A review of technologies that can be enabled by robotics to improve weed control in Australian Cotton Farming Systems

A commissioned report by

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Summary

Robots will change the way we do things, including the way we farm.

Robotic enabled weed control is an evolutionary step in precision agriculture and the dawn of weeding robots is upon us. Over the past 10 to 15 years a lot of investment in robotics research, and the tools that may be fitted to them, have occurred world-wide but few have been commercialised into relevant, practical and therefore functional farm assets. Lack of development investment and subsequent commercialisation are the current barriers to adoption of this technology.

Simply, an agricultural weeding robot consists of hardware and software - a self-steered (unmanned) and propelled platform that hosts an array of weed detection units that in turn activate an array of weeding tools whether that be a spray nozzle, microwave unit or tillage tool as examples.

Within Australia, four agricultural unmanned ground vehicles (UGV or robotic platforms) have been built. Most are still in the prototype testing stage; these include the *Ladybird*, *RIPPA* (both from Field Robotics Research Centre, University of Sydney), and *AgBotII* (Queensland University of Technology). Only one – *Swarmbot* (SwarmFarm Robotics) has been commercially launched and that occurred in late March 2016.

Currently there are only three weed detection/sensing units commercially available in Australia and they include Weedseeker and WeedIT, and more recently the H-Sensor originating from Europe. H-Sensor is able to detect green from green while the other two units detect green from brown which means the former is ideal for in-crop use and the latter are best utilised in fallow.

In it evident in the literature that many weeding tools and non-herbicidal tactics (eg. steam) have been developed but few have been commercialised or are not readily accessible for robotic application. Currently, microwave technology and a targeted tillage implement for weed control are being developed in Australia; the latter for the grains industry to tackle herbicide resistant weeds, but it too is not being developed for robotic enablement.

A brief overview of current weed management practices and the main weed issues of Australian cotton production systems have been described. Herbicide resistance development and species-shifts due to over-reliance on glyphosate arising from the advent of glyphosate tolerant varieties; as well as the management of rogue (volunteer and ratoon) cotton are the major current foci of cotton weed management. Based on this, the areas where robotic enabled weed management might fit have been identified. It is not the intent that robots should undertake all on-farm weed management tasks, but rather the more tedious and time consuming tasks that require maximum efficacy results. The key opportunities include but are not limited to:

- Spot spraying of weeds and rogue cotton plants in-crop and in fallow – low density situations or escapes of broadcast weed management applications; or odd patches of hard-to-kill and or resistant weeds; using alternate modes of action products.
- As above but by spot tillage (or other non-chemical treatment).
- Application via spot or patch spraying of effective but expensive herbicides that might not otherwise be used due to their cost.
- Weed surveillance – monitoring and mapping weeds in the paddock; the grower knows exactly where his weeds and issues are; monitoring for herbicide resistance survivors; becomes the eyes!

Finally, two specific areas where the CRDC might consider further investment in the short to medium term are suggested.

1.   Introduction

Across many industries, robots are changing the way we do things. The deployment of artificial intelligence is rising. In early 2015 farm robotics was described as a major growth area for Australia (Beeby 2015). The dawn of robotic enabled weed management in agricultural cropping systems is upon us, and the Australian cotton industry is not likely to be exempt.

Robotic enabled weed control is an evolutionary step in precision agriculture. It will be an alternative option within the realm of site-specific weed management where an action is only applied where it is needed - very much like hand hoeing or knap-sack spot spraying but without the need for a human presence.

As the report title suggests, this study is a review of technologies that can be enabled by robotics to improve weed control in Australian cotton farming systems. A concise literature review is included but it is far from comprehensive since both literature and technology reviews have recently been undertaken by others both nationally (eg. McCool *et al*. 2015) and internationally (Slaughter *et al*. 2008; Christensen *et al*. 2009). Further, a comprehensive book specifically on this subject – "*Automation: The Future of Weed Control in Cropping Systems*" has been compiled and edited by Young and Pierce (2013). Briefly, current cotton industry weed management practices are described and the opportunities and barriers/issues for robotics are discussed. The report closes with a suggested list of short to medium term investment opportunity recommendations for the Cotton Research and Development Corporation to consider.

This review was undertaken primarily by desktop study method (literature and website searches) in conjunction with some limited contact (meetings, telephone and email discussions) with industry researchers and universities.

Project rationale/background (extracted from the *Commissioned Research Proposal*)
The purpose of this project is to identify weed management technologies that could be integrated with robotic technology to control weeds in a cotton farming system including volunteer and ratoon cotton.

Robotic technology is revolutionising many industries; from manufacturing, and home vacuum cleaners to fully automated mine sites in Western Australia. In the past three years, availability of robotic technology has grown exponentially, with enormous opportunity for agriculture.

Weed control technologies in cotton farming systems have historically been limited by the need to operate in the broad acre outdoor environment.   This new farming system will enable adoption of existing technologies that have been developed, but are not practical on traditional, large machinery and enable new and experimental technologies and techniques to be developed. With swarms of small, lightweight machines, growers can tailor farming techniques to an individual plant or weed. Robotics is a "Step Change" technology that will enable an entirely new farming system.

While there is a large amount of effort in new technologies and sensors from the research community, this project looks to scope the potential for development of existing technologies to enable Australian cotton growers to rapidly adopt this new farming system.

## 2.	Literature Review

### 2.1	Introduction

Generally, weeds in broad-acre cropping situations are controlled by applying herbicides or tillage uniformly over entire fields (Peltzer *et al*. 2009), although the latter has been far less frequent over the past 25 years due the extensive adoption of herbicide dependent minimum and zero till production systems. However, more recently, world-wide agriculture has seen the development of site-specific weed management (SSWM) technologies as a proactive attempt to reduce excessive herbicide use in order to gain economic, environmental and health benefits (Alchanatis 2007; Peltzer *et al*. 2009). Peltzer *et al* (2009) also advocated that intermittent use of non-herbicide weed management via site specific technologies will slow the development of herbicide resistance, while Shaner and Beckie (2013) indicated that SSWM will be essential to the management of herbicide resistant weeds. Further, Fernandez-Quintanilla *et al* (2008) suggested SSWM systems may provide a solution to the recently changed European regulations regarding pesticide use.

The availability of GPS technology for non-military purposes has been a catalyst for much of the research into site-specific management or precision agriculture (Shaner and Beckie 2014). The development of precision farming techniques during the past two decades has promoted site-specific weed management and variable rate herbicide technology (Sakai and Upadhyaya 2007). Christensen *et al* (2009) defined site-specific weed management technologies as machinery or equipment embedded with tools that detect and control weeds. They described the technology as having three key elements: (1) a weed sensing system, (2) a weed management model applying knowledge upon which to base management decisions, and (3) a precision weed control implement – boom with a series of controllable nozzles or a mechanical tool unit. Others have included weed mapping in (1) (Peltzer *et al*. 2009) and described (3) above as the effectors or actuators, actuation tools or actuation system (Perez-Ruiz *et al*. 2015; Young 2012; Emmi *et al*. 2014) of SSWM technology. In the technology review of Christensen *et al* (2009), real-time weed sensing was indicated as the precondition for the adoption of SSWM.

