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Australian Sunn Hemp (*Crotalaria juncea* L.) Strategic RD&E Plan

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'Sunn hemp will be recognised as a versatile, resilient, eco-friendly crop in Australia.'

1. Foreword

To be completed by Agrifutures Australia.

2. Executive Summary

Sunn hemp, *Crotalaria juncea* L., is a native of Bangladesh, Bhutan and India. It is drought-resistant, germinates easily, grows rapidly, and has the potential to become a widely planted crop in Australia.

Globally, sunn hemp is mainly grown as a fibre crop, due to its soft, slightly lignified and strong fibre traditionally used in the manufacture of ropes, strings, twines, floor mats, and fishing nets (Chee & Chen 1992, Sarkar et al. 2015). In the early 21st century, interest in sunn hemp increased as the fibre is both environmentally friendly and biodegradable compared with synthetic fibres. More recently, the interest has developed as sunn hemp was recognised as a valuable inter-, cover or green manure crop, for nematode (biofumigation) and weed control, as fodder or forage for stock, and as a biofuel and in pharmaceuticals (Balkcom and Reeves 2005, Cherr et al. 2006, Hazra et al. 2005, Mendonça et al., 2005, Cook et al. 2005, Ortis et al., 2015).

In Australia, interest has grown over the last 15 years, particularly for the sugar industry where sunn hemp can be grown as a fallow cover crop, potentially delivering a range of benefits including increased soil carbon and organic matter, reducing fallow periods and enhancing soil nitrogen through fixation, with benefits for the protection of the Great Barrier Reef; enhanced soil condition and nematode control; a biofuel source for sugar mills; a fibre crop; and a fodder and forage crop. Other industries, such as cotton, beef, and horticulture could also benefit from using sunn hemp in rotation or as in inter-crop, and it has the potential to grow as a fibre crop in it's own right.

The development of an RD&E Plan, the growing interest in sunn hemp, increased availability of high-quality seed and the enthusiasm for the formation of an industry body bodes well for its widespread use. AgriFutures Australia, identifying sunn hemp's potential and the increasing interest, commissioned the development of this Strategic RD&E Plan. Over 50 stakeholders ranging from producers, investors, advisors, government, sugar and fibre processors, and researchers contributed to the development of the Plan through the latter half of 2021. Together, an industry Vision, Mission and Goals were developed. Twenty-eight potential RD&E Activities were agreed and prioritised, each with Key Performance Indicators. Seven Activities were deemed a Very High priority for early investment including these top three to accelerate industry development:

- the formation of an industry body to drive the plan forward;

- quantifying the multiple environmental and production benefits of sunn hemp; and
- quantifying and optimising the nutritional value of sunn hemp as a fodder crop.

In the short term, sunn hemp can be a highly valued cover crop delivering multiple benefits to soil, as a biofuel and for fodder. In the medium term, there are many opportunities to develop sunn hemp for fibre and other products with adaptation and development of new technologies. Implementing this Plan will assist Australian agriculture enhance production and operational flexibility, and deliver a range of eco-benefits and potential new fibre products.

Vision

Sunn hemp is widely grown for multiple products and numerous environmental and production benefits, as an integral component of several cropping systems, with world leading processing options and products developed.

Mission statement

'Sunn hemp will be recognised as a versatile, resilient, eco-friendly crop in Australia.'

The Australian sunn hemp industry will address this mission by:

- Producing high quality seed.
- Developing high yielding management systems across a broad grower base.
- Forming a complementary component of multiple cropping systems, in particular sugarcane, as a rotation crop/green manure enhancing soil condition, controlling disease, and with the opportunity for dual use.
- Developing fibre extraction process/es.
- Developing innovative fibre products and associated manufacturing processes and facilities.
- Growing for fodder/forage across a range of production systems.
- Harvesting for biofuel.

3. Industry situation analysis

Background

Sunn hemp, *Crotalaria juncea* L., so-called due its bright yellow flowers and use in fibre production, is a leguminous crop of the family Fabaceae. It is a subtropical to tropical annual crop, that germinates readily, with a short growing period of approximately 120-140 days (Muscat et al. 2014).

i. Native range and cultivation

Sunn hemp is native to Bangladesh, Bhutan and India, where it has been cultivated for centuries (Sarkar et al., 2015; Cook et al. 2005). It is now widely cultivated across the world, including India, Bangladesh, Brazil, China, Korea, Pakistan, Taiwan, and North America (Cook et al., 2005; Schomberg et al., 2007). In its main areas of cultivation in India, sunn hemp is found from 17°N to 30°N and grows at altitudes between sea level and 1500 m, where average annual temperatures range between 15-27.5°C. In the USA, sunn hemp will not set seed consistently north of 28° N latitude (Anon. 1999). In Brazil, it grows from the Amazon belt to 22.5°S where the average annual temperature range is 18-27°C. Elsewhere, it is cultivated in areas where average annual temperatures are as low as 8.4°C. Although heralding from the tropics, it can be cultivated in cold temperate steppes providing there is a frost-free growing period of 2-3 months (Cook et al. 2005).

ii. Uses

Fibre production

Sunn hemp has traditionally been used for fibre production, which is extracted from the bark and used to make items such as twine and cord, canvas, fishing nets, camouflage nets (used in defence) as well as paper and pulp (Chee & Chen 1992; Sarkar et al. 2015). Sunn hemp fibre has also been used for currency notes in Brazil and India (Sarkar et al. 2015).

The stems contain about 40% fibre (Chee & Chen 1992), which has greater tensile strength and is more durable under exposure than jute. However, it is not as strong as hemp *(Cannabis saliva* L.) (Chee & Chen 1992). The fibre is also used in car components (Joseph Muscat pers. comm. 2021) and has been trialled as a replacement for cement with fly ash in concrete (Siddique, 2004).

Cover crop/Green manure

Sunn hemp is commonly grown as a green manure, inter crop and a cover crop. It is one of the most widely grown green manures throughout the tropics (Chee & Chen 1992), due largely to its ability to fix Nitrogen (N). When sunn hemp plant tissues decompose, the fixed N is mineralised and released into the soil and is available for subsequent crops (Mansoer et al. 1997; Marshall et al. 2002). Sunn hemp can fix nitrogen by symbiosis with root nodulating rhisobia (Mendonça et al., 2005), at approximately 50-60 kg N/ha within 60-90 days of cultivation and provides 60 kg N/ha to the soil when it is used as green manure (Chee & Chen 1992). Nitrogen concentrations of about 3% in hay and 5-10% in seeds have been reported from the former Soviet Union, but normally they are lower (Chee & Chen 1992).

Sunn hemp has the potential to improve soil properties, to build organic matter and sequester carbon in the soil. It can also be used for soil reclamation (Sarkar et al., 2015). The use of sunn hemp in rotation with sugarcane is becoming increasingly common internationally for the plants ability to fix N and the enhanced soil biodiversity which helps break disease cycles (Brown 2016).

Sunn hemp is used to great effect in wheat and rice rotations (Sarkar et al. 2015).

In vegetable and cropping systems with short rotations, sunn hemp is popular due to its short growing cycle and multiple benefits (Schomberg et al., 2007). Studies have shown that it may be beneficial planted before or after a vegetable crop to increase nutrient and organic matter in the soil (Cherr et al., 2006, 2007; Mansoer et al., 1997; Wang et al. 2005), or in tree crop scenarios to improve growth and disease resistance and as a wind break (Vincent et al., 2017).

It is also utilised as an intercropping species, in cereal fields, or for other cash crops. Sunn hemp has been used as an alternative to winter legume cover crops in the USA, where it has been shown to improve soil properties, reduce soil erosion, conserve soil water, and recycle plant nutrients (USDA, 1999). A study in Hawaii showed that cover crops including sunn hemp, planted as vegetative filters can effectively reduce sediment loads coming from idle and fallow fields on moderately steep volcanically derived highly weathered soils (Ryder & Fares, 2008).

Nematode, weed and pest management

Sunn hemp is a non-host or poor host for many plant-parasitic nematodes including Meloidogyne spp. and *Rotylenchulus reniformis* (Wang et al., 2002; Wang et al., 2001; Rotar & Joy., 1983, Ortis et al., 2015). Sunn hemp is therefore recommended for rotation with crops prone to nematode infection (Sarkar et al. 2015) such as potato, sugarcane and tobacco. The crop may also aid in reducing slug pressure in following crops by drying soil profiles (Anon. 2021).

