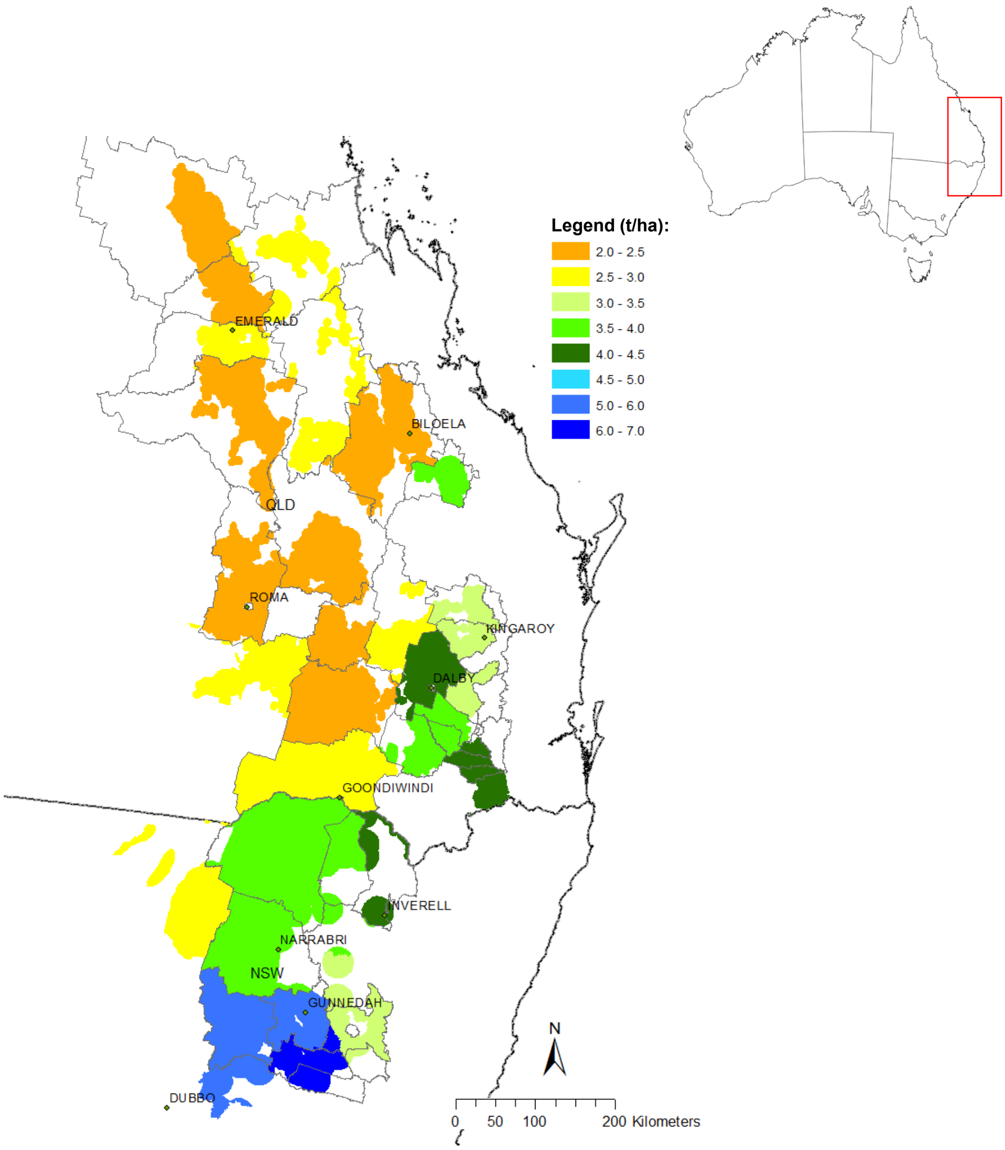

Figure 3 Grain sorghum production areas in Northern NSW and Qld (Reproduced with permission from QAAFI, 2022). The long term median projected yield (t/ha) for each shire, represented by regional boundaries, has been derived from 1901 - 2020 data.

A proportion of the Australian grain sorghum crop is sold on international markets, although the amount varies from season to season (Table 4). Since 2016, China has been buying over 80% of the Australian sorghum grain sold annually in the export market, with a small reduction to 74% in 2020 (UN Comtrade, accessed October 2024). Sorghum is used in China for the production of baijiu, a traditional Chinese toasting drink. Australian sorghum is sought in China for its bright colour and research is underway for other desirable characteristics that would provide similar performance to the Chinese grain in the distilling process (Grain Central, 2017; Baxter, 2019; GRDC, 2020).

Table 4 Australian grain sorghum export volume and value for the period 2016 to 2024 (UN Comtrade, accessed October 2024).

Year	Quantity (t)†	Value ($US)
2016	801,452	$160,365,024
2017	294,954	$73,442,491
2018	438,403	$112,586,131
2019	96,045	$28,115,139
2020	180,791	$49,561,143
2021	1,594,823,	$470,775,671
2022	2,212,140	$729,727,980
2023	2,443,290	$842,748,470

† 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 (Purseglove, 1972; Cothren et al., 2000). Information about the practical aspects of sorghum cultivation can be found within GRDC (2017); NSW DPI (2019). 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 resistance, maturity characteristics for the area of production, drought tolerance and insect and disease resistance are also critical (Vanderlip, 1993; Cothren et al., 2000; Wylie, 2008; NSW DPI, 2019). 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; NSW DPI, 2019). Hybrid lines commercially available in Australia are rated by seed companies for characteristics such as maturity, height, resistance to lodging, reaction to organophosphate application (used for insect control) and midge resistance (GRDC, 2017; NSW DPI, 2019).

2.3.3.1 Temperature requirements

Sorghum is a C_4 species that is very water efficient (Lopes et al., 2011). It requires a warm summer growing period of 4 - 5 months and a temperature of 25 - 30°C for optimum growth and development (Downes, 1972; Tropical Forages, 2020a). Day temperatures do not affect grain yield except at very high night temperatures (Downes, 1972). Day temperatures can be as low as 21°C and as high as 36°C without a dramatic effect on growth and yield as long as night time temperatures are low (19°C) (Downes, 1972). Night temperature affects sorghum development, with high night temperatures of around 31°C reducing yield (Downes, 1972). Night temperatures of 13°C or below can severely reduce grain production and frost can kill the plant. Seed set is also highly susceptible to cold temperature. Constant low temperatures throughout the plant's life cycle delay flowering (Tiryaki and Andrews, 2001), induce male sterility (Downes and Marshall, 1971) and result in scarcity or a total lack of seeds in panicles (Brooking, 1976).

2.3.3.2 Water and soil requirements

Annual rainfall between 500 - 1000 mm is sufficient for sorghum production (Skerman and Riveros, 1990; Philp and Harris, 2013; Tropical Forages, 2020a). Sorghum can be susceptible to drought at both the pre- and post-flowering stage. Drought at pre-flowering can reduce panicle size, seed number, and grain yield. At post-flowering, drought can trigger rapid premature senescence, leading to reduction in seed size, yield loss and stalk lodging (Derese et al., 2018).

Sorghum may be grown as an irrigated crop, mainly via flood (furrow or bay systems) or overhead irrigation. Ideal irrigation periods under flood, furrow or bay systems are 12 hours. Yield losses of up to 50% have been recorded if irrigation time is prolonged and waterlogging conditions exceed 24 hours at an irrigation site (GRDC, 2017).

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

2.3.3.3 Planting practices

Sorghum is used in no-till or minimum-till farming systems, usually planted directly into stubble from the previous crop (Cothren et al., 2000; Spenceley et al., 2005; GRDC, 2017; NSW DPI, 2021). These systems are valuable in conserving moisture and in preventing or minimising soil erosion in the crop (Cothren et al., 2000; Spenceley et al., 2005). Sorghum can also be grown under irrigation. Seed bed preparation practices for irrigated production can be found in several references (Doggett, 1988; Spenceley et al., 2005; Pacific Seeds, 2019a).

Seeds are planted at a depth ranging between 3 and 7.5 cm in moist soil (GRDC, 2017; Pacific Seeds, 2019a). Planting times differ by regions. In most of Qld and Northern NSW, the planting window is between September and January. This difference is related to differences in soil temperatures across regions. The recommended conditions for sorghum planting are soil temperature at 9 am at the intended seed depth (~5 cm) of at least 16°C (preferably 18 - 20°C) for 3 to 4 consecutive days and the risk of frost has passed (GRDC, 2017; Pacific Seeds, 2019a). Cold soil temperatures (~12°C) at planting increase the time for germination and emergence, seed losses of 30 - 40% can be expected, and the risk of diseases and insect attack is also increased (GRDC, 2017; NSW DPI, 2021). In Northern NSW, planting sorghum after late January increases the risk of ergot (GRDC, 2017), see Section 7.3.1.

In Northern NSW, hybrids that are considered quick-maturing flower approximately 66 days; medium-maturity hybrids approximately 73 days; and slow-maturing hybrids approximately 80 days after planting, noting that maturity can be quicker when temperatures are higher. For example, at Moree (Northern NSW), medium-maturity hybrids planted in early October take approximately 80 days to flower compared to approximately 60 days when planted in mid-November (GRDC, 2017).

In Australia, planting densities are 35,000 - 80,000 plants/ha in dryland systems depending on growing conditions and 100,000 - 150,000 plants/ha in fully irrigated systems (GRDC, 2017; Pacific Seeds, 2019a). Up to 250,000 plants/ha in fully irrigated systems can also be achieved (Spenceley et al., 2005). Close row spacing is appropriate under favourable conditions, such as high-yielding hybrids in irrigated and/or in high rainfall environments (GRDC, 2017).

2.3.3.4 Other cultivation practices

Although generally managed as an annual, many grain sorghum cultivars are short term perennials. A trait known as 'stay-green' allows sorghum leaves to remain green and continue photosynthesis at the grain filling phase and after grain maturity, and this trait is also associated with drought tolerance and lodging resistance (Spenceley et al., 2005; Kassahun et al., 2010; GRDC, 2017; NSW DPI, 2019). It is thus necessary to perform chemical desiccation after grain fill, in hybrids with the stay-green trait, 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). Grain with moisture above 12% may require drying before storage (House, 1985).