Automation will be a facilitator of site-specific weed management. Autonomous systems operate independently of humans and include all types of vehicles that can operate on both land and in the sky (Swift 2015). Perez and Gonzalez (2014) believe that the use of UAVs (unmanned aerial vehicles) in combination with the use of multiple cooperative autonomous farm vehicles (eg. agricultural robots or agbots) will be key tools and the next step for precision agriculture. Further, Bochtis *et al* (2014) suggested that the introduction of autonomous vehicles and intelligent machines to agricultural production will provide increased efficiencies and reduced environmental impacts. Professor Sukkarieh, the inventor of the Ladybird robot believes the automation of on-farm tasks will have a major role in minimising inputs and maximising outputs of future agriculture (Hollick 2014).

Young (2012) defined the vision a little differently by suggesting that this smart technology could assist in addressing the current limitations of integrated weed management at the micro-scale while at the same time assist in meeting the demand for food and fibre sustainably at the macro-scale. He further suggested that a single platform with many different weed control tools will bring

increased responsiveness and flexibility to the management of current cropping systems. Young keenly advocates that this real-time integrated weed control system will reduce the reliance on a single tactic, whether it be spraying or cultivating, and will eliminate (1) herbicide resistant weeds, (2) off-target movement, and (3) soil erosion, while reducing overall input costs.

This review of the literature will cover agricultural robotics with a brief touch on unmanned aerial vehicles (eg. drones) for weed control. It will highlight, but not cover in depth, weed sensing / detection technologies. The weed management tools available for robotic enabling will be presented including those that have already been developed or are currently under development for use with such systems. Finally, past and current research and development in robotic weed control within cotton productions systems will be described.

2.2 General robotics and drones for weed control

It is envisaged that agricultural robotic systems will be multi-purpose (eg. sowing, fertilising, spraying, scouting, counting, sensing) and multi-modal (eg. chemical, mechanical, electrical, thermal weed control); long endurance with day/night operation and will ultimately reduce the need for tractor work; will allow for more precise operations; will enable miniaturisation of equipment and will reduce both soil compaction and on-farm labour requirements (Swift 2015; Perez and Gonzalez 2014).

Slaughter *et al* published a comprehensive review of robotic weed control in 2008 focusing on the developments in the four associated core technologies – guidance, detection and identification, mapping and in-row precision weed control. They regarded robust weed detection and identification as the major obstacle to industry acceptance and commercialisation of robotic weed control technology.

The use of small unmanned aircraft systems (UAVs or drones) in weeds research was recently reviewed by Rasmussen *et al* (2013). Drones with cameras have not been widely used in weed research, however they offer low-cost sensing with good flexibility in spatial resolution and this is important because spatial resolution is inversely related to sensing capacity.

Moore (2012) from Western Australia suggested that UAVs such as quadcopters fitted with controlled droplet applicators (CDA) offered the potential to control difficult-to-access weeds. He further demonstrated the success of this ultra-low volume application on gorse weed showing it to be as effective as high volume applications. The UAV platform was most suitable for isolated plant targets since the payload (herbicide and water) was limited to only a few kilograms.

Drones can cover large areas in a short time compared to ground-based sensors. This means weeds can be mapped before weed control is performed allowing planning of herbicide choice and rate as well as adjustment of application parameters. Drone imagery still presents a challenge in terms of distinction and quantification. While image acquisition is relatively easy, analysis and interpretation of the data are less so (Shaner and Beckie 2014).

Further information regarding use of drones for weed management including SSWM can be found in Torres-Sanchez *et al* (2013) and Pena *et al* (2015).

2.2.1 Existing automated weed control systems and robotics

An eclectic array of machines and systems exist across the world. Not all are commercially available at present and most are still undergoing development and refinement.

Hortibot is a semi-autonomous robot with a navigational platform designed to be fitted with different weed management tools to either mechanically remove weeds or precision-spray them. It is being developed by Aarhus University in Horsens, Denmark. *Hortibot* uses a vision based system of downward focused cameras to navigate around the crop. It was to be commercialised after increasing the wheel gauge and clearance to make it suitable for a range of crops (Graham-Rowe 2007). No recent information could be found on progress of the *Hortibot*.

Siemens (2014) described the only four commercially available automated weeding machines at the time. All used a camera-based machine vision system to detect plants and focussed on weed removal/control within the crop row rather than between rows; all are non-self propelled. The following were described by Siemens:

- *Robocrop* – first commercially available robotic weeding machine; developed (by Tillet and Hague Technology Ltd.) and commercialised (by Garford Farm Machinery Ltd.) in the United Kingdom. Utilises a forward looking camera that detects crop plants and a set of rotating disc blades mounted on an off-centre shaft that cultivate around the crop plants within the row. It does not operate effectively in rows with densely and or irregularly spaced crop plants, nor where weeds and crop plants are similar in size.

- *IC-Cultivator* – developed in the Netherlands in 2012 and released in Europe in 2013 in a partnership between industry (Machinefabriek Steketee BV) and Wageningen University. Uses hooded cameras with artificial LED lighting on each planted row to identify crop plants. As the machine moves forward, a pneumatic cylinder opens and closes a set of cultivating knives around the crop plants. Has a modular unit design with working widths of 1.5 – 6.0 m and a hoeing capacity of 3-4 plants s^{-1} at an operating speed of 3 – 4 kmh^{-1}. No performance information was provided as none was available.

- *Robovator hoeing robot* – similar in concept and operation to the IC-Cultivator but is non-hooded with artificial lighting for consistent image quality; developed and available (F. Poulsen Engineering Aps) in Denmark and is also modular with 3-6 row units.

- *Thermal hoeing robot* – developed by the same Danish company as the Robovator. Utilises the Robovator vision system to identify crop plants and a series of plasma jets oriented towards the crop row that deliver flame to kill weeds. Multiple jets are used to deliver a sufficient amount of heat to kill. Operates at 1 – 6 kmh^{-1}.

Siemens (2014) also suggested that the four current-commercialised (in the USA – Ramsay Highlander Inc.; Agmechtronix LLC; Blue River technologies Inc.; Vision Robotics Corp.) automated lettuce thinning machines could be utilised as intra-row weeding robots as they remove unwanted plants from the crop row. All use a machine vision system to locate plants for selective

thinning and herbicide sprays to kill unwanted plants. The units are capable of thinning plants as close as 3.75 cm apart at speeds of $3 - 5\,kmh^{-1}$.

Ecorobotix of Switzerland is developing a small revolutionary robot for ecological and economical weeding of row crops. *EcoRobot* is light-weight and easy to transport. It is solar-powered and can run for several days performing weed control with 95% efficacy. The robot performs weeding by combining an advanced vision system that recognizes weeds and a fast robotic arm to remove them either by spot spray or spinning disk. The company claims the robot will offer a return on investment to European farmers in less than five years (Anon. 2015a).