Three field trials in Hawaii, United States of America investigated the effects of a synthetic nematicide, fluopyram, alone or in combination with a pre-plant sunn hemp cover crop, and a biological nematicide, azadirachtin combined with pre-plant sunn hemp on *R. reniformis,*

Meloidogyne spp. and free-living nematodes (Waisen et al., 2021). The study showed that while *Meloidogyne* spp. and *R. reniformis* can be managed better using fluopyram and azadirachtin, respectively, integrating with sunn hemp mitigated the negative impacts of fluopyram on soil health. Further, integrating sunn hemp with fluopyram increased zucchini yield by >2.3 fold, and with azadirachtin by >1.7 fold. Although no yield improvement was observed on tomato in one trial, integrating sunn hemp with azadirachtin and fluopyram increased tomato yield by 0.23 and 1.12 fold, respectively, in another trial. Marketable yield of sweet potato was increased by 4.5–6.4 fold in all the fluopyram treatments but in the sunn hemp plus azadirachtin treatment, was only increased by 61.5% (Waisen et al., 2021).

In pineapple crops on the island of La R´eunion, France, authorities have banned the use of pesticides for the management of soil-borne pathogens, including the nematode *R. reniformis* (Soler et al., 2021). A recent study showed that an environmentally friendly cropping system, which comprised the rotation of sunn hemp, pineapple, a natural grass fallow and eggplant (cash crop), consistently reduced the inoculum of nematodes. Nematode populations were reduced by 86.4%, 82% and 46.5% under pineapple, sunn hemp and grass fallow respectively compared to infestations of eggplant (3456 nematodes .100g^{-1} of soil) after several rotations (Soler et al., 2021).

Sunn hemp's vigorous growth and dense canopy, combine to impart good weed control (Maroyi, 2011; Cook et al., 2005) and increases diversity in crops grown in monoculture systems.

Sunn hemp flowers may provide nectar and pollen for pollinators and enhance biological control by providing habitat for natural enemies (Meagher Jr. et al., 2017, 2020). Field trials in Hawaii, USA showed that provisioning of an alternate host insect's eggs through flowering plants (provided by cowpea and sunn hemp) is an effective means for enhancing proovigenic parasitoids (*Trichogramma* spp.) (Manandhar & Wright, 2016). The increased parasitism of *Helicoverpa zea* eggs in corn crops planted adjacent to the flowering cowpea and sunn hemp was considered compatible with large-scale farming and did not require dramatic alteration of grower's practices (Manandhar & Wright, 2016).

Fodder and forage

Sunn hemp is commonly used as a fodder and forage. The foliage is a high protein source that can be used to supplement other feeds for cattle and sheep (Chee & Chen 1992). In a study in the USA, across several years, crude protein (CP) was greatest ($P \leq 0.05$) in leaves (281 g kg^{-1} DM) and lowest for stems (81 g kg^{-1} DM), 55 days after planting (Lepcha & Naumann, 2021) . Sunn hemp is shown to be a valuable source of forage without toxic effects (Mosjidis et al., 2012). The seed does not cause acute toxicity to domestic animals because it has only a small amount of the toxic pyrrolisidine alkaloids (Mosjidis et al., 2012) characteristic of the genus Crotalaria (Stegelmeier, 2011). Therefore, its presence as a feed contaminant does not pose a problem (Mosjidis et al., 2012).

Grazing is best prior to flowering to optimise the quality, palatability & recovery (Chee & Chen 1992). In Sri Lanka dried leaves, bark and boiled seeds are fed to cattle. Seed has been used as fodder in southern Africa and the former Soviet Union. It has also shown promise as a forage legume for intercropping with upland rice (Chee & Chen 1992). However, other authors recommend that sunn hemp seed should not be incorporated in animal diets because, depending on the amount in the diet and the length of time that the diet is fed, it may cause weight loss and potential death (Mosjidis et al., 2012).

Biomanufacturing feedstock

As sunn hemp has a high cellulose content and high crystallinity, it is a good biomanufacturing feedstock (Paul & Chakraborty 2018) and can be used for packaging materials, chemicals, plastics, fuel, and prebiotics (Bill Doherty pers. comm. 2021).

Biofuel and bioenergy

The identification of environmentally friendly and renewable sources of alternative energy is an area of global interest. Biodiesel produced from the seed of sunn hemp is considered a possibility after some modifications are made given the high water content and carbon capture and reuse (CCR) value of the oil (Dutta et al., 2014). The energy content of sunn hemp seed oil is 34.128 MJ kg^{-1}, slightly lower than that of gasoline (47 MJ kg^{-1}), diesel fuel (44.8 MJ kg^{-1}) and petroleum (42 MJ kg^{-1}), but higher than that of coal (32–37 MJ kg^{-1}). Other attractive qualities include the low sulphur content and H/C molar ratio fractions that are similar to some of the currently utilised transport fuels (Dutta et al., 2014)

A low-end value use of sunn hemp is in the co-generation of electricity. In a field trial in the USA, an average yield of 11 Mg ha^{-1} of dry biomass was obtained, which led to an energy yield of approximately 200 GJ ha^{-1} by considering a higher heating value of 19 MJ kg^{-1} (dw) (Cantrell et al. 2010). A field trial in Italy showed that intercropping led to improved qualitative feedstock characteristics for bioenergy applications (Zegada-Lisarazu et al., 2021). Mean biomass yields across two years were the highest for sorghum intercropped with sunn hemp at 23 and 19 Mg ha^{-1}, compared with pearl millet intercropped with sunn hemp and monocultures of all three crops. Further, sorghum intercropped with sunn hemp showed increased cellulose content (+17%) and reduced N (− 39%), Mg (− 54%), and Na (− 15%) contents. The authors concluded that intercropping-dedicated lignocellulosic crops may be feasible alternatives for providing a mixture of feedstocks with improved sustainability, yield stability, and biomass quality (Zegada-Lisarazu et al., 2021).

Sunn hemp as a rotation crop used for bioenergy in the sugarcane cycle provides potential to decrease environmental impacts of sugarcane biorefineries (Chagas et al., 2016).

Pharmaceutical and functional food

Crotalaria species, in general, contain a number of alkaloids, and other bio-active compounds, some of which are known for their biochemical, physiological and molecular (pharmodynamic) properties which can be exploited for the development of new drugs (Hazra et al. 2005). In Indo-China it is used medicinally to treat urticaria (hives) (Chee & Chen 1992).

Sunn hemp could also be a potential source of alternative protein and dietary fibre (Lalevash Moghaddam pers. comm. October 2021).

Performance characteristics of sunn hemp

i. Growth

Sun Hemp is an erect annual, up to 3.5 m tall (Cook et al. 2005). It is fast growing and under favourable conditions can reach a plant height of 1.2 m in 60 days and 1.8 m in 90 days (Cook et al. 2005). It has vigorous lateral roots and long taproot that can exploit deeply stored soil moisture. Sunn hemp is a short-day plant, with long day-lengths favouring vegetative growth, although daylength neutral selections exist (Cook et al. 2005).

A trial in a humid and warm location, showed that increasing the sunn hemp seeding rate from 20 to 40 plants m^2 increased the biomass production from 6.7 to 9.4 Mg ha^{-1}, while increasing the seeding rate from 40 to 80 plants m^2 increased the biomass from 9.4 to 10.5 Mg ha^{-1} (Collins et al., 2008). This suggests that biomass production plateaus, and that additional seed did not necessarily mean substantially increased biomass production at the higher seeding rates tested (Collins et al., 2008). Increasing seeding rates can have positive and negative effects in terms of economics, ecosystem services, and crop yields (Ruis et al., 2019). Lower seeding rates may be positive from an economic standpoint, particularly for costly seed, however, it may not be favourable for increasing soil C due to lower biomass input and/or less weed control (Ruis et al.,

2019).

ii. Physical and chemical properties

The physical and chemical properties of sunn hemp include low lignin content (4%), high cellulose (78.3%) and high glucose (80.3%).

iii. Genetics, breeding and pollination

Sunn hemp is largely self-incompatible and requires extensive cross-pollination (Cook et al. 2005), although self-compatible strains have been reported (Anon. 2003).