Sorghum is a useful rotation crop throughout Australia (GRDC, 2017; NSW DPI, 2019). 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 in weeds (Cothren et al., 2000; GRDC, 2017; NSW DPI, 2019). In Australia, sorghum has been grown in rotation with winter cereals, cotton, legumes, chickpea, soybeans, fallow and cover crops (Postlethwaite and Coventry, 2003; Spenceley et al., 2005; GRDC, 2017; Pacific Seeds, 2021).

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

2.3.4 Cultivation practices - forage Sorghum

Forage sorghum may be hybrid lines developed for forage production, *S. bicolor* subsp. *drummondii* lines (Sudangrass) or *S. bicolor × S. bicolor* subsp*. drummondii* 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 the harvesting of 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 is 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 Sorghum 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 × S. roxburghii*) with *S. bicolor* subsp. *arundinaceum* (Cameron, 2014). Perennial sorghum has been used as short-term pasture rotation, in pasture mixes 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

2.4.1.1 Gene pools for breeding

Breeding and cultivar improvement has relied principally on the diversity present in the Sorghum biotypes, however the undomesticated Sorghum species, including those endemic to Australia, offer untapped novel traits and breeding effort was more focused on overcoming technical reproduction constraints to allow use of this material (Dillon et al., 2007b). Sorghum 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 in wider production but have 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 and 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 methanesulfonate) protocols have been optimised for selected Sorghum biotypes to generate random changes in the genome (Dillon et al., 2007b).

2.4.1.2 Development of hybrid varieties

Natural hybrids were initially selected by farmers/breeders to provide new cultivars that were drought tolerant and chinch 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 and Holland, 1954). Early breeding programs in the USA that developed commercial sorghum hybrids resulted in yield increases of 300% between 1950 and 1990 (Rooney and Smith, 2000).

Commercial grain and forage sorghum varieties grown in Australia, North America and Europe are exclusively F_1 hybrids produced utilising CMS (Oz Sorghum, accessed July 2022). A wide range of sorghum hybrids are available for commercial planting addressing maturity, resistance to lodging or standability, tillering, disease and pest management, grain production characteristics, photoperiod sensitivity, drought tolerance and 'stay-green' characteristics among others (GRDC, 2017; QDAF, 2018; NSW DPI, 2019; Pacific Seeds, 2022).

2.4.1.3 Breeding outcomes

Sorghum originated in Northeast Africa and land races are 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 and Rana, 1982). Thus, photoperiod-insensitive germplasm and short sorghum cultivars have been widely used in breeding programs (Rai et al., 1999; Rooney and Smith, 2000; Rosenow and Dahlberg, 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; and post-anthesis tolerance when stress occurs during grain filling (Rosenow et al., 1983; Rosenow and Clark, 1995). Post-anthesis tolerance is referred to as stay-green, with plants maintaining green leaf area and photosynthetic capability under severe stress, resulting in higher grain yields than cultivars without this attribute (Borrell et al., 2000). The physiological components of stay-green 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 positive stalk characteristics (Rosenow and 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 into superior cultivars from Indian, American and Australian biotypes. In Australia, over 80% of the planted area in 1995 utilised cultivars with some midge resistance (Jordan et al., 1998) and all of the commercially available hybrids now have some level of midge resistance (Zull et al., 2020). 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 and this has proven difficult to overcome using conventional breeding (Girijashankar and Swathisree, 2009). This is due both to a shortage of genes for desirable traits such as disease resistance, pest resistance and drought tolerance, and to the difficulty in making wide crosses due to sexual incompatibility (Girijashankar and Swathisree, 2009). Beneficial genes may be incorporated through gene technology coupled with *in vitro* techniques to regenerate GM plants.

Completion of the whole genome sequencing will increase the genomic information available and support the genetic improvement for domesticated sorghum. Initial analysis of the 730 Mb sorghum genome (grain sorghum; BTx623) placed 98% of genes in their chromosomal context using whole-genome shotgun sequences validated by genetic, physical and syntenic information (Paterson et al., 2009). The relatively small genome of sorghum 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). More recently the whole genome sequencing of the sweet sorghum line 'Rio' highlighted differences in genes involved in sugar metabolism and transport compared to BTx623 (Cooper et al., 2019).

One limitation to genetic modification is that sorghum cells are difficult 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 impacting sorghum transformation are its inherent tolerance to antibiotics and the difficulty in selecting appropriate 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; Che et al., 2018), and CRISPR/Cas editing is also achievable (Che et al., 2018; Li et al., 2018; ISAAA, 2019).

2.4.2.1 International approvals of GM sorghum

Other GM sorghum has been approved by other countries. For example, limited field and glasshouse trials of GM sorghum for improved human nutrition (pro-vitamin A, zinc and iron) has been approved by the National Biosafety Authority in Kenya, Burkina Faso and Nigeria (Akinbo et al., 2021).

In the United States, the Department of Agriculture has ruled that two types of GM sorghum are not subject to regulation, as they are not plant pests and do not pose an increased noxious weed risk (USDA letter re TRSBG101S transgenic sorghum, USDA letter re TRSBG101B transgenic sorghum). Health Canada has also approved an herbicide tolerant GM sorghum for food use.

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).

A

B

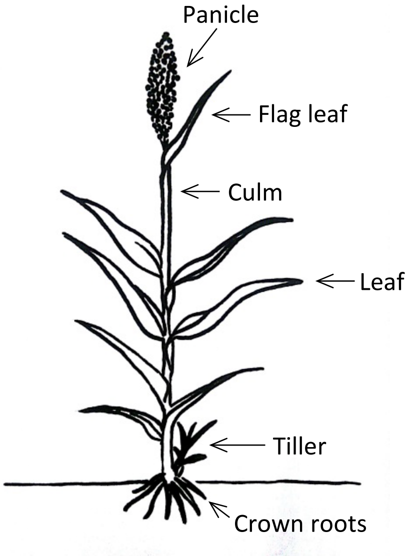

Figure 4 Sorghum morphology. (A) Sorghum plants showing upright stalk growth and alternate leaf pattern. Photo taken by R. R. Kowal, Department of Botany, University of Wisconsin-Madison. (B) Diagram depicting the different parts of a sorghum plant.

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 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 - 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, making it an adaptable crop in marginal dryland farming systems (Whiteman and Wilson, 1965).

3.1.2 Stem (Culm)

The stem can be slender to very stocky, 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 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 Leaves

Sorghum leaves are concentrated near the base in some varieties, while in others they are evenly distributed along the stem. The leaves are broad and coarse, linear to lanceolate in shape and look like maize leaves. They are 90 to 100 cm long and approximately 10 to 12 cm wide. Leaves are usually shorter and smaller at the top, with the top leaf known as the flag leaf. The leaves alternate in two ranks on opposite sides of the stem and 14 - 18 leaves have been recorded on a plant at flowering. The 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 upwards and inwards, reducing transpiration and moisture loss by decreasing the surface area exposed. Irregular shaped silica deposits found in the leaves have been linked to drought tolerance and shoot-fly resistance (Doggett, 1988). Silica deposited on the leaf surface acts as a physical barrier that alleviates water stress by decreasing transpiration and prevents the physical penetration of pests into plant tissues (Ma, 2004).

3.1.4 Tillering

Tillers are plant shoots that grow from a node located at the base of the principal shoot. Sorghum cultivars show great variation in tillering capacity. The number of tillers is dictated by factors such as genetics (hybrids and varieties), carbon supply, water availability and temperature (Skerman and Riveros, 1990; Kim et al., 2010; Jordan and Rodriguez, 2016). It is thought that temperature and day length affect tillering, with 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 (Jordan and Rodriguez, 2016).

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, semi-open (semi-compact) or open, but is usually semi-open to 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 spikelets (Figure 6).

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

The spikelets contain the flowers. The number of flowers per panicle varies from 1600 to 4000 (Stephens & Quinby 1934; Doggett 1988). The spikelets are pedicellate and lance shaped, 3 to 10 mm in length, 2 to 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 2 glumes, a lemma, a palea, 2 lodicules, 3 stamens and an ovary with 2 long styles that end in a plumose stigma (Doggett, 1988).

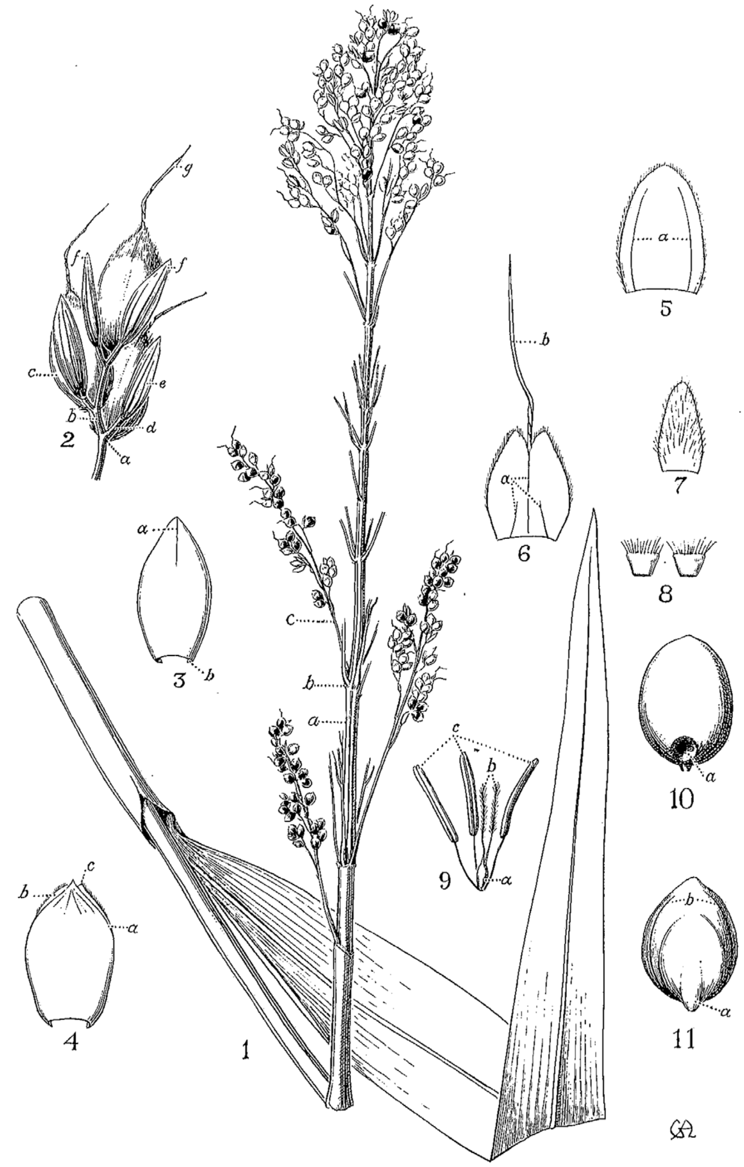

Figure 6 Inflorescence of *Sorghum* (Snowden, 1936).
1, part of panicle: a, internode of rachis; b, node with branches; c, branch with several racemes. 2, raceme; a, node; b, internode; c, sessile spikelet; d, pedicel; e, pedicelled spikelet; f, terminal pedicelled spikelets; g, awn. 3, upper glume: 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. Reproduced with permission, ©Board of Trustees of the Royal Botanic Gardens, Kew.