The agricultural robot, *Ladybird*, named after its resemblance to the beetle (Blucher 2014), was developed at the University of Sydney's Australian Centre for Field Robotics (ACFR) for use on commercial vegetable farms to undertake autonomous tasks such as mapping, surveillance, classification and detection of a variety of vegetables and weed control. It is solar-electric powered and fitted with sensors (lasers, stereo and hyperspectral cameras) to detect vegetable growth, weeds and animal pests. A robotic arm for removing weeds but with autonomous harvesting potential is also fitted to *Ladybird* (Hollick 2014).

In Germany, Bosch, through its start-up company Deepfield Robotics has developed *Bonirob,* an agricultural robot which is the size of a small compact car. *Bonirob* moves around the paddock using video and lidar-based positioning as well as satellite navigation, and it knows its location to the nearest centimetre. The machine was originally developed to speed up plant-breeding processes, however, it also has application in weed management since it has the ability to distinguish between crop and weeds. Fitted with a rod, weeds are mechanically controlled by a simple but swift ramming into the ground (Anon. 2015b) like a punch.

Ackerman (2015) described the *Bonirob* punch as being a better solution since it involves only one action compared to pulling a weed out which requires grasping and then doing something with it. The punch or ramming is fast (0.01 s) and easy making it a task well-suited to a robot. The on-board generator allows it to operate for 24 hours without needing to refuel. The idea is for farms to buy the *Bonirob* and then buy or rent whatever module (task oriented) they need when it is needed rather than having to invest in many single-task robots.

AgBot is a light-weight, golf-buggy sized robot that has been designed by QUT (Queensland University of Technology) as an autonomous vehicle. *AgBot II* is a newer prototype, also developed by QUT to help farmers with seeding, fertiliser application and weed control (Bryant 2014). It was unveiled at the G20 Leader' Summit in Brisbane in 2014 (Berry and Dixon 2015). It is yet to be commercialised.

SwarmFarm Robotics, a regional Queensland company commercially launched their swarming style autonomous vehicles, *Swarmbots* in late March 2016. Currently the *Swarmbots* are fitted with WeedIT or WeedSeeker activated spray nozzles and have been successfully working in fallow paddocks. This light-weight diesel motor-powered *Swarmbots* have been developed by a farmer for farmers (A Bate, SwarmFarm Robotics, pers. comm., March 2016).

Most recently, the 250 kg solar-powered *RIPPA* (Robot for Intelligent Perception and Precision Application) developed by the ACFR at Sydney University with funding from Horticulture

Innovation Australia, was unveiled and put to field testing in Queensland's Lockyer Valley (Hollick 2016). This autonomous vehicle has the ability to collect data using sensors that also map the crop area and detects weeds; and it also detects foreign objects such as stones, glass or metal in the paddock. Currently the machine can estimate crop yield, spray weeds and fertiliser, and can operate up to 21 hours straight.

2.3   Weed sensing / detecting technologies

Much research and development investment has occurred world-wide in weed detection and sensing technology. In the 17 years between 1995 and 2012, 479 scientific papers on weed detection systems were published with approximately 25% of these originating from the USA (Harker and O'Donovan 2013). It is likely that the associated technical and conference papers are also numerous. It is a topic with vast information available.

Various sensing technologies are used for weed detection and these include machine vision, spectral analysis and remote sensing. Machine vision methods are based on digital images within which geometrical, textural or other statistical features are used to detect weeds. Spectroscopic methods use spectral reflectance or absorbance patterns to discriminate between crop and weeds. The combination of computer/machine vision with spectroscopy produces hyperspectral imaging methods in which spectral and spatial data are analysed to aid weed detection (Alchanatis 2007).

Uncontrolled environmental conditions present three major challenges to the application of sensors in weed management – variable lighting conditions; leaf coverage (weeds near crop plants are difficult to classify); and growth status of the weeds. It is likely future sensing techniques will integrate more than one or two detection methods (Shaner and Beckie 2014).

Comprehensive reviews on applied machine vision of plants have been undertaken by McCarthy *et al* (2010a and 2010b) and there is no intention here to reiterate what has already been reviewed. Likewise with the coverage of guidance and weed sensing systems presented in the reviews by Slaughter *et al* (2008) and Lopez-Granados (2010). Christensen *et al* (2009) also provide a succinct overview of weed sensing systems and weed management models, the latter of which is used to make management decisions that drive the actuation systems of SSWM.

There are two approaches to SSWM – sensor based and map based. Sensor based methods utilise on-the-go sensors to identify weeds and apply herbicides (or other actuation tool) nearly simultaneously in the one operation. Current commercial sensors (with the exception of the H-sensor) can only differentiate between soil and plants, or are described as green on brown and are only suitable for fallow and row-crop systems (Peltzer *et al*. 2009). WeedSeeker and WeedIT are examples of this sensor type. Sensors that differentiate green on green and can therefore distinguish between crop and weeds and between weed species are much rarer with several currently under development. The H-sensor is an example of this type.

The map based approach is a two-step process. Weed maps are prepared to develop variable rate application plans. These are then used by differential GPS controlled sprayers to apply herbicides to only those areas of the paddock that require it (Peltzer *et al*. 2009).

2.3.1 WeedSeeker

WeedSeeker was developed in the 1990s by Patchen in California and is now owned by NTech. It works by assessing the ratio difference of red and near infrared reflectances of vegetation and background. It has red and near infrared LEDs to improve accuracy. The electronic circuits analyse the reflected light and fast-fire solenoid valves. When it detects green leaves (of weeds) from the different coloured soil or stubble background, it triggers a directed spot spray (Fillols 2014; Baillie 2013). While best suited to fallows use, Osten and Cattell (2011) demonstrated effective use of WeedSeeker applying broad-spectrum non-selective knockdown herbicides in wide-row chickpea and sorghum crops in conjunction with the use of shields.

2.3.2 WeedIT

WeedIT was developed in the Netherlands and is managed by GPS-AG in Australia. This sensor uses red light that is partially shifted to near infrared when it passes over live plant chlorophyll (green plant material). Unlike WeedSeeker, WeedIT does not require ongoing in-field manual calibration. One sensor can control five solenoids and sensors are usually spaced at 1 m intervals across a boom. They operate at a height of 1 m above the ground (Baillie 2013).

2.3.3 H-sensor

H-sensor, developed in Germany, is the first commercially available sensor that can detect green on green which means it can distinguish between crop and weeds and between weed species. The sensor houses specially designed cameras that automatically recognise different plant types. It has its own light source so can be operated around the clock. Its robustness allows it to be operated at working speeds of up to 12 kmh^{-1} (Agricon website). Current in-field broadacre development work in Australia with the H-sensor will assess the sensor for classification accuracy (1) under various crop stubble conditions; (2) rye grass in wheat and barley; (3) wild radish rosettes in cereals and legumes and with other weeds; and (4) carrot like weeds with other broadleaf weeds in cereals and legumes (Anon. 2016).