Successful efforts in breeding for self-compatibility have been reported (Ribeiro et al., 1977), however the development of self-compatible germplasm should be accelerated for the development of true breeding stable pure lines (Sarkar et al. 2015). A genetic study to determine the inheritance pattern of seed yield and plant height for sunn hemp showed that there is the possibility to exploit heterosis as long as pollination can be controlled via genetic mechanisms (Miranda 1991). Further, preliminary findings suggest that plant height (final) and basal diameter are positively correlated with stalk dry matter, suggesting that selections for these traits could result in high yielding cultivars (Cook and White, 1996; Kumar et al. 2008).

Pollination of the large yellow papilionaceous flowers of Crotalaria (Fabaceae) spp. occurs when bees land on the flower keel and wing petals and drive their tongues into the nectar found at the base of the standard petal (le Roux & van Wyk, 2012). Pollination of sunn hemp flowers generally requires large-bodied bees, such as *Xylocopa* spp. (Hymenoptera: Apidae) and *Megachile* spp. (Hymenoptera: Megachilidae) (Amaral-Neto et al., 2015; Jacobi et al., 2005; Meagher Jr. et al., 2019, 2020).

A wide range of cultivars and elite lines are available. India in particular has a wide range, with most developed for their fibre quality and production (Cook et al. 2005). There are also varieties that have been developed for forage or green manure (Sarkar et al., 2015), and there is scope for selecting for specific traits such as disease and pest resistance and high yielding varieties for fibre or forage.

iv. Seed and sowing rates

Sunn hemp is propagated by seed (Chee & Chen 1992). Most sunn hemp cultivars require seed inoculation in Australia. Peat inoculant is available from several inoculant suppliers. AGF Seeds produce a sunn hemp inoculant, with 1 pack treating 25kg seed (Brown 2020). Seed production of up to 1.8 T ha^{-1} has been reported (Cook et al. 2005). Although the pods are dehiscent, there is no indication of sunn hemp being dispersed to a major extent by seed (Cook et al. 2005).

Sowing rates of 40-45 kg ha^{-1} are used when it is sown as a forage crop or as green manure, but when it is sown for fibre, rates of 100-240 kg ha^{-1} are used (Chee & Chen 1992). In Australia, most crops grown for seed or as cover crops are sown at a rate of 10-20 kg ha^{-1} (Tony Matchett pers. comm. July 2021). Sunn hemp nodulates readily with native cowpea type rhisobia (Chee & Chen 1992), but there are other native rhisobia that are superior providing increased crop growth (Tony Matchett pers. comm. July 2021).

v. Soil

Sunn hemp does well on a wide range of soils provided they are well-drained, as it does not tolerate water-logging (Heuzé et al. 2018); tolerance of salinity is generally low but there have been reports of moderate tolerance (Cook et al. 2005). When it is grown for fibre, sunn hemp does better on fairly light textured soil (sandy loam or loam) of moderate or good fertility. For other purposes, it is possible to grow it on clay soils of low fertility, provided they are well-drained. On low-lying clay soils, vigorous growth occurs, but the fibre is coarser and the yields are lower (Chee & Chen 1992). A neutral range of pH is preferred (Sarkar et al. 2015) but sunn hemp can grow on soils with

pH ranging from 5 to 8.4 where phosphorus and calcium are available.

vi. Climate

Sunn hemp is adapted to hot, semi-arid and arid areas (Chee & Chen 1992) and is a drought-resistant species that can grow where average annual rainfall is as low as 200 mm (Heuzé et al. 2018). However, it thrives under high humidity (Heuzé et al. 2018). Sunn hemp can withstand light frost (not less than -2°C) without injury (Cook et al. 2005). Irrigation is necessary for maximum growth and nitrogen fixation, where rainfall is inadequate (minimum of 25 mm of water/week required) (Heuzé et al. 2018).

vii. Pest, disease and weeds

A range of pests and diseases may attack sunn hemp, although most don't cause economic damage. Pests at the seedling stage may require treatment, with seed treatments an option, however the crop typically outgrows most pests once it gets beyond the establishment phase. Pod-boring insects can reduce seed production and beetles of the genus Exora can cause serious defoliation (Chee & Chen 1992). In India and Australia, *Utetheisa pulchella* L. (Lepidoptera: Erebidae) can cause economic damage (Chee & Chen 1992). In Australia, the crotalaria podborer, *Argina astrea* Hübner (Lepidoptera: Erebidae) and the lucerne seed web moth '*Etiella*', *Etiella behrii* (Lepidoptera: Pyralidae) can cause economic damage to the seed pods (Joseph Muscat pers. comm. June 2021 and Tony Matchett pers. comm July 2021 respectively).

Diseases that impact the economic return from sunn hemp include vascular wilt, sunn hemp mosaic virus (also known as sunn hemp rosette virus and other names), and anthracnose (Sarkar et al. 2015). Tobacco streak virus (TSV; family Bromoviridae, genus Ilarvirus) has also been identified in India, and more recently Hawaii (Kong et al. 2018).

Sunn hemp has a vigorous and competitive growth habit, and rapidly produces a thick ground cover that smothers weeds, with most crops not requiring weed control (Brown 2016).

viii. Yields

Sunn hemp can be hand or mechanically harvested. The total green matter yields average from 18-27 T ha^{-1} with forage yields ranging from 5-19 T ha^{-1} (Chee & Chen 1992). Green manure crops sown after rice in Thailand, yielded 2 T ha^{-1} of high quality DM in 6-8 weeks (Chee & Chen 1992). Sunn hemp fibre yield (10 q ha^{-1}) is below that of other bast fibre crops like jute (25 q ha^{-1}) and mesta (20 q ha^{-1}) (Sarka 2015).

Sunn hemp industry globally

i. Annual production/Dimensions of the industry (volume, value, geography)

India followed by Bangladesh and Brazil are the largest producers of sunn hemp fibre (Sarkar et al. 2015), with Pakistan, China, and Korea also major producers (Bhandari et al. 2016); Taiwan, Africa (Sarkar et al. 2015) and the USA also produce sunn hemp. In India, annual production of fibre is around 18.8 thousand tonnes from 31,000 ha (Sarkar et al. 2015). There are no internationally recognised codes for sunn hemp, therefore it is difficult to obtain values for producing countries.

Sunnhemp Research Station, established in 1963 at Pratapgarh, India, is the only research station (ICAR-CRIJAF) globally that is focused on this crop (Sarkar et al. 2015).

ii. Varieties

Multiple sunn hemp varieties have been developed since the 1900's. K-12 yellow is considered one of the best varieties in India, a high-yielding variety developed for its fibre (Sarkar et al. 2015). In the 1970's, a day neutral variety, T-6, was developed that was suitable for green manure as well as for fibre. An elite strain SH-4 has more recently been released for its higher fibre yield potential (Sarkar et al. 2015).

In Australia, growers have accessed sunn hemp lines through Genebank (Tony Matchett pers. comm. July 2021), and have also brought in international lines including from Hawaii (Tony Matchett pers. comm. July 2021) and four separate suppliers across four geographically diverse international locations (Andrew McNaughton pers. comm. July 2021). It is likely that industry will select varieties specific to end-product requirements (e.g. fodder, fibre etc). Currently, seed increase is being carried out on an imported variety, but this will soon be replaced with new imported/selected lines, with plant breeders rights (PBR) established for them.

Sunn Hemp in Australia

i. Where can it be grown?

Although sunn hemp performs best in subtropical and tropical climates, it can be grown throughout Australia during the warmer months, with productivity directly proportional to heat and moisture (Tony Matchett pers. comm. July 2021). Sunn hemp grown in Queensland had a production time of approximately 120-140 days when planted early in the year (Muscat et al. 2014). Seed provided to Agriculture Victoria as a summer legume trial grew well, but did not achieve the levels of biomass observed in the north of Australia (Tony Matchett pers. comm. July 2021).

ii. Key market dimensions (domestic/export, import competition) and dynamics (growing steady or declining)

Domestic production has largely involved small-scale trials for biofuel across Australia, and in 2019 sunn hemp was valued at an estimated $0.1-0.5m (Coriolis 2020). Australia currently imports the vast majority of seed with a probable value of less than $1m. There are no international exports.