SECTION 4 DEVELOPMENT

4.1 Reproduction

4.1.1 Asexual reproduction

Sorghum cannot reproduce vegetatively, but it can be propagated vegetatively from stem cuttings since root primordia are present at the nodes (Thomas and Venkatraman, 1930; Purseglove, 1972; Schertz and 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 and Cuthbertson, 2001a, c).

Sorghum may possess the genetic potential for asexual seed production without the need for the introduction of new genetic material (transgenes). For example, through a combination of mutagenesis arising through tissue culture and conventional selection, Belyaeva and colleagues produced an asexual sorghum line that had functional components of apospory (the development of the 2*n* sexual cell phase, without meiosis and spores), parthenogenesis and autonomous endosperm development (Belyaeva et al., 2021). Thus, genes imparting asexual reproduction traits are likely to already be present in sorghum but may not be active due to epigenetic regulation of its DNA (Belyaeva et al., 2021).

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 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 temperature range, flowering may be delayed (Schertz and Dalton, 1980).

Flowering lasts typically one week but may vary from 2 to 15 days. Stigmas are receptive for 48 h before anthesis and can remain in a receptive state for 5 to 16 days, depending on the cultivar (Stephens and 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 4 to 5 days (House, 1985). Pollen is reported to require light and only germinates on the stigma after daybreak (Artschwager and McGuire, 1949). Once the viable pollen reaches the receptive stigma, it germinates and fertilisation occurs within 2 hours (Artschwager and McGuire, 1949; Schertz and Dalton, 1980; Doggett, 1988).

4.2 Pollination and pollen dispersal

4.2.1 Pollen viability

Pollen is short-lived and very sensitive to drying. Sorghum panicles may produce up to 24 million grains of pollen, which remain viable for 3 to 6 hours (Stephens and Quinby, 1934; Karper and Quinby, 1947; Doggett, 1988; Lansac et al., 1994). Weather conditions including temperature and humidity may affect pollen viability (Schertz and 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 h, while in the field, pollen stored in the shade in pollination bags could remain viable for over 20 h (Sanchez and 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 a self-pollinating crop species (Schertz and Dalton, 1980). Under natural circumstances, fully-fertile plants are approximately 70 - 95% self-pollinated (Ellstrand and Foster, 1983; Pedersen et al., 1998; Smith and Frederiksen, 2000; Djè et al., 2004). Outcrossing does also occur, with sorghum pollen dispersed predominantly by wind and convection currents (Schertz and Dalton, 1980).

There is indirect evidence of insect pollination based on observations of honey bees and wild bees in sorghum trials (Schertz and Dalton, 1980; Schmidt and Bothma, 2005; Schmidt and Bothma, 2006). Examination of insects collected from a trial sorghum crop found sorghum pollen grains attached to the body of collected insect individuals, although there was no demonstration that pollination occurred via this means (Schmidt and Bothma, 2005; Schmidt and 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 and Bothma, 2005). Pollen dispersal by bees may extend up to five kilometres as opposed to few hundred metres by wind dispersal (Arriola, 1995; Schmidt and Bothma, 2005). The role of bees or other animal species in sorghum pollination in Australia is currently unknown. Sorghum flowers possess the characteristic features of wind-pollinated plants, with the exception that some sorghum flowers are bisexual, facilitating self-pollination (Stephens and Quinby, 1934; Doggett, 1988; Schmidt and Bothma, 2005). Therefore, sorghum is clearly adapted for wind pollination rather than insect pollination. If sorghum is pollinated by insects, it is expected that the rate of insect pollination would be far lower than the rates of self-pollination or wind pollination, and insect-mediated pollination could only comprise a very small fraction of total pollination.

4.2.3 Outcrossing

Outcrossing rates in cultivated sorghum are estimated at 5 to 30% based upon multiple methods of calculation (Schertz and 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 and 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 and 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 are consistent 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 plants/ha.

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 to 6 g per 100 seeds (Stephens and Quinby, 1934; Whiteman and Wilson, 1965; Purseglove, 1972; House, 1985; Doggett, 1988; Vanderlip, 1993; FAO, 1995; Spenceley et al., 2005; Pacific Seeds, 2022).

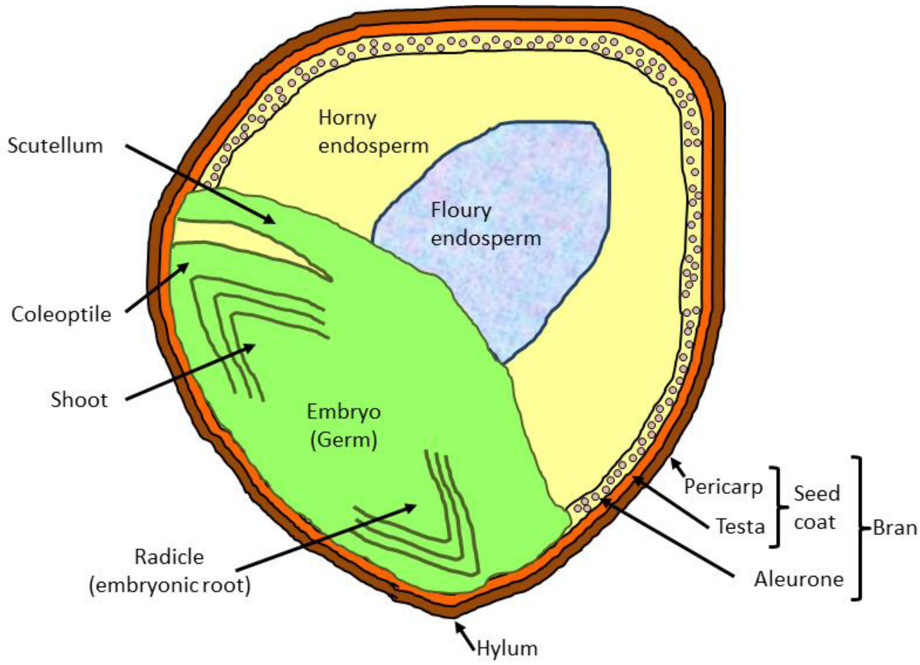

Figure 7 Illustration of a sorghum grain.

4.3.2 Seed development

Seed development begins within 7 days following pollination (Schertz and 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 the cultivar, and has been estimated to take from 25 to 55 days (Schertz and 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 to allow the efficient harvest of grains (Hoffman et al., 2002; Ejeta and Grenier, 2005). Initial domestication of sorghum involved selection against wild types with small shattering seeds and loose panicles and selection for types 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 and deVicente, 2010). Humans can also accidentally disperse sorghum seeds on clothing, harvest machinery and vehicles (Andersson and deVicente, 2010).

Sorghum seeds could 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 and Black, 1983). Sorghum seeds are consumed by livestock, rodents, birds, and seed-eating ants (Andersson and deVicente, 2010; see Section 7.2.2). All these organisms could disperse sorghum seeds with distance travelled dependent on the biology of each animal. Australian native and introduced mice have been documented to collect and disperse viable grain, as do sheep, deer and water birds (Randall, pers. com. 2017). Sorghum seeds have also been shown to pass undamaged through the digestive tract of wild deer and to germinate on deer excreta in the USA (Myers et al., 2004).

4.4 Seed dormancy, longevity and germination

Seed dormancy is another trait together with seed shattering that has been lost during sorghum domestication (Purseglove, 1972; Dahlberg, 1995; Tropical Forages, 2020a). Seed dormancy occurs less frequently in sorghum than in other crops like barley or oats and for most sorghum varieties seed dormancy is lost 3 months after harvest (Brown et al., 1948; Gritton and Atkins, 1963). Of 147 sorghum varieties investigated in one study in the USA, only 5 were found to be partially dormant (Brown et al., 1948). It was also found that storage temperature affected the length of the dormant period, with lower temperatures prolonging the period. Nevertheless, average germination rates for these varieties (number of seeds from the total that germinate) were 98% after being stored for one month at 40°C and 96% after 3 months at 10°C. All varieties lost seed dormancy after the grain had been stored for 2 months at 40°C. In a different study, the germination rates of 33 sorghum varieties was scored 2 weeks, 1 month or 3 months after harvest (Gritton and Atkins, 1963). Tests initiated 3 months after harvest resulted in germination percentages of 90% or above for all but 3 varieties. Therefore, it was concluded that seed dormancy was of little consequence 3 months after harvest.

Due to the low dormancy of sorghum seeds, pre-harvest sprouting is a problem in sorghum production. Pre-harvest sprouting is the germination of seeds in the sorghum head that occurs when weather conditions are humid close to the harvesting time. This results in the deterioration of the sorghum grain. Considerable variation in susceptibility to pre-harvest sprouting exists between varieties of sorghum (Steinbach et al., 1995; Steinbach et al., 1997; Rodríguez et al., 2011).