2.3.4 Others

Ultrasonics – ultrasonic sensor to discriminate between grasses and broadleaves based on their height with georeferencing and registering the echoes reflected by the ground or by the various leaf layers. It offers significant promise for development of real-time spatially selective weed control techniques and can be the sole detection unit or used in combination with other tools (Andujar *et al*. 2011; Andujar *et al*. 2012)

X-rays – a real-time, non-contact stem detection system using a tractor mounted portable x-ray source that projects an x-ray beam perpendicular to the crop row and parallel to the soil surface. It has been developed for weed control in tomatoes. At travel speeds of 1.6 kmh^{-1}, the system correctly identified 91% of main stems of tomato plants (Haff *et al* 2011).

Lasers – (photonics) a real time plant discrimination system that employs two visible red and one near infrared laser diodes. The lasers sequentially illuminate the target ground area and a linear sensor array measures the intensities of the reflected laser beams. Can detect green from green at

travel speeds of 3 kmh^{-1} (Symonds *et al.* 2015) and narrow leaved plants with a width of 12 mm in one study (Paap *et al.* 2007) and 20 mm in another (Sahba *et al.* 2006).

Fluorescent crop seed coatings – crop seeds are coated with a fluorescent material prior to planting. As they emerge and for a couple of weeks post- emergence the new crop plants will emit a faint fluorescent glow (transient) that will be detected by special sensors on a robotic cultivating machine. Plants without the glow (weeds) will be cultivated (UC Davis Cooperative Extension Unit 2015).

2.4   Weed management tools

Weed control tactics such as spraying, mowing and cultivating produce different effects on weeds and without a thorough understanding of the biology and ecology of the target weeds and crop, the development of efficient and effective robotic systems will be challenging (Young 2012) just like it is for any weed management technology.

A comprehensive but succinct review of weed management tools with potential for robotic enabling has recently been completed by QUT staff and students as a milestone report for a Queensland Government (DAFF) Strategic Investment project in Farm Robotics (SIFR). The milestone report by McCool *et al* (2015) reported on studies on weed identification and weed destruction. While it also covered robotic vision for weed detection and classification, and apart from the appendices, the majority of the report focussed on state of the art weed management and choosing a robotic weed destruction method. In the latter, the authors developed a set of weighted criteria (energy usage, complexity, safety, soil disturbance, effectiveness and speed) which they then applied to each weed control method to arrive at an individual utility score. An overall utility score above 0.7 deemed the tool appropriate for robot-based weed destruction. The four tools to achieve a sufficient utility score were (1) tube stamp, similar to the Bonirob punch, (2) spinning blade, (3) custom weed pulling tool, and (4) microwave. It is feasible to suggest that a group of differently skilled and knowledgeable people may arrive at a different set of utility scores.

Again, since a fairly thorough recent review of weed management tools has already been undertaken, this report shall only draw attention to what has been covered rather than reiterate the same information. However, potential tools that have not been identified in QUT report will be done so here.

The report of McCool *et al* (2015) presents good summary information along with the pros and cons of each tool and a comparison table within each grouping for following weed management tools:

- Broadcast tillage (chain harrows, flexi-tine harrows, rotary hoes)
- Inter-row tillage (brush weeders, disc hoe and rolling cultivators, basket weeders)
- Intra-row tillage (torsion weeders, finger weeders)
- Thermal weed control (flame, microwave, infrared, ultraviolet radiation, hot water and hot foam and electrocution)

- Robotic weed management (very similar to list below for "*Specific weed control tools already developed for agbots*", plus direct chemical application akin to cut-stump but at much smaller scale)
- Chemical control (spot spray with WeedSeeker and WeedIT as opposed to broadcast spray) (no comparison table for the different spraying options is provided)

An area of chemical weed control not listed in McCool *et al* (2015) but worthy of consideration is banded over the crop row pre- and or post-emergence herbicide application with either spot spray or mechanical / thermal applications in the inter-row.

Other weed management tools not identified by the QUT study that might be applicable for robotic enabling include:

- *Direct-fired steam weeder* (non-pressurised) – steam is derived by spraying fine mist water into hot exhaust gases from a burner, causing it to evaporate quickly. The design is diesel powered but could also run on renewable fuels such as vegetable oils (Merfield *et al.* 2009)

- *Air-propelled abrasives* – abrasive grit made from corn cobs expelled from a sand blaster at 517 kPa pressure in a one split-second blast at a target distance of 300 mm killed the target weeds without damaging the crop in a study conducted by Forcella (2009a). In a second study by the same author (Forcella 2009b), granulated walnut shells were air-blasted at the same pressure but this time at 300 to 600 mm from the target. Cotyledon to 2-leaf stage weed seedlings were killed from a single split-second (< 1 s duration) blast of grit but unaffected from compressed air alone. Larger weeds at 4 to 6 leaf stage required up to 10 blasts of grit before death occurred. This demonstrates an effective a non-chemical, non-tillage based weed control option.

- *Pneumat weeder* (a weed blower) – developed by Lutkemeyer in Europe, uses compressed air to control weeds by blowing them out of the crop row. Compared to other tools, it has twice the power needs compared to ordinary hoeing (Van Der Weide *et al*. 2008)

- *Food-grade organic fatty acids as "herbicides"* – fatty acids such as pelargonic acid and caprylic acid are effective non-selective herbicides for a broad spectrum of annual weeds and their activity can be enhanced by the addition of food-grade organic acids like diammonium succinate and succinic acid, as well as l-lactic acid and glycolic acid. (Coleman and Penner 2008). These could be spot applied to weeds.

2.4.1   Specific weed control tools already developed for agbots

Apart from the tools already commercialised (see Existing automated weed control and agbots section above), Christensen *et al*. (2009) cite numerous authors (not being listed here) that have developed highly accurate weeding implements for intelligent SSWM (guided) systems, including the following:

- Mechanical knives
- Rotating hoes
- Transverse direction rotating basket weeder
- Smart hoe – rotating plate with spring-loaded knives

- Cycloid hoe – 8 rotating tines
- Vertical disc with cut-out sections with peripheral bevels acting as a hoe
- High-voltage electrical discharge probes
- Precision flame weeder
- Continuous wave diode lasers

Many of the above are also mentioned in Slaughter *et al.* (2008) and again in Young (2012).

The 10 mm diameter *stamping tool* developed for use on Bosch's *Bonirob* punches weed 3 cm into the soil. It was designed for use of newly germinated weeds, but for larger weeds it can perform multiple hammer actions in a very short time. The maximum capability of the machine is 1.75 weed s^{-1} at a speed of 3.7 cm s^{-1} and a weed density of 43 weeds m^{-2}, but at lower densities the speed can increase to 9 cm s^{-1} (Ackerman 2015). Deepfield Robotics is currently developing a selective spraying system with working widths of 6 – 7 m using foldable booms (Anon. date unknown).