It is projected that by 2030, the industry will be valued between $2m and $5m, with modest domestic demand, however the growth trajectory is currently not clear (Coriolis 2020). Savannah Sun Foods forecasts limited export opportunity, but that by 2026, they will be producing sufficient seed to plant 200,000 ha across all end use market sectors nationally, thus expecting that sunn hemp will surpass $10M GVP by this time (Tony Matchett pers. comm. July 2021).

iii. Current uses and opportunities for Australian grown sunn hemp

Reduction in fertiliser

The use of sunn hemp in agricultural systems may allow for a reduction in the amount of nitrogen applied to the soil and thus reducing nitrogen runoff. This is particularly important in catchments (Zhao et al., 2021) of the Great Barrier Reef. A sugarcane crop is typically fertilised with 120 kg ha^{-1} N in the Herbert region of tropical Queensland (Lawrence di Bella, pers. comm. October 2021). Research shows that application of N can be reduced by 80-90 kg ha-1 following a sunn hemp cover crop. A Reef Trust Credit is currently being explored because of the N reduction (Lawrence Di Bella pers. Comm. October 2021).

Seed production and supply

Sunn hemp seed can be successfully and economically produced in the sub-tropics, thus providing a local seed supply option (Coriolis 2020), subject to the single biggest limiting factor, the lucerne seed web moth *E. behrii*.

Cover crop/green manure

Planting sunn hemp as a rotational crop on farm delivers a beneficial environmental outcome, reducing erosion and improving soil health for following crops (Muscat et al. 2014). Adding value at the farm gate also creates a profitable business which has direct beneficial social impact (Muscat et al. 2014). It can be used in between winter crops, planted as a cover crop after harvest or hay cutting. Sunn hemp may be planted into stubble prior to a cereal crop to provide soil cover, increase organic matter and fix N. There is potential to mix it with Tillage Radish to leave root

channels for following crops (Brown 2016). In sugarcane, sunn hemp may be grown between plantings to aid in breaking the disease cycle and fixing nitrogen after fields are terminated and prior to replanting. Sunn hemp could be used as a green manure in horticultural rotation, as a 45-60 day break crop for increasing organic matter with N fixation and potential nematode suppression. It could also be grown over short durations in the northern cotton system, to about 30 cm in height as a soil mulch/insulation and terminated before seeding cotton into 'cooler' soil (Tony Matchett pers. comm. July 2021).

Sunn hemp fits in well with the Australian sugarcane farming system enhancing the productivity of the following sugarcane crop, with a key advantage being the use of existing miller, harvester and grower infrastructure (Muscat et al. 2014, 2017). The potential benefits of cover crops during the sugarcane fallow period in the summer wet season in the Australian tropics include improved groundcover and protection against erosion, reduced NO_3^- leaching, increased carbon (C) inputs into soils and improvements in soil biological populations related to cane health (di Bella et al., 2021). A trial on a commercial sugarcane farm in Queensland, conducted over two seasons, showed that monocultures of sunn hemp (cv. Global sunn) had the greatest biomass in a drier than average season (>10 t dry matter ha^{-1}), soybean (*Glycine max* cv. Leichardt) produced the most biomass in a wetter than average season (5.3 t dry matter ha^{-1}), while mixed-species cover crops showed strong weed suppression, and were among, but not the top treatments for biomass production each year. Further, mixed-species cover crops accumulated substantial amounts of N in aboveground biomass, but the fate of cover crop N after termination in tropical environments requires further research. The authors indicated that the inclusion of multiple species in a short-term cover crop in the tropics where extreme weather events can occur should be considered as a risk mitigation strategy (di Bella et al., 2021).

While there has been a great deal of focus of the use of sunn hemp in sugarcane systems in Australia, the international literature suggests that there are opportunities for it to be explored in a range of systems including vegetables, pineapples and other agricultural crops. For example, it has been used a legume rotation crop with cotton in Kununurra. Another possibility is the use of sunn hemp as a high value legume in beef cattle production. It takes up to 2 years to breed cattle, especially on poor soils (David McNeil pers. comm. August 2021). Sunn hemp could be used as an irrigated crop in rotation, and mixed with maize and cotton seed, and fed to stock (David McNeil pers. comm. August 2021). Sunn hemp is also being used as an inter-crop under lychees, longans and avocados, where it is harvested and placed under the trees (Lawrence Di Bella pers. comm. October 2021).

Sunn hemp could also be planted under dryland saline conditions as an annual summer crop, where perennial lucerne is currently utilised, however salt tolerant varieties need to be identified (Tony Matchett pers. comm. August 2021). There is also interest in using sunn hemp to remediate or enhance production limited soils in WA – utilising sunn hemp's ability to add nitrogen and organic matter, and potentially break us the subsoil (Ken Sharpe pers. comm. October 2021).

Fodder

Another use is in summer fodder production, for grazing or hay as a high protein summer feed source for cattle, sheep and goats or as a single cut high protein summer hay crop. Depending on the region, moisture content at harvest and the market, sunn hemp could be produced as silage, haylage, hay or pelletised (Michael Gray pers. comm. October 2021). Further, sunn hemp may be planted as a companion to sorghum and millet grazing and hay crops to add protein and quality, fix N and add diversity.

Feed tests are underway with sunn hemp as a forage crop for cattle (Jack Robertson pers. comm. August 2021). Early results suggest that the protein and energy was good, however the palatability/digestibility was quite poor. Further research is identifying the best time to harvest sunn hemp for forage (Jack Robertson pers. comm. August 2021). Recent results from a trial planting in

north Queensland show 21% crude protein content and 3.43% N (dry matter basis; Tony Matchett pers. comm. October 2021). In another Queensland trial, analysis of the seed and flowers showed effectively no toxicity (0.80 mg kg^{-1} Prussic Acid and 116 mg kg^{-1} Nitrate), with the nutritional value for stock to be assessed (Neil Maitland pers. comm. October 2021).

Biofuel

Sunn hemp has potential as a biofuel in Australia, revealed through both laboratory and pilot studies, however it is yet to reach commercial scale (Coriolis 2020). For example, sunn hemp is a feasible option to replace coal feedstock for electricity generation. At the Racecourse Mackay Sugar co-generation facility, sunn hemp was used to effectively power the steam boiler to generate electricity (Muscat et al. 2014). It was shown that 90,000 tons of fibre was needed to allow for the total replacement of coal. Further, the fibre feedstock would attract a green certificate value as sunn hemp is a renewable source. Mackay Fibre Producers showed that sunn hemp can move through the bagasse handling system with chlorine at an acceptable level (Muscat et al. 2014).

A newly constructed green energy power plant at the MSF Sugar Tableland Mill converts 100 per cent renewable sugarcane fibre, i.e., bagasse, into green energy (Anon. 2021). The power plant produces 24 megawatts of electricity, which is enough to power 26,280 homes, equivalent to the entire population of the Queensland Tableland region. To complement supplies of bagasse, MSF Sugar are actively exploring additional crops that will stabilise power production for 12 months of the year (Anon. 2021). This mill could potentially utilise 40,000t of sunn hemp alongside their bagasse (Tony Matchett pers. comm. July 2021).

The high-end value of fibre is in strong demand in the world (Muscat et al. 2014). The market strength is considered high, with markets in aviation, defence and automotive all increasingly developing products derived from fibre (Muscat et al. 2014).

Current major limitations of producing sunn hemp in Australia

- ***Pre-harvest***
  - ***Seed***

The lack of Australian seed availability and the biosecurity risk associated with the import of seed has been a major limitation and driving factor for domestic production of seed. Savannah Sun Foods are currently addressing this issue by producing locally grown seed, suitable for Australian conditions and uses, for sale to producers (Tony Matchett pers. comm. July 2021).

  - ***Lodging***

Sunn hemp may lodge at various stages through its growth, with plants taller than 3.5 m more vulnerable; erectness of the crop most evident when the weather was fine and hot (Muscat et al. 2014).

  - ***Pests including impact on seed supply***

In sunn hemp seed crops planted in Australia, the crotalaria moth, *U. pulchella,* crotalaria pod borer, *A. astrea* (Muscat et al. 2014) and *E. behrii* considerably impact seed production (Tony Matchett pers. comm. July 2021). *Etiella behrii* is the seed pest of most concern and although a spray program was developed for this pest, it was intensive and expensive (Joseph Muscat pers. comm. 2021). However, more recently permits for chlorantraniliprole (PER90762) and deltamethrin (PER90763) have been obtained with the APVMA for the control of *Etiella* in sunn hemp grown for seed. Crops grown for their fibre, not seed, are not at risk from these pests with the exception of *U. pulchella* which also feeds on the foliage of sunn hemp and may cause losses in fibre yields (Sarkar et al. 2015).