A study about seed longevity in soil found that few grain sorghum seeds of the variety 'RS671' were viable 4 months after burial regardless of burial depth and none were viable eight months after burial (Jacques et al., 1974). Seed longevity upon storage has been found to be enhanced in dry and low temperature conditions (Karper and Jones, 1936). Almost half of the seed could be germinated after 10 years when stored this way, but seed viability was lost quite rapidly thereafter. There was almost no viable seed after 20 years of storage (Karper and Jones, 1936).

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 to 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, often resulting in poor crop establishment. The percentage of germinated seeds gradually decreases with temperatures below 20°C, with the exception of 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 soil temperatures of 40 to 48°C also inhibit sorghum germination (Peacock, 1982). In Australia, sorghum takes 11 to 14 days to emerge when the soil temperature is 15°C, this is reduced to 7 to10 days at 17°C (GRDC, 2017).

4.5 Sorghum life cycle

The developmental stages of sorghum's life cycle are described in House (1985), Vanderlip (1993) and Spenceley et al. (2005) and are summarised in Table 5 below. The vegetative phase includes three stages (growth stages 0 to 2) and occurs from plant establishment to flower bud initiation; the floral phase includes growth stages 3 to 5 from inflorescence development to commencement of flowering (anthesis); and the grain filling phase, growth stages 6 to 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 life cycle will generally take between 90 and 140 days to complete (House, 1985; Vanderlip, 1993; Spenceley et al., 2005).

Emergence occurs when the coleoptile first breaks through the soil surface, generally 3 to 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).

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

Developmental phase	Growth Stage	Days after germination*	Identifying characteristic
Vegetative	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
Flowering	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
Physiological maturation	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 (USA).

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 3 or 4 leaves are fully expanded with about 80% of total leaf area present. The lower first to third leaves may be lost at this point. 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 at its maximum 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 lost with 8 to 12 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). 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 are affected by 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 and Conn, 1981; Business Queensland, 2018a). 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). The risk of poisoning is low when animals feed on flowering and seeding plants or silage (Business Queensland, 2018a). Grain and sweet sorghums have higher levels of dhurrin than forage sorghums (Business Queensland, 2018a).

Sorghum seeds contain trace amounts of dhurrin (1 - 29 ppm), whereas sprouts of the same seeds grown for three days in the dark at 30˚C contain 258 - 1030 ppm of dry weight (Panasiuk and Bills, 1984). Drying and grinding of sprouts to produce a meal does not reduce the 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 and Bills, 1984).

Farm workers have been overcome by cyanide fumes in large industrial scale sorghum silage operations. The LD_{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 plant nitrate (expressed as potassium nitrate; KNO_3) above 1.5% KNO_3 per feed dry weight are considered dangerous (Business Queensland, 2018b). 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 (Business Queensland, 2018b). Sorghum has the capacity to accumulate nitrates when soil nitrate content is high (Business Queensland, 2018b).

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 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, 2016b). The effects of these diseases on the sorghum plant are discussed further in Section 7.2.

5.1.3.1 Ergot toxins

Ergot is a fungal disease of sorghum caused by *C. africana*. The fungus produces fungal sclerotia, 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% sclerotia by weight for sorghum intended for stock other than feedlot cattle, where a 0.1% sclerotia by weight limit is imposed. Contaminated grain can be mixed with ergot-free grain to achieve sclerotia levels below the limits set for each use (QDAF, 2016a).

The effects of ergot toxins 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, 2016a).

5.1.3.2 Aflatoxins

Alternaria alternata, *Aspergillus* spp. and *Fusarium* spp. can infect sorghum (QDAF, 2016b). Toxins may be produced by fungi on weathered grain that has been exposed to high moisture before harvest. Mycotoxins produced by *A. alternata* and *Fusarium* spp. are strong, but levels rarely reach concentrations of concern. Pigs and poultry are more susceptible than cattle (QDAF, 2016b).

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, 2016b).

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 and 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 (reviewed in Davies, 2014), however it has been found to cause the least severe reaction amongst five tropical grasses (Sridhara et al., 1995). 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). At least 5 proteins in sorghum pollen are the cause of the patients' allergic reactions. Allergenic proteins in the pollen designated Sor b 1, and the panallergens profilin (Sorb PF) and polcalcin (Sorb PC) have been identified (Sridhara et al., 2002; Davies, 2014; Sekhar et al., 2015).

Pollen of tropical grasses are important air-borne allergens in subtropical Australia (Davies et al. 2012). *S. 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, 77% showed a positive allergic reaction to pollen of *S. halepense* (Lomas et al., 2012), where the proteins Sor h 1 and Sor h 13 in the pollen have been identified as the main cause of the allergic reaction (Lomas et al., 2012). It is not known what percentage of Australian grass pollen-allergic patients are allergic to sorghum and whether any cross-sensitivity to pollen of sorghum and *S. halepense* exists.

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 widely found 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 and Rooney, 2007). Sorghum tannins have anti-nutritional effects that are discussed here but also beneficial effects 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 and Miller, 1982; Awika and 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 USA has been almost entirely restricted to non-tannin types (Rooney and Miller, 1982; Awika and 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 contain condensed tannins; and type III sorghums contain tannin both in the testa and the pericarp (Rooney and Miller, 1982). Dykes and 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 and 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 plant 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 (see Figure 7) 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 to 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.

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 (hard) 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 to 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 to 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, and therefore they are difficult to break down during digestion (Hulse et al., 1980; Dicko et al., 2006).

Grain sorghum is a 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 also contains 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 (see Section 5.3.2).

Sorghum is a rich source of phytochemicals including tannins, phenolic acids, anthocyanins, phytosterols and policosanols (Awika and 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 and 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, antimutagenic, antimicrobial and other beneficial properties (Chung et al., 1998; Awika and Rooney, 2004). These effects may be related to the anti-oxidative properties of tannin, which protect 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 and 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 the production of compounds that lower cholesterol in a commercial context (Awika and 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. These characteristics account for its success as a crop in semi-arid regions of the world where prolonged periods of drought and temperature extremes are common (ICRISAT and FAO, 1996).

6.1 Nutrients

Adequate soil nutrition is necessary to meet the growth and yield potential of sorghum (Vanderlip, 1993; Wylie, 2008; GRDC, 2017; Pacific Seeds, 2019b). The 2 principal nutrients required for successful production of sorghum are nitrogen (N) and phosphorus (P) (Wylie, 2008; GRDC, 2017; Pacific Seeds, 2019b). Other nutrients may be added to cropping soils less frequently. These include zinc (Zn), sulphur (S) and potassium (K) (Wylie, 2008; GRDC, 2017; NSW DPI, 2019; Pacific Seeds, 2019b). In Australia, sorghum is often grown in rotation with other crops (see Section 2.3.3.4) so different nutrients may be added depending on the other crops grown in the rotation and the nutrient availability in the soil (GRDC, 2017; NSW DPI, 2019).

Application of N is often necessary before floral initiation so as to increase yield (Vanderlip, 1993). If N is applied at planting, seeds must be protected as release of ammonia can damage the germinating seeding (GRDC, 2017).

Sorghum is more tolerant to low soil P than wheat or barley (NSW DPI, 2019) and deficiency is most likely to occur after long fallow, due to low levels of soil microbes (GRDC, 2017). Application of P needs to be carefully managed as it can induce Zn deficiency, which in turn reduces N uptake (GRDC, 2017). P is best applied either in the seed furrow or adjacent (20 - 50 mm) to the seed at sowing (Pacific Seeds, 2019b).

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 some clay soils of Northern NSW and sorghum growth has been affected by the soil salinity in this region (NSW DPI, 2019).

Subsoil sodicity occurs when an excess of exchangeable sodium cations is 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 the germination of sorghum (NSW DPI, 2019).

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 and 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 deficit and waterlogging

Sorghum’s water requirements have been presented in Section 2.3.3.2. While sorghum can tolerate periods of water deficit, it does respond well to rainfall and to soil moisture conservation (Rosenow et al., 1983; GRDC, 2017; NSW DPI, 2019). Even with inherent tolerance, extreme conditions reduce sorghum’s productivity and nutritional quality, and there has been considerable focus on the genetic basis of drought tolerance as part of breeding programs (Abreha et al., 2021). Sorghum has a number of morphological and physiological features (Muimba-Kankolongo, 2018) that contribute to its drought resistance:

- 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
- the leaves have a waxy coating and can roll inwards in drought conditions
- low evapotranspiration; e.g. it requires less water than maize to produce the same amount of dry matter
- 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 (Philp and Harris, 2013; GRDC, 2017). Water flow into furrows may carry herbicides applied at planting, 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, 2017). Waterlogging is more likely under irrigation, intense rainfall, or under adverse soil conditions, such as sodicity as stated in Section 6.2.

SECTION 7 BIOTIC INTERACTIONS

7.1 Weeds

Dryland cultivated sorghum is most sensitive to weeds during crop establishment. 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, 2021). Delaying weeding one, 2 and 3 weeks compared to standard practices reduces sorghum yield 4%, 12% and 18%, respectively (Burnside and Wicks, 1969). Weeds that germinate later than 30 days after sowing have little effect on yield (Burnside and Wicks, 1969).

From 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 found to be *Sonchus oleraceus* (sowthistle), *Rapistrum rugosum* (turnip weed), *Echinochloa* spp. (barnyard grasses) and *Urochloa panicoides* (liverseed grass) (Osten et al., 2007). This survey also found that few growers were using integrated weed management and that herbicide resistance in weeds had been and continued to be an issue in this region. The herbicides approved for use in sorghum cultivation in Australia are shown (Table 6).

Table 6 Herbicides registered for use in sorghum as presented in NSW DPI (2019).