Other tools/tactics tested with robotics but not covered in the QUT report include:

- *Hot organic oil* – food grade canola oil heated to 160°C applied by precision, pulsed-jet, micro-dosing system delivering 0.85 mgcm-2 in 10 ms pulses. At 15 days post-application, the treatment had killed 96% of the targeted *Solanum nigrum* and 94% of the *Amaranthus retroflexus* plants with only 2.4% of the crop plants (tomatoes) receiving any significant damage (Zhang *et al*. 2012).

- *On-row band steaming* - to kill weeds prior to planting (Sorrensen (2005) cited by Young 2012).

2.5   Past and current R, D and E with robotics in cotton

Papers covering robotics research, development and extension in cotton were limited. The papers found are from across the world (USA, Australia, Greece, Israel and China) and none of the studies are related.

Lamm *et al* (2002) developed and tested a real-time robotic weed control system in commercial cotton fields in the USA. The overall objective was to develop automated weed control technology for cotton growers using machine vison to detect the crop and weeds and then eliminate the weeds during the early stages of growth when control is critical. The system needed to correctly classify occluded and non-occluded cotton plants and grass-like weeds from cotyledon to second true-leaf stage during the first couple of weeks post cotton emergence using non-morphological machine vision techniques. It also needed to reach real-time detection and removal rates for a system traveling continuously at speeds above 0.45 ms^{-1}.

The robot used in Lamm's research consisted of a real-time machine vision system, a controlled illumination chamber, and a precision spray applicator. The objectives were achieved with the algorithm being robust to occlusion and able to discriminate between cotton and grass-like plants to within 19 x 14 cm region of the crop row. Averaged across 14 field trials, the system correctly sprayed 89% of the weeds while correctly identifying and not spraying 79% of the cotton plants, all

while traveling at the required speed. The execution time including image acquisition was rapid at 163 ms. The weed elimination rate was considered acceptable compared to cited research of similar earlier robots and hand-hoeing which only achieved 48% and 75% weed control respectively.

In 2005, a six metre *Robocrop* precision guided hoe (previously described in a section above) was brought to Australia and demonstrated on-farm to cotton growers in the Hay district of New South Wales. The unit was fitted with bean knives and Alabama sweeps (ridging units). It was applied at 10 kmh^{-1} to a very young crop (cotyledon - one true leaf stage). Crop guards were not required at this speed as it did not create much soil throw. At faster speeds (18 kmh^{-1}) the guidance was maintained but crop burial was unacceptable. It was suggested that better ground engagement could have been achieved with additional crescent knives and smaller sweeps. The demonstration showed that robotic weeding:

- Is unaffected by wind allowing weeding operations to occur when spraying cannot.
- Operator fatigue can be reduced.
- Works at night very effectively under standard tractor lamps.
- Can be done at reasonable speed and at higher precision levels with less crop root injury than that using manual guidance and heavy equipment.
- Adds an option for IWM which will assist in avoiding development of herbicide resistance. And
- Difficult to control weeds like fleabane may have "met their match" with the high operating speeds, high accuracy and around the clock capability (Taylor 2005).

An Israeli research effort by Efron *et al* (2007) set about developing a cost-effective method for weed map preparation designed to be used for on-the-go herbicide application in cotton crops. The method involved combining information from a hydro-thermal model with image processing algorithms. The images are captured by tractor mounted RGB (red green blue) cameras on the spray boom and sent to the on-board computer for analysis using MatLab® software along with incoming data from the hydro-thermal model. The end-result is a 'weed map' calibrated with differential GPS data that was collected during the image acquisition stage. No information was provided about how this was utilised by an actuation system to kill the weeds.

Wang *et al* (2008) describe a new method of cotton recognition using a machine vision based system with the intention for it to be used by a cotton harvesting robot. Some information and therefore understanding is lost unfortunately in the translation of this Chinese study, although those with sound sensing/imaging knowledge would most likely have no issue. The recognition method is based on colour subtraction information for different parts of the cotton plant and accuracy of this is enhanced when Freeman chain coding is used. In four experiments, 85% accuracy levels were achieved and this was considered high performance.

Papadopoulus and Chachalis (2012) have undertaken similar research to that of the Israeli study of Efron *et al* (2007) described above. In this Greek research, weed mapping using ground and remote sensing was developed in a cotton field with the objective to spatially record and map weed density using multispectral ground-based sensors; analysing high resolution satellite images; and digitally processing RGB photos. NDVI maps were created and overlaid from all the sensors.

Field data on weed species and densities were also collected and used to check the accuracy of the maps. Preliminary analysis showed the map derived weed density estimates correlated well with the actual field data collected allowing the field to be divided into spatial zones of different weed pressures which could then be treated differently to achieve better weed management with optimised input costs and reduced environmental impacts.

Currently the Cotton Research and Development Corporation is funding a student scholarship at the QUT, Brisbane to assist with the development of different tillage tools to target the problematic weeds of cotton. The tools are to be robotic enabled (Susan Maas CRDC pers. comm. May 2015).

2.6   Conclusions

The future remains largely unpredictable despite all of the recent exciting and innovative advances made in SSWM including robotics. Shaner and Beckie (2014) describe the future of agricultural weed management as challenging - it will require growers to have more knowledge, planning, time, costs and risks compared to the past; and the growers who can adapt to this reality will be the ones who survive and make profit. Growers will not adopt technology that is perceived as being costly, time-consuming or complicated.

The advances made since the technology review of Slaughter *et al* (2008) has still not resulted in many commercially available agricultural robots, particularly for broad-acre agriculture in Australia. Still the main hindrance has been the commercial availability of sensing/detection systems that discriminate green on green (crop from weed; weed species differentiation) even though much research and development has and is still being undertaken in this field. It is time to make this technology relevant and put it to use at the commercial scale.

With the continual evolvement of herbicide resistant weeds and shifts towards those species more difficult to chemically control, robotic weed control systems that enable several different modes of action (chemical, physical, thermal) on the one platform at the same time, will facilitate and deliver real integrated weed management (IWM) to cropping systems. IWM is often touted but has rarely been properly implemented, and (hopefully) this is about to change.

Since precision weed control has previously been successfully demonstrated in cotton (Lamm *et al*. 2002; Taylor 2005) there is no reason why it would not succeed in the future. The reasons for needing and using it will have changed from previous since the widespread adoption of herbicide tolerant GM crops has occurred bringing with it the evolution of herbicide resistant weeds.

3.   Weed management tools under development (not covered in the literature review)

A Grains Research and Development Corporation (GRDC) funded collaborative targeted tillage project between the Australian Herbicide Resistance Initiative (ARHI), the Queensland Department of Agriculture and Forestry (QDAF), and the University of Queensland (UQ) was funded in 2015 for a 3 year period (Dr M Walsh, pers. comm., July 2016). The project's major output is to develop and

validate minimal disturbance spot tillage equipment that can control weeds and which can be integrated with weed detection systems (GRDC External Investment Plan 2015-16, pp. 54-55).

The targeted tillage tyne has been developed with the assistance of engineers at the University of Western Australia and is currently (as at mid-2016) being field tested. The project team have retrofitted a tractor drawn Shearer trash worker with the new hydraulically activated tyne system. The tynes respond individually to weeds detected via WeedIT sensors. The concept could be robotic enabled, however the tyne in its current form is not suitable for a robotic platform; it would require some re-development to make it suitable (Drs M Walsh and M Widderick, pers. comm., July 2016).