An advantage of sunn hemp over several other crops including sorghum, *Sorghum bicolor* L. is that it is a poor host for fall armyworm, *Spodoptera frugiperda* (J. E. Smith) and several other important

moth pests (Meagher et al., 2004).

- ***Disease***

Sunn hemp mosaic virus occurs naturally in leguminous plants in Australia (Varma 1986) with some variants causing severe leaf distortion (Verma and Awasthi, 1976). Tobacco streak virus (TSV; family Bromoviridae, genus *Ilarvirus*) reportedly infects sunn hemp in India where it is associated with chlorotic and/or necrotic spots on leaves, veinal and bud necrosis, and sudden wilting and death of young plants (Prasad et al., 2005). Recently, TSV was reported in Hawaii, and while its entry pathway is unknown, infected seed represents a possibility, with local thrips populations providing a vehicle for short-distance dissemination in the state (Kong et al., 2018). As Australia currently imports all of its sunn hemp seed, this disease is of biosecurity concern. Similarly, other diseases not present in Australia will present a biosecurity threat if sunn hemp is exposed along the import pathway.

- ***Weeds***

A trial in Queensland showed reduced weed pressure once the sunn hemp crop had a canopy, although some broad leaf vines remained evident in the crop (Muscat et al. 2014). Herbicides have been identified as safe for use in sunn hemp and permits will be sought from the APVMA so that they can be utilised in the crop if required (Tony Matchett pers. comm. July 2021).

- ***Harvest and Post-harvest***

- ***Pollination***

It is not clear what pollinator species are important for the pollination of sunn hemp in Australia: this is an area that warrants research.

- ***Harvestability***

A key trait of sunn hemp shown in a trial in Queensland is that it will stand ready for harvesting for an extended period without any deterioration, thus reducing the risk of loss at harvesting.

However, harvesting sunn hemp for forage has proved difficult when the crop is lodged. While a 6 metre kemper front was unable to present the sunn hemp stalks to the chopper mechanism, a cane harvester, which are designed to manage lodged sugarcane crops was effective (Muscat et al. 2014).

- ***Processing, including facilities***

The ability to source mechanically separated fibres in large volumes is limited around the world (Muscat et al. 2014). At present, Germany are world leaders in the dry separation process of fibre at 5 t ha^{-1}, however, increases in efficiency and cost-effectiveness are key for this to be commercially viable. A study in Queensland showed that it is possible to separate the sunn hemp fibres utilising components of sugar mills (Muscat et al. 2014). The next step is to develop a pilot separation unit which could lead to a commercial separation unit with anticipated separation rates that will exceed 50 t ha^{-1}, however this has not yet occurred. It is recommended that sugar mill components are investigated to separate fibre using a wet separation process to obtain high rates of fibre separation (Muscat et al. 2017). Japan are exploring a wet separation process that could take it to over 100 t ha^{-1} (Joseph Muscat pers. comm. 2021).

- ***Logistics and transport***

The freight costs are a limiting factor impacting the use of sunn hemp as a feed stock for co-generation (Muscat et al. 2014). In the Mackay Sugar region, it is feasible that the rail transport system currently operated for sugarcane could dramatically reduce transport costs. However, the benefits are reduced with the capital investment required to remove the product from the tippler and present it to the storage area or directly into the boiler (Muscat et al. 2014). Therefore, positioning infrastructure close to production areas will be advantageous.

The logistic and transport for other sunn hemp uses, including fibre production, have not been considered. However, it is likely that industry will position the infrastructure for other processing uses near to sugar mills, or close to production areas (Tony Matchett pers. comm. July 2021). This is unlikely to be an issue for uses such as fodder.

Strengths, Weaknesses, Opportunities, Threats

STRENGTHS

- Fast growing, drought tolerant, nitrogen-fixing, eco-friendly crop, that germinates readily and grows quickly, with economic and technical feasibility studies demonstrating its potential.
- A legume that can potentially fix large amounts of organic nitrogen (300 kg ha^{-1}), especially if appropriate rhizobia are available, to enhance productivity of succeeding crop.
- Ability to accumulate biomass of over 100 t ha^{-1} (approximately 50-60 t dry matter).
- Potential dual use as green manure and a fibre crop: after the fibre crop is harvested, the tender top portion (30 cm from top) can be incorporated into the soil.
- Biofumigation properties, especially to root rot nematode.
- Herbicides are infrequently required, typically only at establishment, as the crop effectively suppresses weeds. If required, it is tolerant of Verdict herbicide which may be used in sugarcane systems.
- Open up land for other crops by improving soil health (e.g. adds organic carbon and nitrogen to the soil) and shading out weeds.
- Could add value to all sectors of the sugar industry including the growing, harvesting and milling sectors, thus providing a competitive robustness for the Australian sugar industry.
- A feedstock with many applications; its high tensile strength and light weight material makes it an attractive alternative to fossil based non-renewable materials.
- Potentially a high feed value for livestock.
- Industry has strong linkages with research organisations including Universities and State Governments.
- Permits available (through the APVMA) for *Etiella* control in seed crops.
- A non-host for the recent invasive exotic fall armyworm, *Spodoptera frugiperda*, and several other moth pests.

WEAKNESSES

- No seed produced domestically, and significant biosecurity risks with import.
- Broad lack of producer knowledge and expertise on production parameters.
- Economics of growing seed domestically didn't stack up (grower return expectations) for the Ord region.
- Lack of a sunn hemp specific inoculant.
- Lack of suitable cost-effective control options for the lepidopterans, *Etiella*, *Argina astrea and Utethesia pulchella.*
- Lack of economic assessment of soil health benefits (e.g. N, C, biofumigation)
- Challenging to harvest in the wet – access to the paddock.
- Processing system for fibre, specifically the inability to extract the fibre from the skin at a cost-effective rate; separation of fibres is the single biggest issue for producing fibre!

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- The economics for maintaining production of fibre crops to meet current markets, as competition for land with higher value crops typically overrides the production of fibre crops, which tend to show low margins, is unknown.
- Availability of fibre as a feedstock in commercial quantities is a limiting factor globally.
- Possibility of movement of pathogens/insects from sunn hemp to inter-crops, or crops within the area, is unknown.

OPPORTUNITIES

- A well strategised and targeted RD&E plan, that provides pathways to high value products utilised for identified key markets.
- Multiple value add opportunities for existing copping systems:
    - Cover crop/ break crop (nitrogen fixing benefits, break disease cycles e.g. between sugarcane plantings)
    - Source of high nitrogen grazing fodder
    - Dry-matter feedstock for biofuel (ethanol) generation
    - Fibre use in building materials, automotive and aviation components, body armoury, paper, textile and geo-textile products
    - pharmaceutical products
- Diversification of farm businesses, especially single-commodity producers including fibre cropping and processing that will produce value-add end products. Synergies between sugarcane and a fibre plant are considerable.
- Government programs that incentivises pathways to commercialisation.
- Utilisation of linkages and partnerships with industry and research organisations, including Universities, to commercialise RD&E findings.
- Selection for improved lines suitable for Australian conditions, that meet production and customer needs (increase biomass and quality).
- Sunn hemp fits in well as a multi-species fallow; competes well with other species.
- During heavy flowering periods, sunn hemp attracts beneficial insects and could be used in habitat management.
- Inter row cropping between orchards, particularly organic orchards (currently plant wheat to minimise nematodes). Potential wind-break crop in orchards.
- Explore options to increase the efficiency and cost-effectiveness of dry and wet fibre separation processes.
- Utilisation of current infrastructure (such as sugar milling equipment, cane transport systems and cane harvesting equipment) and processing infrastructure to increase efficiencies (e.g. sugar industry factories).
- Identification of key markets, understanding customer requirements and development of clear pathway to commercialisation.
- Development of an industry body and associated website, newsletter/magazine and regular industry conferences.
- Development of industry standards and certification.
- In sugarcane growing areas, mills require a consistent high supply of biomass feedstocks – has the potential to replace bagasse at power plants.
- Eco-friendly benefits of enhanced soil carbon, enhance cover crop and reduced N inputs may reduce impacts on the Great Barrier Reef.
- Educate sugar milling companies on benefits of incorporating sunn hemp in cane production system.
- Development of biofertiliser range by combining milling bi-products with sunn hemp.