Herbicide		Group	Sorghum use pattern			
			Pre-plant	Post-plant / pre-emergent	Post-emergent	Pre-harvest crop desiccation
Residual activity – check plant back period	2,4-D amine	I (4)	✓		✓	✓
	atrazine	C (5)	✓	✓	✓	
	dicamba + atrazine	I & C (4 & 5)	✓	✓	✓	
	flumioxazin	G (14)	✓			
	fluroxypyr	I (4)			✓	
	S-metolachlor	K (15)		✓	✓	
	S-metolachlor + atrazine	K & C (15 & 5)		✓		
	triclopyr	I (4)	✓		✓	
	tribenuron-methyl	B (2)	✓			

	Herbicide	Group	Sorghum use pattern			
			Pre-plant	Post-plant / pre-emergent	Post-emergent	Pre-harvest crop desiccation
Knockdown activity	glyphosate	M (9)	✓			✓
	amitrole + paraquat	L & Q (33 & 22)	✓			
	diquat	L (22)	✓			✓
	paraquat	L (22)	✓			
	paraquat + diquat	L (22)	✓			

© State of NSW through NSW Department Planning, Industry and Environment, 2019. Note that the letter-based herbicide mode of action groups has recently changed to a numerical system, presented in parentheses. The numerical system is as presented in CropLife Australia (2022).

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 (NSW DPI, 2019).

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 (Osten et al., 2007).

7.2 Pests

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, 2018). The introduction of the fall armyworm (FAW; *Spodoptera frugiperda*)) into Australia in 2020 poses concern for sorghum crops as they are a favoured host. Information on the damage, monitoring and management of FAW can be found on the State authority websites (QDAF, 2020; Business Queensland, 2021; Spafford, 2021). 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, 2018; NSW DPI, 2019).

Table 7 Details of common sorghum pests in Australia, as presented in 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*) and 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

Plant stage[a]	Pest	Status in Australia	Damage	Control
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*); and Dayfeeding armyworm (*Spodoptera exempta*)	Minor, irregular	Larvae defoliate young plants; mature plants may outgrow damage, but seed yield is reduced; signs include chewed leaf margins, faecal pellets	Chemical
Flowering; seed	Corn earworm (*Helicoverpa armigera*)	Major, widespread, regular	Larvae feed on developing seeds	Biocidal; Nuclear polyhedrosis virus (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

7.2.1.1 Management

Helicoverpa (*H. armigera*) can be controlled with an IPM approach using Nuclear polyhedrosis virus (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, 2018).

Armyworms and soil insects are important pests during the early stage of crop development (Spenceley et al., 2005; QDAF, 2018). These pests do not often occur at levels requiring control, but may be a problem in cool conditions or in compacted soils (Spenceley et al., 2005; QDAF, 2018).

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, 2018).

7.2.2 Vertebrate Pests

Feral pigs, kangaroos, mice and various bird species, especially parrots, will eat sorghum grain once it is at or near maturity. Cattle, horse and sheep will all graze on sorghum. Australian native and introduced mice have been documented to collect and disperse viable grain, as do sheep, deer and water birds (Randall, pers. com. 2017). Plague mice have been shown to reach numbers of up to 3,000/ha in sorghum crops (Kaboodvandpour and Leung, 2008).

Birds, particularly large parrots such as galahs (*Eolophus roseicapilla*), cockatoos and cockatiels (both members of the *Cacatuoidea*) are attracted to sorghum when it is mature, especially to sorghum with white or yellow seed coats as these are more palatable than red or brown seeded types (Doggett, 1988). Other bird species known to consume sorghum include sparrow (*Passer domesticus*), pigeon (*Columba livia*), and red-billed quelea (*Quelea quelea*) (Xie et al., 2019). Sorghum is also a common component of native and introduced bird seed mixes for feeding.

7.3 Diseases

Most of the diseases of sorghum found 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.

Photosynthesis drives grain development and filling during the grain filling phase, with over 90% of photosynthesis taking place in the sorghum head and the top 4 to 5 leaves (Fischer et al., 1976). Thus, loss in available leaf area for photosynthesis due to diseases would affect grain filling and yield. Planting hybrids with good disease resistance at the correct time will help manage such disease problems (Spenceley et al., 2005).

7.3.1 Ergot

Ergot, a fungal disease caused by *Claviceps africana* (GRDC, 2017), was first recorded in Australia in 1996, is endemic to Qld, and has been found in Northern NSW (Ryley et al., 1996; NSW DPI, 2019). Some sorghum lines from Africa have good resistance to ergot and this provides a basis for the development of resistance in commercial Australian lines (QDAF, 2016a).

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 fungal body known as the sclerote (QDAF, 2016b). 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, 2016a). Factors which result in poor or uneven pollination, such as rainy conditions, increase grain sorghum's susceptibility. For sorghum with late tillers, forage sorghum and male sterile lines, infection can occur under a broader range of conditions (QDAF, 2016a). Ergot is readily identified by the honeydew oozing from sorghum flowers (Figure 8) that dries up into a white powder. This powder is often observed on the leaves and on the soil under affected plants.

Ergot reduces grain set and consequently yield. It also affects grain quality due to lower nutritional value and the presence of sclerotia (QDAF, 2016a). Ergot can survive all year in honeydew on other hosts including *S. halepense*, Columbus grass (*Sorghum × almum*) and volunteer grain and forage sorghum, but it does not survive on sorghum stubble or as sclerotes in the soil (QDAF, 2016b, a). Spores are generally spread by wind, but also by insects, animals, humans and machinery.

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

7.3.2 Sorghum 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; GRDC, 2017; NSW DPI, 2019). 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; GRDC, 2017; NSW DPI, 2019).

7.3.3 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, with lodging being the first obvious sign of infection (GRDC, 2017; NSW DPI, 2019). However, sorghum stalks can be infected by *Fusarium* but not lodge, possibly due to the strength of the stalk, the speed of infection, severity of other stressors and tolerance of the hybrid. The use of non-host crops in rotations and practices to minimise moisture stress are recommended (GRDC, 2017).

7.3.4 Head smut

Smut is a soil-borne disease caused by *Sporisorium reilianum*. Symptoms usually appear at the boot stage when the head is replaced by a mass of black spores covered in a white fungal membrane (GRDC, 2017). This membrane breaks open on emergence of the head and disperses the spores. Heads that are partially affected become sterile (GRDC, 2017). 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 (GRDC, 2017).

7.3.5 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 (GRDC, 2017). The fungus can survive on undecomposed sorghum residues, volunteer sorghum and *S. halepense* plants. If the disease is severe, pinched grains are formed, resulting in lower yields (GRDC, 2017). 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 (GRDC, 2017).

7.3.6 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 (GRDC, 2017).

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.

Cultivated sorghum species are exotic to Australia and its distribution in the country is widespread (see Figure B1 in Appendix B). This species includes cultivated sorghum and its wild relatives (see Section 1). Both forms have been introduced in many parts of the world, however only the wild relatives are considered to be problematic weeds (Ejeta and Grenier, 2005). Weedy or wild sorghums, namely *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *arundinaceum*, are commonly found near cultivated grain sorghum crops and these subtaxa are fully inter-fertile with cultivated sorghum (see Section 8.6 and Section 9). The hybrids between cultivated sorghum and these two subspecies are also weedy (see Section 8.6). Some references about weediness and weed databases describe the weediness of the species without distinguishing between the three subspecies. This makes it difficult to estimate the weediness status of cultivated sorghum. For the sake of clarity, the three subspecies will be treated separately in this biology document.

Some other well-known weeds are closely related to, and sexually compatible with cultivated sorghum. These are *S. halepense*, *S. × almum* and perennial 'Silk' sorghum (see Section 8.6 and Section 9). The hybrids between cultivated sorghum and these species are also weedy and can become a problem in agricultural systems (Clark and Rosenow, 1968).

8.1 Weediness status on a global scale

Cultivated sorghums are not recognised as weeds although individual plants volunteer after crop harvest. There are only ten references to *S. bicolor* subsp. *bicolor* listed in the book '*A Global Compendium of Weeds*' (Randall, 2017). There are four entries in North America listed as casual alien, cultivation escape and naturalised; listed as naturalised in Peru, Mexico and New Zealand; a casual alien listed in Namibia; a single entry listed as cultivation escape and dispersed by humans on a global scale; and one mention in Australia with the non-specific category of 'weed'. This Australian entry lists *S. bicolor* and *S × drummondii* as cultivated annuals found naturalised in disturbed sites (Richardson et al., 2011).

8.2 Weediness status in Australia

Groves et al. (2003) defined naturalised non-native plant species as those that have been introduced and become established and that now reproduce naturally in the wild, without human intervention. Naturalised species were ranked according to their invasiveness in agricultural and natural ecosystems in the categories shown (Groves et al., 2003); (Table 8).

Invasive plant species can be listed as 'noxious weed' (alternate names are 'listed' or 'proclaimed') in States or Territories by noxious weed legislation. Similar legislation is used throughout Australia, but any 'noxious weed' is only recognised within the State or Territory that listed it. Noxious weed listing recognises 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 has been described as a category 3 weed in agricultural systems according to Groves et al. (2003), being a minor problem in Qld and NSW. It was also listed as a category 2 weed in natural ecosystems but considered mainly an agricultural or ruderal weed (Groves et al., 2003). Sorghum does not appear in the weed list of the Weeds in Australia database, accessed October 2024.

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
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

Category	Explanation
+	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

In agricultural ecosystems, sorghum volunteers are commonly found along roadsides, around sheds, silos and intensive animal feeding enterprises within geographic areas of cultivation. These are usually 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).

8.4 Control measures

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

8.5 Weed risk assessment

The weed risk potential of sorghum has been assessed in Appendix C 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 plantings is driven by economics, as well as factors such as climate and soil suitability.

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

- have a low ability to establish amongst existing plants and weeds
- have a low tolerance to average weed management practices in cropping and intensive land uses
- have a short time to seeding from planting (less than one year)
- have low ability to establish in any land use
- rarely reproduce by vegetative 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 cultivated sorghum in Australia summarised in Section 8.2, and provides a baseline for the assessment of GM sorghum.

8.6 Weediness of other *Sorghum* taxa

The ability of cultivated sorghum to outcross and hybridise with a number of relatives which are recognised weeds warrants the consideration of their weediness in this section.

Five *Sorghum* taxa are naturalised in Australia that belong to the gene pool groups GP1 and GP2 and therefore are able to outcross with cultivated sorghum (Table 9; see Section 9). Of these, three species have been declared noxious in NSW: *S. halepense*, *Sorghum × almum* and Silk forage sorghum (NSW WeedWise; accessed June 2022). *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, 2016).