The previously mentioned DAFF funded SIRF project being undertaken by QUT recently reported (Bawden *et al.* 2016) results from current weed detection and classification trials in the glasshouse and field, as well as weed management trials with the Agbot II fitted with spray units and a weeding hoes. The results in the glasshouse reflect a 95% success rate for the broadleaf weed detection and classification (sowthistle and cotton) and 96% success for the grass weeds (feather Rhodes, barnyard and wild oats). Cotton detection has been 99% successful. In the field, the success rate was a little lower for the vision module. For the in-field weed management trials, successful control was achieved with the spray units as well as the hoe units when used individually as well as in tandem (cotton was sprayed while sowthistle and grass was hoed).

These results are showing that the QUT research has the concept working quite well, however, after viewing the video during a visit to the QUT lab, it is very doubtful that the hoe system is robust enough for soils other than soft friable loams and sands. The mechanical module in its current state would not withstand clods, heavy clays, stones and rocks commonly seen in broadacre paddocks. To get this module fit-for-purpose in cotton fields will take some extensive redevelopment and engineering of both the weeding tool assembly and possibly the Agbot itself.

4. Weed management in Australian cotton production systems

4.1 Overview of current practices

Australian cotton farming systems are fairly much herbicide dependent although they are not complete zero tillage systems. It was not that long ago that hand chipping of weeds was undertaken across most cotton production districts – this was during the pre-glyphosate tolerant cotton period. With the introduction of herbicide tolerant varieties (2000/01), hand-weeding started to decline and by the 2006/07 season became non-existent with the introduction of Roundup Ready Flex (RR Flex) variety (Maas 2015; Werth and Cameron 2016).

Prior to the introduction of herbicide tolerant cotton varieties, most production districts employed strong integrated weed management systems with several herbicides of different modes of action, hand chipping and frequent pre-plant and in-crop cultivation. Residual herbicides were used pre-plant and at planting and as a lay-by. Post-emergence herbicide use was mostly the Group A grass selective products and some Group B (pyrithiobac or trifloxysulfuron) for the broadleaves. The risks for herbicide resistance were fairly low (Werth and Cameron 2016).

The use of glyphosate tolerant varieties climbed from 0 to 70% of the total production area from 2000/2001 season to the 2005/2006 season. By the 2008/2009 season, over 95% of the total production area was sown to glyphosate-tolerant varieties, with most being RR Flex. By the 2011/12 season, 99% of the industry area was RR Flex (Maas 2015).

The advent of the RR Flex cotton variety resulted in a rapid decline in the use of other modes of action herbicides and much less tillage leading to a cropping system heavily reliant on glyphosate with increased risks of herbicide resistance development. For this reason, the cotton industry developed a "Herbicide Resistance Management Strategy" or HRMS for growers to adopt to delay the onset of glyphosate resistance (Guest *et al.* 2015).

The industry-wide HRMS follows a formula: 2 non-glyphosate tactics for both grasses and broadleaf weed during the cotton crop + 2 non-glyphosate tactics in summer fallow that target both weed types + 0 survivors of glyphosate applications permitted (must not be allowed to set seed). In back-to back irrigated cotton systems, the summer fallow does not exist. In dryland scenarios, cotton is usually produced every second summer with a long summer fallow in between (Guest *et al*. 2015).

Maas *et al*. (2015) and Maas (2016) provide a succinct but thorough description of all the current tactics for weed management in Australian cotton including on-farm hygiene, fallow, in-crop and post-harvest weed control covering chemical, cultural and mechanical options.

Liberty Link is another herbicide tolerant crop variety technology that permits the use of glufosinate as Liberty 200 Herbicide (Group N) over the top of the crop (Bayer Crop Science). It is not as widely used as RR Flex. Coming very soon is a variety with stacked herbicide tolerance traits – glyphosate, glufosinate and dicamba (Groups M, N and I) (Maas 2015).

4.2   Weed and weed management issues

The most likely weed issues in cotton are going to be those that are driven by the production system itself. In the majority of cases the issue weeds are those that are favoured under high glyphosate useage combined with minimal to no-tillage. Continual use of glyphosate results in a shift towards the species that are not well controlled by this herbicide, including those that have developed glyphosate resistance. In minimal and zero till systems, since little soil disturbance occurs, large seeded weeds tend to die out while small seeded species tend to thrive. Large seeded species need soil disturbance in order to have their seeds buried at depths required for germination. Small seeds species have the seeds retained in the very upper layers of the soil and favour surface germination.

In irrigated cotton systems the major or dominating weeds prior to the introduction of glyphosate tolerant varieties included cowvine/peachvine, bladder ketmia and barnyard grass; but in 2015 well after the introduction of RR Flex, barnyard grass remained but the broadleaves had changed to fleabane and sowthistle – small seeded surface germinating species. In dryland cotton systems the dominant weeds in 2001 were bladder ketmia and sowthistle, and in 2010 these still dominated but were joined by fleabane (Werth and Cameron 2016). The major species are also often considered difficult-to-control, hence their domination.

The frequent use of glyphosate in cotton has resulted in overall good nutgrass management; however species inherently tolerant of the herbicide such as legumes and vines are becoming more problematic.

With respect to glyphosate resistance, there are now 12 weeds confirmed as resistant in Australia – 3 winter grasses, 5 summer grasses and 4 broadleaves (Werth and Cameron 2016). Eight of these weeds (annual ryegrass, barnyard grass, liverseed grass, sweet summer grass, feathertop Rhodes grass, windmill grass, fleabane and sowthistle) are commonly found in cotton production systems. If the HRMS is not followed, it will only be a matter of time before more resistant population members are selected for. In fact, resistant populations of the 8 weeds listed above have already been recorded in both dryland and irrigated cotton systems in Australia (Maas 2016).

Another major weed management issue is the control of volunteer and ratoon cotton plants. These volunteer and rogue plants often act as green bridges for diseases and insects so need to be controlled. Clean-picking and crop stover management are the best ways to reduce the amount of viable seed remaining in the paddock post-harvest. Pre-irrigating will often stimulate volunteer emergence allowing for easier control prior to crop planting. The main problem with volunteers arises when they emerge with or slightly after the planted crop. Management of these will require in-crop tillage of both the furrow and the hill to avoid strips. Escapes from this may need follow-up hand-chipping.

Ratoon plants usually occur in systems with minimal tillage or where post-harvest stover management has not provided a clean sever of the stem from the root system allowing these plants to continue to grow albeit in a toughened state (R Anderson, pers. comm. 2016). These hardened rogue plants become difficult to control with herbicide and tillage is often the only effective option. Stacked-trait herbicide tolerant ratoon plants will be the nightmare of the future!

4.3   Opportunities for robotics for weed control

So where do robotics fit in the cotton farming system - what are the opportunities?