THREATS

- Requires warm nights (+25°C) for optimal seed production; a balance between temperature and summer rainfall is a challenge.
- Risk of biosecurity incursion with the import of seed.
- Difficulty in routinely propagating and produce planting seed on the east coast of Australia due to *Etiella.*
- Inability to cost-effectively separate fibres.
- Competition with cheaper synthetic fibres.
- Not financially viable for biofuel.
- Competition with other forms of alternative cropping, e.g. safflower, other forms of mustards/brassicas for biofumigation etc, and competition with high value commercial crop production, e.g. soybeans.

4. Industry consultation process

This sun hemp Strategic Research, Development and Extension (RD&E) Plan has been developed in consultation with a diverse group of key stakeholders, the Sunn Hemp Industry Reference Team (SHIRT). The SHIRT was established in June 2021 and expanded through the life of the project. Over 50 individuals were identified through the proposal and development phase with AgriFutures Australia, industry and project partners, comprising:

- Consultant/advisor: 14
- Industry – grower: 15
- Industry – processor: 3
- Industry – supplier: 6
- Industry – association: 4
- Research Investor: 2
- Researcher: 11
- Government: 10

In June 2021, the SHIRT was contacted by email to introduce the project (it's objectives, phases and timelines), the funders and the project team.

The first stage was an electronic survey to establish a baseline understanding of the extent of use and knowledge about sunn hemp, the level of interest, and the challenges and opportunities. Concurrently, and then using the survey data, the project team prepared the first draft of the Situation Analysis and Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, to be reviewed by the SHIRT. Three 'interview' style online workshops were held for the SHIRT in early August to:

i. Provide feedback on the industry situation analysis and SWOT.
ii. Develop a 10-15-year Vision and Mission.
iii. Develop the Goals and Strategies.

The first full draft of the Strategic RD&E Plan was subsequently prepared including revision of the Situation Analysis and SWOT, and development of the Goals, Strategies, Activities and Key Performance Indicators. The foundations of a Communication and Extension (C&E) Plan were also developed.

Three workshops were then held in early October, with face-to-face workshops in Brisbane and Cairns, followed by an online workshop. In total, 19 SHIRT members attended. In addition, follow up conversations were held with three SHIRT members who were unable to attend workshops. The project team also initiated conversation with senior management in areas of Queensland

Department of Agriculture and Fisheries (QDAF) not currently represented on the Endorsement Group to enhance engagement and input. Combined, these SHIRT members became the 'Endorsement Group' who prioritised each of the 28 Activities.

Additionally, senior members of Sugar Research Australia (SRA) were engaged to ensure understanding of the opportunity, development of the Plan and potential next steps.

Subsequently, the endorsement draft of the Plan was sent, and the endorsement group invited to an online briefing and endorsement meeting in early November. …

5. Industry Strategic RD&E Plan on a Page

Vision

Sunn hemp is widely grown for multiple products and numerous environmental and production benefits, as an integral component of several cropping systems, with world leading processing options and products developed.

Mission statement

'Sunn hemp will be recognised as a versatile, resilient, eco-friendly crop in Australia.'

The Australian sunn hemp industry will address the mission by:

- Producing high quality seed.
- Developing high yielding management systems across a broad grower base.
- Forming a complementary component of multiple cropping systems, in particular sugarcane, as a rotation crop/green manure enhancing soil condition, controlling disease, and with the opportunity for dual use.
- Developing fibre extraction process/es.
- Developing innovative fibre products and associated manufacturing processes and facilities.
- Growing for fodder/forage across a range of production systems.
- Harvesting for biofuel.

Goals

Agronomic challenges – growing sunn hemp with the variety selected and managed according to product/use/cropping system for optimal benefit.

- Varieties and cultivars selected, and seed produced in Australia
- Planting techniques (seeding rate, inoculation, irrigation) are well understood
- Weed control is managed early in establishment phase
- Pests are managed – especially *Etiella* for seed production, IPM systems identified
- Develop and optimise the use of sunn hemp as a rotation across multiple cropping systems
- Adapt existing or develop harvest techniques to suit sunn hemp
- Understand and quantify benefit from N fixation, increased carbon/organic matter, biofumigant properties, root aeration, soil conditioner, reduced erosion in cropping systems.

Fodder and forage – develop the opportunity to use sunn hemp as a fodder and forage crop

- Toxicity management is in place to understand and minimise risk
- Nutritional value is understood and optimised as needed

Biofuel – develop options to utilise sunn hemp for biofuel

- Transport and logistics assessed and optimised to localised/regional system
- Economics and environmental credentials of bioenergy system(s) assessed

Fibre and other products – develop extraction, logistics and innovations for sunn hemp

- Transport and logistics assessed and optimised to regional processing
- Fibre extraction techniques developed/optimised, including investigation of sugar mill components to separate fibres
- Innovative fibre products (biobased products such as bioplastics and biocomposites (e.g., biopolyethylene), chemicals (e.g., 5-chloromethyl furfural, levulinic acid), pharmaceuticals (e.g., phthalide intermediates), packaging materials (including nanocellulose) and hempcrete) are developed.

Industry capacity, community awareness and acceptance, industry body to support industry growth

- Industry capacity and capability is developed, including for agronomists and consultants
- R&D capacity is developed to support industry, especially in the innovative fibre products field.
- The agricultural community in the relevant growing regions is informed, engaged and supportive.
- Good practice guidelines are developed in concert with relevant cropping systems.

The road ahead

The Sunn Hemp RD&E Strategic Plan detailed below is nominally a five-year plan. However, achieving the 2027 Goals is contingent upon many factors, including the establishment of a group to drive the plan forward and the level of funding and investment that is secured to advance sunn hemp as a profitable component of a production system, or a product in its own right.

Achievement towards the Vision and Goals can be monitored through the life of the Plan, and evaluated in the final year, using the Strategies, Activities and Key Performance Indicators. Each Strategy and Activity in the Plan directly links to the Goals. Each Activity describes potential RD&E investment area/s, that when completed and combined will deliver on each Strategy. Each Activity includes one or more key performance indicators (KPIs) and the ideal timeframe in which the KPI would be completed.

In addition, and acknowledging that funding may be limited, each Activity is prioritised as Very High, High, Medium and Low according to its relative importance to achieving the industry's Vision and Mission.

For sunn hemp to become a viable industry in its own right, an industry leadership group or association should be formed and take ownership of the RD&E Plan. The industry leadership should co-ordinate the plan's implementation, including seeking funding for Activities.

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6. RDE Plan Body

Goal 1. **Justification**	**Agronomic challenges** The industry needs access to a reliable source of clean seed that is produced in Australia where feasible. The variety chosen by a producer will need to be selected and then managed according to product/end use and the cropping system to optimise production and benefit. Growers need to understand how best to produce and harvest the selected variety of sunn hemp across growing regions and under various conditions.
STRATEGY 1.1	Varieties and cultivars selected, seed produced in Australia, and pollination enhanced.
Activity 1.1.1	Select a range of varieties and cultivars suited to product/end use; import seed as required. KPI: (ongoing) Identify varieties/cultivars suited to products/end use KPI: (year 1) Development of a seed certification scheme by adapting existing standards used for other crops Priority: Very High
Activity 1.1.2	Develop seed production systems including management of pests and identification of optimal soil types. KPI: (ongoing) Establish seed production systems and capabilities including knowledge of seeding rate, pest management, soil and water requirements for production. Priority: High
Activity 1.1.3	Develop an understanding of enhanced pollination strategies. KPI: (year 2) Develop knowledge of key and potential pollinating species and management strategies (that consider nutrition, pest pressure etc) to enhance pollination. Priority: Low
STRATEGY 1.2	Potential geographical range for production and suitable soil types identified, incorporating existing information, grower surveys and trials.
Activity 1.2.1	Determine the potential geographic range of sunn hemp, taking into account climate and incorporating international data. KPI: (year 1) Potential growing regions identified and key successful parameters recorded, including identifying potential regions when removing key constraints (e.g. water). Priority: Medium
Activity 1.2.2	Identify the soil types and soil condition (abiotic and biotic) suited for sunn hemp in Australia from existing information, grower surveys, previous trials, and new trials, as required.