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

Name	Alternate name (s)	Category[1]	Gene Pool
S. *bicolor* subsp. *drummondii*[1,2]	Shattercane, Sudangrass *S. × drummondii* *S. bicolor* nothosubsp. *drummondii*	+	GP1
S. bicolor subsp. *arundinaceum*[1,2]	*S. bicolor* subsp. *verticilliflorum* *S. arundinaceum*	5	GP1
S. halepense[1,3]	Johnson grass	5	GP2
S. × almum[1,3]	Columbus grass	5	GP2
S. sp. hybrid cv. Silk[1,3] (*S. halepense* × *S. roxburghii* 'Krish') × *S. arundinaceum*	Silk forage sorghum	n/a	GP2*

[1] Source: Groves et al. (2003)
[2] Source: Parsons and Cuthbertson (2001b)
[3] Source: Weeds in Australia database, accessed October 2024
* Silk forage sorghum is a tetraploid with $2n = 40$ (CSIRO, 1978), therefore it probably belongs to GP2 although no reference has been found to support this conclusion

8.6.1 Wild sorghums of the species *Sorghum bicolor*

8.6.1.1 S. bicolor subsp. verticilliflorum (formerly known as arundinaceum)

S. bicolor subsp. *arundinaceum* contains wild and weedy races of *S. bicolor* that have been introduced to tropical Australia. *S. bicolor* subsp. *arundinaceum* is classified as a category 5 weed in Groves et al. (2003) being a problem in agricultural ecosystems in Qld. It has also been reported to be a widespread weed in the coastal areas of Qld and Northern NSW (Simon and Alfonso, 2011).

8.6.1.2 S. bicolor subsp. drummondii (shattercane and Sudangrass)

S. bicolor subsp. *drummondii* (now known as *S. bicolor* nothosubsp. *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 they are growing amongst is harvested, leaving the seeds in the field. In highly mechanised cultivation systems their spread may not be controlled (Ejeta and 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 and 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 USA (USDA, 2015) but in Australia is classified as a category 3 weed in natural ecosystems and category '+' in agricultural systems (Groves et al., 2003); see Table 8 for the explanation of the different categories used. 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, accessed October 2024.

8.6.1.3 S. bicolor hybrids

Cultivated sorghum pollinated by wild *S. bicolor* relatives produces shattercane seed that is indistinguishable from cultivated sorghum seed. If sowed in the field, contaminated seed produces off-type sorghum plants that are weedy and distinguishable only when the plant reaches the flowering stage (UC IPM, 2016). Off-type sorghum plants compete with grain sorghum and other crops for water, nutrients and sunlight (Clark and Rosenow, 1968) These plants are fertile and may produce seed that will contribute to a severe volunteer problem in succeeding years (Clark and Rosenow, 1968).

To control volunteer off-type sorghum plants from seed already in the soil, an effective practice is to rotate with broad-leaved crops such as cotton or soybeans and apply herbicides recommended for controlling grasses in these crops (Clark and Rosenow, 1968). Buying good seed, continuous roguing in grain sorghum fields, and appropriate control measures in rotations are the only approaches to reducing the problem of off-type sorghums (Clark and Rosenow, 1968).

8.6.2 *Sorghum halepense* (Johnson grass)

The most widely recognised sorghum species that is a noxious weed in Australia 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 into Australia 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 acting as a host for crop pests and diseases. It's 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 serious weed threat to agricultural systems in many countries from the Mediterranean through the Middle East to India, Australia, central South America and the USA (Holm et al., 1977). There are over 680 references citing *S. halepense* as a weed that may be declared noxious, invasive and subject to quarantine restrictions in some areas (Randall, 2017).

Seeds from *S. halepense* disperse by shattering and also by wind, animals and humans (Parsons and Cuthbertson, 2001b). Its seed does not survive long at 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 and Cuthbertson, 2001b). The rhizomes produced by this species are extensive and can regenerate after cutting during cultivation (Warwick and Black, 1983). *S. halepense* occurs sympatrically with grain sorghum and has overlapping flowering times. Consequently there is a high likelihood for genetic exchange between these two species and hybridisation has been observed in field trials in the USA (Arriola and Ellstrand, 1996, 1997; Ejeta and 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 and Cuthbertson, 2001b).

S. halepense readily invades arable areas in high rainfall regions. In lower rainfall areas, it appears to be more restricted to roadsides, 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 and Cuthbertson, 2001b).

Control measures used for *S. halepense* are difficult because of the regeneration of the plant from rhizomes (Parsons and Cuthbertson, 2001b). Rhizome production 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 competition by paspalum has been successful in the Darling Downs (Parsons and 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 and Cuthbertson, 2001b).

8.6.3 *Sorghum × almum* (Columbus grass)

Another aggressive weedy species is *S. × almum*, it is also called Columbus grass and is a hybrid between S. *bicolor* and S. *halepense.* This annual grass has been cultivated as a forage sorghum in Australia. *S. × almum* appears mostly along roadsides, fence lines and in natural environments but is considered to be less problematic than *S. halepense* (Parsons and Cuthbertson, 2001b). It is dispersed by seed, which float 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 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 and 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. The best results are obtained by slashing or burning in December, and spraying the regrowth at early flowering (Parsons and Cuthbertson, 2001a).

8.6.4 Perennial ('Silk') sorghum

Perennial ('Silk') sorghum cultivated in the NT as forage sorghum is declared noxious in parts of NSW. It has potential to harbour disease and insect pests of, and outcross with annual grain and forage sorghums (NSW WeedWise; accessed October 2024).

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 (Tropical Forages, 2020b).

Additional information about these species as weeds in Australia can be found at https://weeds.org.au/.

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 that is, 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; Ellstrand, 2003; Stewart et al., 2003; Ejeta and Grenier, 2005; Andersson and deVicente, 2010).

9.1 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 agroecosystem (Arriola and Ellstrand, 1996, 1997; Ejeta and Grenier, 2005). The *Sorghum* genus has been divided into three distinct gene pools based on the degree of cross compatibility (Harlan and de Wet, 1971).

The primary sorghum gene pool (GP1) contains members of the subgenus *Eusorghum* that are sexually compatible (Figure 9). It includes all subspecies of *Sorghum bicolor* (*S. bicolor* subsp. *bicolor, S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *arundinaceum*) and *S. propinquum*. These species are fully inter-fertile and the high level of compatibility permits spontaneous hybridisation, outcrossing and introgression (Ejeta and 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. × 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 and Ellstrand, 1996, 1997).

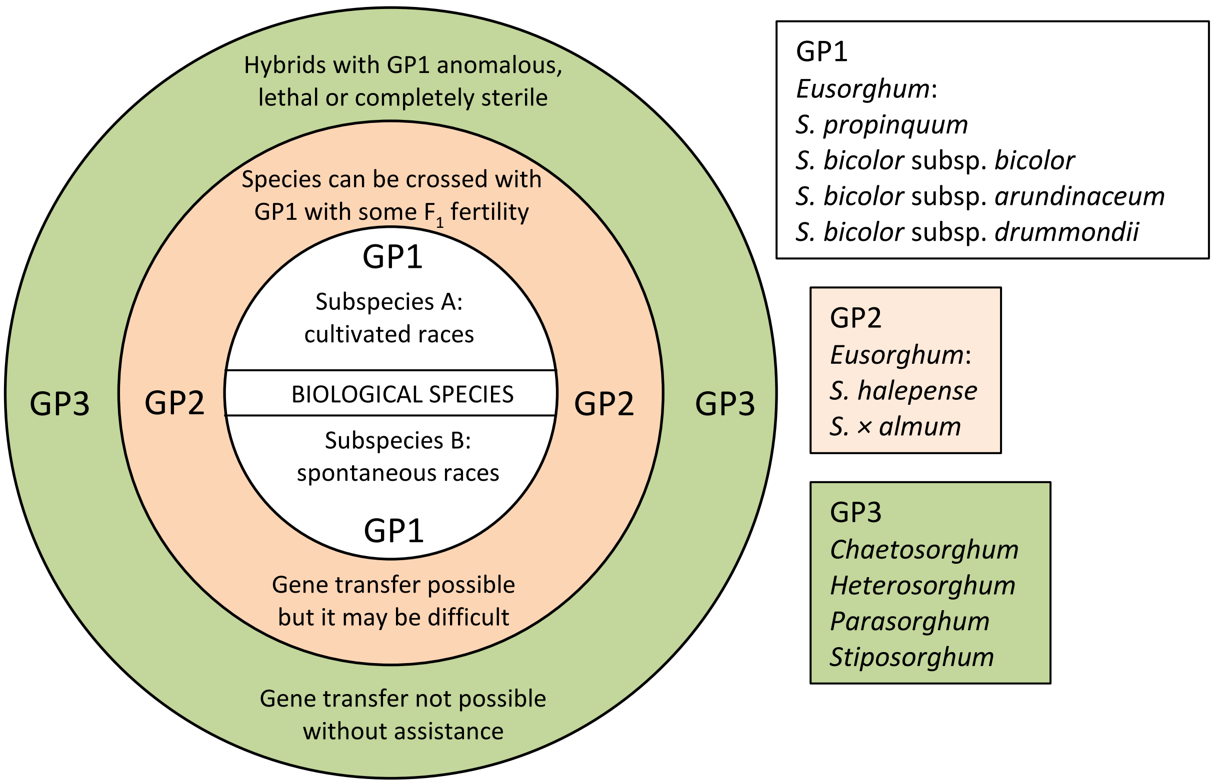

Figure 9 The sorghum gene pools. Adapted from Harlan and de Wet (1971); Ejeta and Grenier (2005)

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 Section 9.4 below).

Gene flow between cultivated sorghum and other *Sorghum* taxa is an important matter. From a breeding perspective, genetic material from wild relatives could be incorporated into cultivated sorghum to improve agronomic traits. On the other hand, introgression of cultivated sorghum genetic material into the sorghum wild species could potentially affect their weediness, making them more invasive.

9.2 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 and Grenier, 2005; Andersson and 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 and Grenier, 2005).