The use of robots for agricultural weeding purposes brings many benefits as described previously in the literature review section. Being light-weight, agricultural robots will be able to enter the paddock after rain/irrigation well before conventional heavy farm equipment. They will be able to operate all day and all night at slower speeds without the need for human presence. They will act only where they detect a weed or rogue cotton plant (volunteer or ratoon), delivering a chemical, a microwave, or a flame, or some soil disturbance for example only where it is needed. Site-specific actions resulting in economic, environmental and social benefits.

It is not the intention for agricultural robots to undertake all weed management activities in cotton production systems, but rather use them for the tasks that require tedious attention and maximum efficacy such as escape and survivor management; or where weed densities are considered too low for broadcast/broadacre application. The weeds or ratoon cotton plants that survive the broadcast applications of chemical or tillage are the ideal targets for agricultural robots. Robotic platforms fitted with weed detectors /sensors plus spot sprayers, spot tillage implements and or microwave units or any other actuation tool, could roam the crop or fallow

seeking out the weed escapes and then destroy them on the spot. Or, robotic platforms could be sent into paddocks shortly after the broadcast weed management treatments to provide further control actions upon known patches of difficult to control weeds.

Specifically, WeedSeeker / WeedIT / H-sensors could be used with or without shields (depending on crop versus fallow application; or type of herbicide being used in-crop and whether or not it is cotton-safe) to spot-spray a variety of effective mode of actions including expensive products not normally used (due to cost) to control problematic weeds (hard-to-control and or glyphosate resistant species) and rogue cotton plants. This could be deployed in-crop and in the fallow.

The same sensors could also be used in conjunction with a spot tillage implement or other non-chemical tool to target escape weeds and ratoon and volunteer cotton plants – in-crop and fallow. Both this and the suggestion above provide options applicable to the HRMS which is now critical to weed management in cotton production systems.

Monitoring the crop for weeds is another opportunity for robotic platforms fitted with weed detection and classification units. The robots could roam the paddocks collecting data on what weeds are present and their precise locations in the paddock. The farmer can then assess the priorities for management and how these weeds might be best managed – broadcast versus site-specific management. Robotic enabled surveillance can also assist with scouting for potential herbicide resistant weeds and or hot spots in the paddock; and robots will do it much more accurately than the calibrated human eyeball technique through a windscreen or open window traveling at 30 kph.

As cotton farmers begin to use robotic platforms and become confident and comfortable with the technology, they themselves will begin to identify other tasks that might be performed by the robots, possibly tasks not currently considered.

4.4   Barriers to the robotic opportunities and or issues

4.4.1   Existing

It is apparent that while there is communication between university robotic researchers there is minimal collaboration. It is difficult to ascertain exactly what the focus of the current research is for individual institutions, or to compare the potential of technologies being developed as the required information is claimed to be either the subject of IP or commercial in confidence. Research in the agricultural robotic field is the smallest component of bringing a new product to market. The overwhelming largest component is development and extension. Delays in having commercial partners collaborating with research ultimately delays access of technology to farmers.

University ownership of undeveloped research IP, and consequent quest for royalties, when negotiating licencing agreement discourages potential commercial partners to engage before the project has a known outcome. Early collaboration and partnerships with commercial businesses would guide researchers to produce more relevant outcomes sooner and commercial partners would be more advanced in development and release of the technology.

It is now apparent that there are no weed control attachments for autonomous platforms resulting from Australia research to be commercially released in the foreseeable future. Newly developed autonomous platforms will need to use existing technology, or modifications of it, to control weeds. This in itself is not utilising the potential of robotics for the cotton industry or any Australian agricultural industry for that matter.

4.4.2   Potential barriers/issues

All robotic enabled weed management technology developed now and in the future needs to be robust but simple; and the tools must be cost-effective and time efficient, otherwise they will never be adopted.

For any new robotic products or services to be successful they must integrate with the rest of the farming system and be user friendly. The cotton industry prides itself on being tech savvy which will allow it to adopt robotic technology readily, however speed of adoption will still be limited by the availability of a single user interface that controls most operations on the farm and can be used by the majority of permanent labour/management. The more crop management tasks that are conducted by the robotic platform the more comfortable and skilled farmers will become with the user interface. The user interface needs to be the new mobile phone that farmers carry 24/7.

The release of new technology to apply pesticides will require changes to herbicide use pattern registrations (label and permit). The required data for updating labels cannot be collected until the technology is available. However, the commercialised technology then cannot be used to full potential until label changes have been approved by authorities. Any delays in label changes to methods of application will stifle the uptake of new technology. And for the interim, it is not clear whether the relatively new "flexible" APVMA Pesticide Permit (Permit 11163) (see Cook 2012) would cover all potential uses, particularly in-crop use (eg. WeedIT or WeedSeeker applications via robotic platform with or without mounted shields), and or all herbicides that are likely to be identified as useful / effective in cotton systems (currently 23 herbicides or proprietary mixes covered by the permit at higher than usual label rates of application).

The ever increasing speed of technology is followed by obsolesces. Investment in technology requires a short payback period. Risk of any delays in taking technology to market will result in the technology not being developed. These risks could be from many sources such as bureaucracy, extremists, industry downturn. To encourage investment in new technology industry must help in clearing the path for the rapid deployment of new technology.

Robotic hardware used for weed control in cotton will generally be first developed for other industries with the potential to pay more. When the price of this hardware reduces, specialised algorithms will be developed or modified for cotton/agriculture. An investment in developing algorithms and packaging the technology specifically for cotton/agriculture will be assessed against the base hardware being made obsolete before the investment has been recovered.

The agricultural robotic platform of the future will need to incorporate more than just weed management tools. They will need to be functionally attractive, that is, they will need to perform

other crop management tasks besides weed management. If they do not multi-task, adoption may be hindered.

5.   Recommendations for short to medium term strategic investment by the Cotton Research and Development Corporation (CRDC)

In this instance the short to medium term is defined as a one to five year timeframe.

5.1   Research opportunities

Investing in further research associated with weed sensing/detection is not likely to provide the CRDC with any further benefits over and above what they will gain from their current funded research within the NCEA (University of Southern Queensland) led by Steven Rees (CRDC Project NEC1402) (CRDC Investments 2016-17), provided that project does deliver a stable commercialised weed detection system.

In terms of actuation tools and systems, a wealth of research already exists so further investment here is not likely to yield anything new. More appropriately, the investment opportunities that will yield greatest value for the cotton industry sit within development and extension. The CRDC currently funds a short term Summer and Honours Scholarship: Efficacy of robotic methods for the detection and treatment of herbicide resistant weeds (CRDC project QUT1602) (CRDC Investments 2016-17) but this is unlikely to result in any commercialised tool in the near future.

5.2   Development (D) and extension (E) opportunities

Herbicide resistant weeds as well as volunteer and ratoon herbicide tolerant cotton remain the weed management hurdles for the cotton industry. There is an urgent need to develop a stable commercialised weed detection system and the weed destruction tools to go with it. This should be a priority for the CRDC if the organisation is keen to engage with robotic technology. These tools could be used on existing tractors, or they may be more suited to the autonomous platforms that are commercially available or are about to become so. There is research around the world on various methods of detection and destruction but there appears to be no firm plans for development and commercialisation here; and that which has been commercialised overseas is not necessarily suitable for cotton in Australia.