	KPI: (year 1) Suitable soil types identified. Priority: High
Activity 1.2.3	Investigate whether there are varieties/cultivars with salinity tolerance suited to Australian conditions, including in comparison with sugarcane. KPI: (year 3) Varieties/cultivars with salinity/sodic tolerance identified. Priority: Low
STRATEGY 1.3	Planting techniques (seeding rate, inoculation, irrigation) are well understood.
Activity 1.3.1	For each production system, develop and refine planting techniques to optimise establishment, including seeding rate and density, inoculation and irrigation. KPI: (year 2) Preferred inocula identified (including native rhizobia) and available to industry. Priority: High KPI: (year 2) Establish the seeding rate for each end-use. Priority: Low
STRATEGY 1.4	Weed challenges early in the establishment phase are understood and management options developed and communicated.
Activity 1.4.1	Document current known and identified weed challenges at a district level, develop management options and disseminate information. KPI: (year 2) Information is collated on weed management and application for APVMA permits for key weeds are submitted. KPI: (year 2) Current and new knowledge for weed management in the establishment phase is collated and published in good practice guidelines. Priority: Very High
STRATEGY 1.5	Water use and requirements, including limitations are understood.
Activity 1.5.1	Identify research gaps and undertake trials on crop water use through the life cycle to optimise production and product quality and develop good practice guidelines to manage. KPI: (year 3) Comparative trials on water use and needs to identify the best cover crop under different systems and regions. KPI: (year 5) Develop good practice guidelines for water use, accounting for product/end use. Priority: Low
Activity 1.5.2	Investigate tolerance to water logging and drought through life cycle. KPI: (year 3-5) Performance trials completed including waterlogging and drought assessments.

	Priority: Low
STRATEGY 1.6	Pest and disease are managed in production systems – especially for *Etiella behrii*, but also *Argina astrea* and *Utethesia pulchella.*
Activity 1.6.1	Develop integrated pest, disease and weed systems for sunn hemp crops. KPI: (year 2/3) Integrated pest, disease and weed systems trialed in key production systems. Priority: Low
Activity 1.6.2	Develop and implement pest and disease management options for sunn hemp seed crops. KPI: (year 1) Integrated pest and disease management options reviewed, documented and shared with industry. KPI: (as required) Information is collated on pest management and application for APVMA registration. Priority: High
STRATEGY 1.7	Sunn hemp established as a viable rotation crop option for multiple cropping systems.
Activity 1.7.1	Develop and optimise the use of sunn hemp as a rotation crop across multiple cropping systems. KPI: (year 1) Investigate opportunities for incorporation of sunn hemp as a rotation crop across multiple cropping systems. Priority: Very High KPI: (year 4) Undertake integrated cropping system projects in identified systems, such as cotton (e.g. in Kununurra), horticulture, grains, mixed pasture and beef sectors. Priority: High
STRATEGY 1.8	Harvest techniques to suit sunn hemp production systems and end-use, have been developed or adapted.
Activity 1.8.1	Develop and adapt techniques for harvesting sunn hemp, suited to each production system and end-use. KPI: (year 2) Cost-effective mechanical techniques established and published (e.g. fact sheet) for harvesting sunn hemp for bioenergy, fodder and forage, and fibre KPI: (year 1) Cost-effective mechanical techniques established for harvesting seed Priority: Medium
STRATEGY 1.9	The benefits of sunn hemp from N fixation, increased carbon/organic matter, nematode and disease management, root aeration, soil conditioner, soil health (abiotic and biotic) and reduced erosion in various cropping systems is

	quantified, including economic benefit in marginal and productive lands.
Activity 1.9.1	Research the benefit from N fixation, increased carbon/organic matter, nematode and disease management, root aeration, soil conditioner, soil health and reduced erosion, and quantify economic value of benefits. KPI: (year 3) Assessments of soil N, soil C/Organic Matter benefits completed under at least three cropping and management systems. KPI: (year 3) Assessments of enhanced nematode and disease management, root aeration, soil conditioning and reduced erosion benefits completed under at least three cropping and management systems. KPI: (year 4) Economic assessments of benefits completed. Priority: Very High
Goal 2 Justification	**Fodder and forage.** Sunn hemp can be used as a forage and fodder crop with an enhanced understanding of the potential benefits that can be derived, and the potential risks and how they can be managed.
STRATEGY 2.1	The nutritional value of sunn hemp is understood and optimised during production
Activity 2.1.1	Quantify and optimise the nutritional value (nitrogen, fat, energy, protein, palatability) of sunn hemp when used as forage or fodder. KPI: (year 1) Engagement with food and fodder distributors, to identify value of sunn hemp per tonne (pelleted/square bale etc). KPI: (year 3/4) The nutritional value of sunn hemp varieties (based on market use) produced under Australian conditions and a range of abiotic stresses is assessed and published. KPI: (year 4/5) Management systems are developed to optimise forage/fodder value, e.g., timing of harvest. Priority: Very High
STRATEGY 2.2	Understand the role and potential for inclusion of sunn hemp in the diet of livestock, and develop appropriate feeding strategies, including whether used as silage, haylage, hay, or pelleted.
Activity 2.2.1	Identify best practice use of sunn hemp when fed to livestock, including limiting proportion of ration, timing of harvest, breeding low toxin sunn hemp and inoculation of livestock as appropriate. KPI: (year 5) Studies on the optimal feeding strategies, including digestion (e.g. methane production) for livestock undertaken and published. KPI: (year 5) Identify the minimum scale of production required for economic viability, working with QDAF and Meat & Livestock Australia (MLA). Priority: High
Goal 3	**Biofuels.**

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Justification	Sunn hemp produces significant amounts of biomass that can be used as a new feedstock in bioenergy systems, replacing fossil fuels or other energy sources. Sunn hemp can be used as a feedstock for processing into advanced diesel-like biofuel. Biofuel can be produced from sunn hemp through fermentation of sugars and fibre or through hydrothermal liquefaction technologies, (or pyrolysis) from the whole biomass. Densification of biofuel is required before use.
STRATEGY 3.1	The economic and environmental credentials of sunn hemp for biofuel are quantified.
Activity 3.1.1	Undertake life cycle assessment (LCA) for using sunn hemp as feedstock in existing bioenergy systems, especially for use in sugar mills/refineries as a replacement for fossil fuel or bagasse. KPI: (year 3) Further case studies of potential to use sunn hemp for bioenergy in sugar mills/refineries, including feasibility and long-term impact on sugarcane milling infrastructure KPI: (year 4/5) LCA of using sunn hemp as bioenergy, including a comparison to other feedstock, assessing calorific value, energy production and GHG balance using contemporary LCA modelling for other biofuels. Priority: Medium
Activity 3.1.2	Explore potential for using sunn hemp as a biofuel, including chemical properties, scale of plantings, logistics and economics. KPI: (year 3) Characterise Australian-grown sunn hemp, including agronomic performance and end user preferred traits, for potential use as biofuel KPI: (year 3) Explore interest to use sunn hemp with fuels industry and government. Priority: Low
STRATEGY 3.2	Transport and logistics assessed and optimised to localised/regional bioenergy production
Activity 3.2.1	Research transport and logistics options for localised bioenergy production to assess practical and economic feasibility incorporating relevant infrastructure, e.g. sugarcane. KPI: (year 2) Identify how to overcome the challenge of bulk density (densify). KPI: (year 2) Identify the cost/tonne to transport via road or rail from harvest to mill/processing facility (that could be incorporated in a feasibility study). Priority: Medium
Goal 4 **Justification**	**Fibre and other products** Sunn hemp's characteristics make it particularly suited to the production of fibre products, and potentially innovative new manufactured fibre products and as an alternative protein.
STRATEGY 4.1	Fibre extraction techniques reviewed and developed/optimised, including investigation of sugar mill components to separate fibre and mechanised