Field-based gene transfer studies in the USA 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. This suggests 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 hybridisation study 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 demonstrated that if flowering time overlaps, hybridisation between sorghum and shattercane occurs at least at 200 m.

9.3 Crosses between sorghum and GP2 species

The most widely recognised 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 USA (Arriola and 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 and 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 and Ellstrand, 1996). This may be attributed to the abundance of pollen availability near the crop increasing the likelihood of hybrid formation (Arriola and 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. × almum* from various locations worldwide, including *S. halepense* samples from across the USA with differing exposure to cultivated sorghum. The presence of 77 cultivar-specific alleles in the USA samples of *S. halepense,* but absent from worldwide samples of weedy sorghum relatives, suggested that introgression had occurred. Within the USA, 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. × almum* (2*n* = 40), a perennial rhizomatous weed commonly referred to as Columbus grass (Doggett, 1988). Restriction fragment length polymorphism (RFLP) analysis revealed that both *S. × 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 sorghum naturalisations such as *S. halepense*, *S. × almum* and perennial (Silk) forage sorghum. Distribution maps for these species are shown in the Appendix B (Figures B2, B3, B4 and B5).

9.4 Crosses between sorghum and GP3 species

Cultivated sorghum does not hybridise naturally with the wild Australian species of *Sorghum* 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, thus embryo formation does not occur. 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 and 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 × S. macrospermum*, *S. bicolor × S. angustum* and *S. bicolor × 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 technically possible to incorporate novel genes into future cultivars (Price et al., 2006; Kuhlman et al., 2010).

9.5 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 and 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 and 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 maize (*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 and Bennett, 1989).

SECTION 10 FINAL REMARKS

An earlier version of this biology document (version 1.1) was finalised in July 2017 to assist in the evaluation of licence applications for dealings involving the intentional release of GM sorghum plants into the environment. The OGTR would like to thank the Gene Technology Technical Advisory Committee and a body of experts in the fields of weed biology and agronomy who reviewed the earlier document.

The website links as used in this document were assessable at the time of their referencing.

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APPENDIX A SYNONYMS FOR *SORGHUM* SPECIES

Table A1: Selected synonyms for Sorghum species[a]

Name used	Synonyms
S. bicolor subsp. *bicolor*[†]	*S. basutorum*
	*S. bicolor**
	S. bicolor var. *arduinii*
	S. bicolor var. *saccharatum*
	S. bicolor var. *subglobosum*
	S. bicolor var. *technicum*
	S. cafforum
	S. cafforum var. *brunneolum*
	S. cafforum var. *cafforum*
	S. cafforum var. *lasiorhachis*
	S. caudatum
	S. cernuum
	S. cernuum var. *agricolarum*
	S. cernuum var. *cernuum*
	S. cernuum var. *orbiculatum*
	S. conspicuum
	S. conspicuum var. *conspicuum*
	S. conspicuum var. *pilosum*
	S. conspicuum var. *rubicundum*
	S. coriaceum
	S. coriaceum var. *coriaceum*
	S. coriaceum var. *subinvolutum*
	S. dochna
	S. dochna var. 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. membranaceum var. *membranaceum*
	S. miliiforme
	S. nervosum
	S. nigricans
	S. notabile
	S. roxburghii
	S. roxburghii var. *hians*
	S. roxburghii var. *roxburghii*
	S. saccharatum
	S. simulans
	S. splendidum
	S. subglabrescens
	S. subglabrescens var. *compactum*
	S. subglabrescens var. *oviforme*
	S. subglabrescens var. *rubidum*
	S. subglabrescens var. *subglabrescens*
	S. technicum
	S. vulgare
	S. vulgare var. *caffrorum*

Name used	Synonyms
	S. vulgare var. *durra* *S. vulgare* var. *roxburghii* *S. vulgare* var. *saccharatum* *S. vulgare* var. *technicum*
S. bicolor subsp. *drummondii*[†] Now known as *S. bicolor* nothosubsp. *drummondii*[†]	*S. bicolor* var. *drummondii* *S.* × *drummondii** *S. hewisonii* *S. niloticum* *S. sudanense* *S. vulgare* var. *drummondii* *S. vulgare* var. *sudanense*
S. bicolor subsp. *arundinaceum*[†] *Now known as* *S. bicolor* subsp. *verticilliflorum*[†]	*S. aethiopicum* *S. arundinaceum** *S. brevicarinatum* *S. lanceolatum* *S. macrochaeta* *S. pugionifolium* *S. stapfii* *S. usambarense* *S. virgatum* *S. vogelianum*
S. × *almum*	(= *S. bicolor* × *S. halepense*)
S. amplum	
S. angustum	*Sarga angusta*
S. bipennatum	
S. brachypodum	
S. bulbosum	
S. ecarinatum	
S. exstans	
S. grande	
S. halepense	*S. controversum*[†] *S. miliaceum* *S. miliaceum* var. *miliaceum* *S. miliaceum* var. *parvispicula*
S. interjectum	
S. intrans	*Sarga intrans*
S. laxiflorum	*Vacoparis laxiflora*
S. leiocladum	*Andropogon australis* subsp. *leiocladus* *Sarga leioclada*
S. macrospermum	*Vacoparis macrosperma*
S. matarankense	
S. nitidum	*S. fulvum* *Andropogon serratus* *A. tropicus* *A. tropicus* var. *tropicus* *Holcus fulvus* *Holcus nitidus*
S. nutans	*S. nutans* *S. nutans* subsp. *nutans*
S. plumosum	*Andropogon australia*
	A. australia subsp. *australis* *Holcus plumosus* *Sarga plumosa*
S. propinquum	*Andropogon propinquus*

Name used	Synonyms
S. purpureosericeum	*S. dimidiatum* *Andropogon purpurosericeus* *Sarga purpurosericea*
S. rigidifolium	
S. stipoideum	*Sarga stipoidea*
S. timorense	*S. australiense* *S. brevicallosum* *Andropogon tropicus* var. *timorense* *Sarga timorensis*
S. trichocladum	
S. trichopus	
S. versicolor	*Sarga versicolor*

[a] Source: (USDA ARS, 2022).
[†] 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.
* Scientific names accepted by The Australian Plant Census for the Australian flora. The taxonomy and nomenclature adopted for the APC are endorsed by the Council of Heads of Australasian Herbaria.

APPENDIX B DISTRIBUTION MAPS OF SORGHUM SPECIES IN AUSTRALIA

Figure B1: Distribution map of *S. bicolor* in Australia (ALA S. bicolor, accessed October 2024).

Figure B2: Distribution map of *S. bicolor* subsp. *arundinaceum* in Australia (ALA S. arundinaceum, accessed October 2024)

Figure B3: Distribution map of *S. bicolor* subsp. *drummondii* (Sudangrass & shattercane) in Australia (ALA S. × drummondii, assessed October 2024).

Figure B4: Distribution map of *S. halepense* (Johnson grass) in Australia (ALA S. halepense, accessed October 2024).

Figure B5: Distribution map of *S. × almum Parodi* in Australia (ALA Sorghum × almum, accessed October 2024).

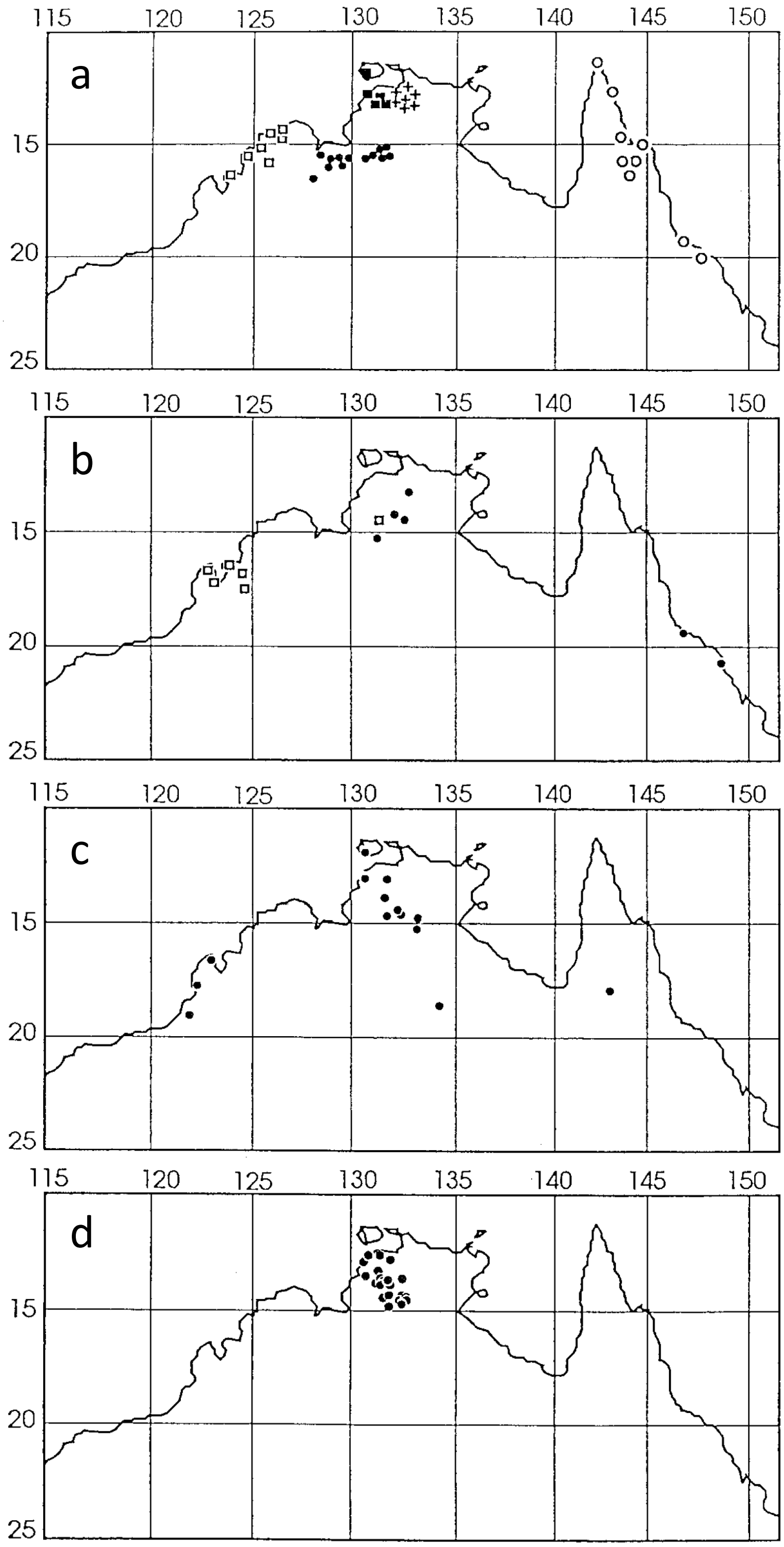

Figure B6: Distribution of endemic Sorghum species in Australia from collections of: (a) ☐*S. amplum*, ○*S. angustum*, ●*S. bulbosum*, +*S. brachypodum*, ■*S. exstans*; (b) ☐*S. ecarinatum* and ●*S. grande*; (c) ●*S. interjectum*; and (d) ●*S. intrans*. Figure reproduced with permission from Lazarides et al. (1991), (see CSIRO publication).