Taking full advantage of robotic development in other industries requires a paradigm change in agriculture away from reliance on big fast machinery and broad acre application of pesticides. The cotton industry and the CRDC could lead this paradigm change in Australian agriculture.

5.2.1   Development of a robotic platform mounted targeted tillage tyne

An opportunity exists for investment in developing and field testing the targeted tillage tyne (of Narrabri based Dr Walsh) described above in section 3 to enable it via a high clearance robotic platform for use in both the fallow and in the inter-row of cotton crops to mechanically control ratoon herbicide tolerant cotton plants. This tyne in its current state is not suitable for robotic platform application; however some re-engineering and modifications (eg. of the hydraulics

system) should result in a fit-for-purpose robotic-enabled weed management tool. This is akin to the oldest site-specific weed management option known - hand hoeing/chipping, but via a robot in lieu of a person.

This tyne will not only serve to control ratoon and rogue cotton plants but it will have application for any weed in the inter-row, including escapes from other weed management tactics. This tool presents a viable effective integrated weed management option and could do much to protect the effectiveness of glyphosate, glufosinate and dicamba. In doing so, it will also help to maintain and possibly extend the life of the herbicide tolerant cotton varieties.

There is added opportunity to field test (in-crop) a re-developed tyne with the current commercially available weed sensors: H-Sensor, WeedIT and WeedSeeker, however, the latter two sensors would require angle mounting such that the field of detection excludes the crop rows since neither sensor can detect green on green; or skirts could be fitted to the robotic platform to exclude crop-row detection.

5.2.2   Development of a robotic mounted spot-spray system with and without shields

Osten and Cattell (2011) have previously demonstrated safe and effective use of WeedSeeker triggered shielded sprayer applications of non-selective broad-spectrum herbicides in chickpea, albeit the spray boom was tractor drawn. There is no reason to believe the same cannot occur in cotton but with the shields and weed detection units mounted on a high clearance robotic platform. Using shields allows for a much wider range of herbicides to be utilised, which is also key to helping with herbicide resistance avoidance. This is a further area worthy of development investment. The spot-spray system, for example, on the SwarmFarm platform currently works very well in fallow situations, however the system would need some modifications and additions (eg. shields or skirts) to have it operate effectively and safely in-crop. Field-testing of the commercially available H-Sensor in cotton also warrants some development attention and investment.

In some instances, in-crop applications via shield-less WeedSeeker / WeedIT / H-Sensor will also be appropriate, for example, targeting glyphosate tolerant or resistant grass species such as feathertop Rhodes grass, sweet summer grass and barnyard grass with higher dose grass selective herbicides.

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7. Organisations accessed (via websites) and perused in detail

The websites of the following organisations were searched for information and activities relevant to robotics and weed management:

Funding organisations:
- The Grains Research and Development Corporation (GRDC)
- The Cotton Research and Development Corporation (CRDC)
- Horticulture Innovation Australia (HIA)
- Sugar Research Australia (SRA)
- The Rural Industries Research and Development Corporation (RIRDC)
- Meat and Livestock Australia (MLA)

Australian Universities:
- The University of Queensland (UQ)
- Queensland University of Technology (QUT)
- The University of Southern Queensland (USQ) – National Centre for Engineering in Agriculture (NCEA)
- James Cook University (JCU)
- The University of Central Queensland (CQU)
- The University of Sydney (USYD) – Australian Centre for Field Robotics (ACFR)
- The University of New South Wales (UNSW)
- The University of New England (UNE)
- Charles Sturt University (CSU)
- The University of Wollongong (UW)
- The University of Newcastle
- Macquarie University
- The University of Technology Sydney (UTS)
- University of Western Sydney (UWS)
- The University of Western Australia (UWA)
- Curtin University (CU)
- Edith Cowan University (EDU)
- Murdoch University
- The University of Adelaide (UA)
- The University of South Australia (US)
- Flinders University (FU)
- The University of Melbourne (UM)
- RMIT University (RMIT)
- La Trobe University (LTU)
- Swinburne University of Technology (SUT)
- Deakin University (DU)
- Monash University (MU)
- The Australian National University (ANU)
- The University of Tasmania (UTAS)

Government organisations / departments:
- Queensland Department of Agriculture and Fisheries (QDAF)
- Queensland Alliance for Agriculture and Food Innovation (QAAFI)
- Department of Agriculture and Food Western Australia (DAFWA)

- New South Wales Department of Primary Industries (NSWDPI)
- South Australian Research and Development Institute (SARDI)
- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Australian Herbicide Resistance Initiative (AHRI)

Professional associations / Grower groups:
- The South Australian No-Till Farmers Association (SANTFA)
- The Western Australian No-Tillage Farmers Association (WANTFA)
- The Society of Precision Agriculture Australia (SPAA)
- Birchip Cropping Group
- The Council of Australian Weed Societies (CAWS)

International organisations / Universities:
- The Weed Science Society of America (WSSA)
- European Weed Research Council (EWRC)
- International Weed Science Society (IWSS)
- Rothamsted Research
- Wageningen University
- University of California
- Purdue University
- Texas A & M University
- American Society of Agricultural and Biological Engineers

8. Meetings and contacts held/made with key researchers and personnel in Industry and Universities

We duly acknowledge and thank the following people and organisations for providing information relevant to this review study:

- **Drs Craig Baillie** and **Cheryl McCarthy**, and **Stephen Rees** [Director and Researchers, NCEA at USQ, Toowoomba] – this project team provided us (Neville crook and I) with an overview of the weed sensing/detection research they are undertaken and what they have achieved in collaboration with weed scientists from Sugar Research Australia in terms of sensors being able to distinguish guinea grass from sugar cane; in person – March 2016.

- **Dr Tristan Perez** [Director Robotics and Autonomous Systems, QUT, Brisbane] – Dr Perez gave Neville Crook and I an overview of the robotics research specific to weed management that his unit has completed and that which is currently being undertaken. We were shown some limited data and video of the agbot in action with tillage implements working in the paddock; in person – March 2016.

- **Dr Michael Walsh** [Director of Weeds Research (Northern Region), University of Sydney, Narrabri] – regarding targeted tillage project originally with AHRI, WA; telephone and email contact – June and July 2016.

- **Dr Michael Widderick** [Weed Sciences Team Leader and Principal Research Scientist, QDAF, Toowoomba] – regarding QDAF involvement in QUT robotics research, and targeted tillage project of Dr M Walsh; telephone and email – May and July 2016.

- **Mrs Renee Anderson** [Regional Manager (Central Queensland) Cotton Australia and local cotton grower] – discussion on current weed management practices in the EIA and the weed related issues faced by the cotton industry, particularly in the central Queensland region; informal face-to-face chat – July 2016.