	decortication systems.
Activity 4.1.1	Develop new, and enhance existing fibre extraction techniques including those used in other industries (e.g. Industrial hemp) and consider options to increase the efficiency and cost-effectiveness of dry and wet fibre separation processes, and existing manufacturing and mechanised processes. KPI: (year 2/3) Identify the most suitable existing dry and/or wet fibre separation technology for Australian systems. KPI: (year 2/3) Develop at least two new fibre extraction R&D projects. Priority: Medium
STRATEGY 4.2	Transport and logistics assessed and optimised to regional processing and infrastructure
Activity 4.2.1	Undertake economic optimisation modelling of transport and logistics to assess practical feasibility of developing regional separation facilities. KPI: (year 1) Feasibility study to identify requirement for developing existing infrastructure (e.g. sugarcane industry) or creating new infrastructure. KPI: (year 2) Modelling and optimisation complete for three regions, including economies of scale. Priority: Very High
STRATEGY 4.3	Innovative fibre/biobased products developed: such as bioplastics and biocomposites (e.g., biopolyethylene), chemicals (e.g., 5-chloromethyl furfural, levulinic acid), pharmaceuticals (e.g., phthalide intermediates), packaging materials (including nanocellulose), hempcrete, and functional food/protein.
Activity 4.3.1	Identification of existing (watching technology brief) and research new fibre and biobased products (noting this will be varietal dependent). KPI: (year 5) Two new products developed as proof of concept, that demonstrate a competitive advantage (physical and chemical properties) over other fibre crops Priority: Low
Goal 5 **Justification**	Industry body, capacity and community awareness In order to rapidly grow the production of sunn hemp, the productivity and eco-benefits of sunn hemp need to be widely known in the community, generating support for its widespread use. A key factor in driving growth of a sunn hemp as industry will be the establishment and leadership of a proactive, representative and resourced industry body.
STRATEGY 5.1	An industry body is developed and is actively leading industry development including ownership of the RD&E Strategic Plan. The body needs to include stakeholders from all parts of the industry, including seed producers, growers, agronomists, processors and researchers.
Activity 5.1.1	Establish industry body representative of the value chain, with clear role,

	mission and resources. KPI: (year 1) New industry body established including exploration and identification of external funding. Priority: Very High
STRATEGY 5.2	Industry capacity and capability is developed, including for agronomists, consultants and growers.
Activity 5.2.1	Develop and deliver accredited training programs for industry. KPI: (year 2) Develop training program, including collation of existing and new knowledge. KPI: (year 5) Ten accredited agronomists/consultants/growers. Priority: Medium
STRATEGY 5.3	RD&E capacity is developed to support industry, especially in industry field trials and the innovative fibre products field.
Activity 5.3.1	Industry body to work with universities, other research providers and industry to develop sunn hemp-related post-graduate research and field trial opportunities. KPI: (year 5) Three post-graduate students supported (for example with industry co-investment in scholarships) to complete sunn hemp industry specific activities. Priority: Low
STRATEGY 5.4	The community in the relevant growing regions is educated, engaged and supportive.
Activity 5.4.1	Develop communication products around management, potential and multiple benefits of sunn hemp. KPI: (year 1, 3 & 5) Evidence-based communication plan developed (and revised at year 3 & 5) that is targeted at communities. KPI: (ongoing) Science-based communications prepared and disseminated. Priority: High
STRATEGY 5.5	Develop and publish good practice guidelines for each cropping system.
Activity 5.5.1	Development of good practice guidelines for use of sunn hemp as a rotation crop for multiple benefits in a range of cropping systems. KPI: (year 1, 3, 5) Good practice guideline's developed and published for sunn hemp in sugarcane farming systems. Priority: Medium

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7. Communication and extension (C&E) plan

The objectives of the communication and extension plan are to:

1. Promote the economic benefits of incorporating sunn hemp in cropping systems.
2. Increase awareness and understanding of sunn hemp as a rotation crop for multiple benefits and uses.
3. Increase awareness of the RD&E plan, especially amongst potential funders to generate funding of Activities.
4. Generate increased awareness in existing industries (e.g., sugar cane) of the potential role of sunn hemp.
5. Generate increased state and federal government support for industry development.
6. Raise awareness of the current and increased availability of clean and/or Australian produced sunn hemp seed.
7. Enhance the adoption of RD&E outputs.
8. Raise awareness of eco-friendly aspects of sunn hemp within communities and farming systems to optimise support:
    - Substantial N fixation; subsequent reduced requirement for N application, and resulting reduced run-off and impacts on reef
    - Enhanced nematode and disease control
    - Improved root aeration
    - Acts as a soil conditioner increasing C and OM, and soil health (abiotic and biotic)
    - Reduced erosion when used as a cover crop during fallow period.

The primary audiences for sunn hemp communications are existing and potential producers, sugar mill managers who may use sunn hemp as bioenergy feedstock, fibre industries, communities, governments (local, state and federal), researchers and research investors.

Communication and extension activities should be largely led by key industry stakeholders and the industry group formed under the plan (Activity 5.1.1). Communication and engagement activities will need to evolve and expand as interest, awareness and production grows.

Integral to the communication products and any associated communication will be the description of the demonstrated economic opportunities, and that sunn hemp:

- delivers multiple benefits in a crop rotation, including environmental and production;
- is an extremely fast growing species;
- is drought tolerant;
- can be used as feedstock for bioenergy; and
- could generate a range of potential fibre products.

The key communication and extension activities include:

- Grower champions and word of mouth;
- Industry bodies and advisors, e.g. agronomists, consultants, productivity services, RD&E service providers, local and state government (ie existing communication channels)
- Media on the back of good news stories, including social media;
- Farm open days;
- Development and distribution of sunn hemp information fact sheets;
- Targeting specific industry events, networks and contacts, e.g. in the sugar industry, Regen Cane, Project Catalyst, Evoke Ag
- General industry events, especially in potential production areas;
- General agricultural media in potential production areas; and
- Other related industry (e.g. cotton, horticulture, mixed pasture, beef), government, Research and Development Corporations and grower group communication platforms.
- Commercial opportunities, e.g. GrowAg.

- Coordination and communication with AgriFutures around potential capacity and capability programs.

8. Implementation

The development of this RD&E Strategic Plan has initiated the discussion and confirmed amongst key industry stakeholders the need for a sunn hemp industry association (see Goal 5). There was enthusiastic agreement to establish such a leadership group that could provide a single representative voice to increase awareness and understanding of the multiple production and environmental benefits that sunn hemp can provide, to oversee the implementation and co-ordination of this RD&E plan, and ensure that the use of sunn hemp in multiple cropping systems developed quickly. Specifically, such a sunn hemp association, in representing the diversity of interested stakeholders across various industries and through the value chain, will need to work closely with its stakeholders will:

- Seek to secure funding
- Proactively develop opportunities to attract and co-ordinate RD&E investment, particularly of the highest priorities Activities;
- Seek opportunities to partner with science agencies to develop and undertake RD&E Activities;
- Further develop the Communication and Extension Plans, lead their implementation to achieve the industry Vision and Mission; and
- Lead the continual evaluation and review of the Plan.

The key risks and mitigation strategies for implementing this Strategic RD&E Plan are:

Risk	Mitigation measure
Clean and accessible sunn hemp seed is not able to be produced or imported cost-effectively.	Key RD&E activities (Goal 1) need implementation; and communication/promotion of available seed undertaken.
A lack of interest in promoting sunn hemp from relevant industries and government.	The proposed sunn hemp industry association needs to be proactive in communicating the environmental and production benefits producing sunn hemp.
There is a lack of interest in growing sunn hemp from potential producers.	Key stakeholders and the proposed sunn hemp industry association must ensure key activities and communications outlined in the Plan that are targeted at producers in relevant growing regions.
There is no industry-wide ownership and leadership, and co-ordinated implementation of the RD&E Plan.	The proposed sunn hemp industry association needs to be formed by a proactive and committed group of stakeholders. The industry association needs to secure funding to lead co-ordination of the Plan and associated development activities.
Strategic RD&E Plan not widely known or accepted.	The publication of this Plan must be strongly promoted to key industries, and in particular the sugarcane industry, Sugar research Australia and the Queensland government. These communications must be largely led by key industry stakeholders and facilitated by the proposed association.
Lack of RD&E funding - science investors don't engage with and support the Plan.	Key sunn hemp stakeholder must actively communicate the benefits of sunn hemp and the existence of the Strategic RD&E Plan, working with RD&E agencies, in order to generate funding from

Risk	Mitigation measure
	multiple sources for implementation of the Plan.

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