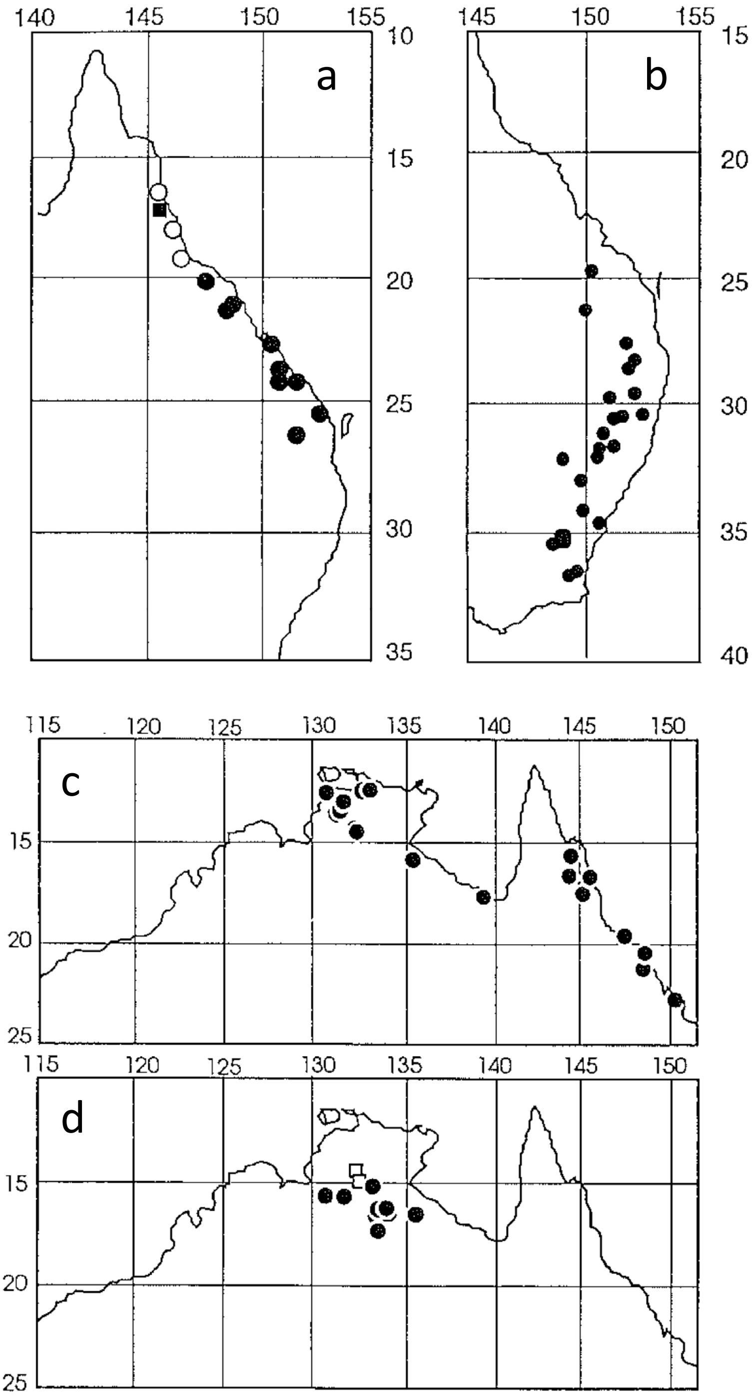

Figure B7: Distributions of endemic *Sorghum* species in Australia: (a) *S. nitidum*: ●awned, ○awnless, ■intermediate forms; (b) ●*S. leiocladum*; (c) ●*S. laxiflorum*; and (d) □*S. macrospermum*, ●*S. matarankense*. Figure reproduced with permission from Lazarides et al. (1991), (see CSIRO publication).

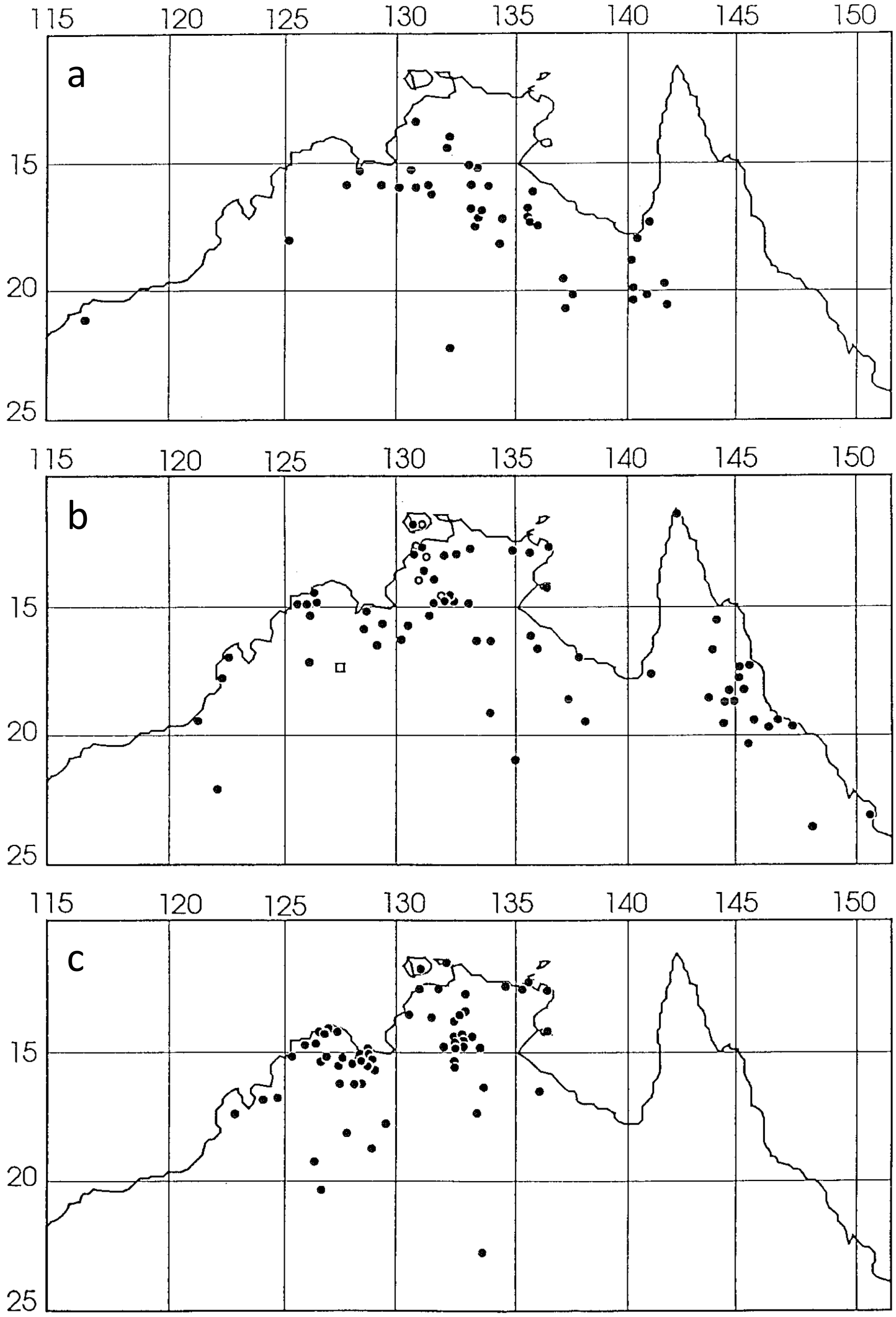

Figure B8: Distributions of endemic Australian *Sorghum* species; (a) ●*S. timorense*; (b) *S. plumosum*, ●var. *plumosum*, and ☐var. *teretifolium*, O unknown hybrid, probably *S. plumosum × S. intrans*; and (c) ●*S. stipoideum*. Figure reproduced with permission from Lazarides et al. (1991), (see CSIRO publication).

APPENDIX C WEED RISK ASSESSMENT

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

Relevant land uses (according to ALUM[5]):

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).

Unless cited, information in this WRA was sourced from The Biology of *Sorghum bicolor* (L.) subsp. *bicolor* (*Moench*) (Sorghum) (2024) and the references within this document.

[5] ALUM refers to the 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: high (> 1000 seeds/m^2) in all relevant land uses** A sorghum panicle can bear between 800 and 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(Rew et al., 2005). Assuming sorghum volunteers are controlled in intensive use areas, and that they produce the upper range of 6000 seeds per panicle, it is likely that more than 1000 seeds/m^2 are produced from volunteer sorghum in all land use areas.
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 USA.
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. Deliberate spread of volunteer sorghum plants by humans 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 roadsides, 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 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** Weedy sorghum species are a refuge for insect pests and diseases that affect cultivated sorghum and other crop species like sugarcane (Tropical Forages, 2020b) and volunteer sorghum would also be a compatible host. Volunteer sorghum is susceptible to conventional weed management practice, so the risk of volunteer 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 and 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.