PART II – MANAGING SOIL AND STUBBLE

Bad old days: Mouldboard ploughing in clay soils (year) – sheen of polished surfaces that bake hard and require 'defensive tillage' (Courtesy: Jim Pratley)

On the journey: Direct drilling at Wagga Wagga (year) after a clean burn (Courtesy: Jim Pratley)

Compromises: Cool, late stubble burn Wagga Wagga (year) for summer cover but less issues with stubble at seeding with stubbles (Courtesy: Jim Pratley)

Challenges: Stubble trouble with high residue load (around 7 t/ha), long straw and inadequate machinery clearance (Courtesy: Jim Pratley)

Chapter 6

Machinery evolution for conservation agriculture

Jack Desbiolles, Chris Saunders, James Barr, Glen Riethmuller, Gary Northover, Jeff Tullberg and Diogenes Antille

Introduction

Australia lies among the top five countries worldwide to adopt *en masse* conservation agriculture (CA) farming systems (Kassam *et al*. 2015). No-till (NT) practice is still growing having reached 80-90% of crop area in many regions (Llewellyn *et al*. 2012, see also Chapter 2). This unprecedented rate of change has led to a rapid evolution in machinery for CA systems. This chapter reviews the evolution of machinery for CA systems witnessed in Australia over the last 30 years. It is structured around 4 key groups of machinery, namely tractors as the power source, crop seeding/planting, spraying and harvesting machinery covering the key phases a crop establishment, protection and grain harvesting. A final section also covers the topic of controlled traffic farming (CTF) and associated machinery adaptations, as CTF plays an increasing role in Australian cropping, occupying an estimated 22% (6.75 M ha) of grain cropping area (ABS 2017).

Tractor market evolution in Australia 1989-2017

Some 23% of farms now crop more than 1,200 ha (ABARES 2018). While 25% of cropping farmers are rated as high innovators, CA cropping equipment is shown to be the most common type of innovation adopted by Australian farmers (Nossal and Lim 2011). Australia’s agricultural machinery market has undergone significant changes over the last 30 years and has been subjected to the various highs and lows of the cropping industry. Tractor demand is often considered the litmus test for the health of the agricultural sector by the machinery industry at large and, over the last ten years, the industry has shown record demand in Australia for new tractors. The agricultural machinery industry currently separates tractor sales below and above 60 horsepower (HP) – 44 kilowatt (kW) – segregating the rapidly evolving hobby farm/lifestyle market from the traditional farming sector, respectively. Table 1 depicts selected trends within the >60HP tractor market, highlighting the increasing diversity of models, the predominant role of front wheel assist tractors and the decrease in average size in the top 10 selling tractors since the mid-2000s, explained by the increasing availability of lower priced tractors originating from Asia.

The range of tractor brands has not changed greatly over the past 30 years (Table 1), but there have been several mergers and consolidations, one of which includes the gradual merging of tractor brands under CNH Global such as Ford-New Holland (1986), Fiatagri (1991), Case-IH and Steyr (1999), restructured in 2013 under the *New Holland Agriculture* brand, part of the CNH Industrial Group. Similarly, AGCO Corporation purchased a large number of farm machinery companies, including Massey Ferguson (1994), Fendt (1997), Challenger (2002) and Valtra (2004) tractors. Smaller mergers in Europe have included the SDF company created in 1995, from a gradual merging of SAME Trattori with Lamborghini Trattori (1973), Hürlimann (1979) and Deutz-Fahr (1995) tractor brands. These mergers have consolidated manufacturing locations for these brands and intensified dealership sales, service and backup activities. Over the period, new brands have also appeared on the market, particularly lower cost brands from Eastern Europe and later from Asia.

In 2017, the Australian tractor market stood at $1.32b (TMA 2017), remaining above the $1b threshold for the 10th year in a row: 36.5% (=4,632) of the total number of tractors (=12,674) were dedicated to the lifestyle market sector (less than 60 HP), which continues to increase annually at a rate of 5-10%. In the traditional farming sector, the average tractor size continues to rise, *e.g.* from 131 HP in 2007 to 163 HP in 2017. The average cost of horsepower in this sector increased from $801 (2008) to $888 (2017), in contrast with the lifestyle market sector, where the average cost per HP, fell from $731 (2003) to $657 (2017).

Table 1. Snapshot at 5-year intervals of tractor sales and key market features in Australia

Year	>60HP annual market size, units	Type: % 2WD / FWA / 4WD (track)	HP of top 10 selling tractors	Notes
1989	6,382	24% / 70% / 6% (-)	77	14 brands (295 models)
1994	5,083	13% / 78% / 8% (-)	109	14 brands (301 models), track machines appear and show promise
1999	6,484	5% / 84% / 8% (4%)	140	17 brands (326 models)
2004	7,633	2% / 91% / 6% (1%)	161	13 brands (392 models) – market adjusting to post-brand merger period
2009	7,864	1.5% / 93% / 5% (1%)	128	16 brands (458 models) – new brands appear, stronger demand for lower power row crop and high-end utility tractors
2014	6,411	1% / 91% / 4% (4%)	102	17 brands (496 models) – increased model customization via direct factory ordering. 60-100 HP utility market demand continues
2018	7,909	2% / 92% / 3% (3%)	103	15 brands (535 models) – Above trends continue

Source: Tractor Machinery Association State of the Industry reports, for the respective years shown
Keys: 2WD: 2-wheel drive, FWA: Front wheel assist, 4WD: 4 equal wheel drive, HP: Horsepower

Evolution in tractor technology

Tractors with diesel engines provide the main power source in CA systems. The features of modern tractors provide a far more adaptable and functional unit than in the past, with technologies that assist in driver comfort, safety and farm management. Overall, tractors have become more powerful for their weight and size and can run longer on a given tank of fuel; they are cleaner for the environment and have also become mechanically more reliable.

Engines

The 1990s brought a boom in engine improvements, transmission features, and use of electronics along with many other evolutionary advancements that have made tractors what they are today. Engines have become more powerful, more energy efficient, less noisy and smoother running; in part due to the introduction of electronic common rail direct injection technology, using high-pressure fuel rail and computer controlled electronic injectors able to promote complete and accurate fuel combustion. While the emission control strategies and tail pipe emission standards of agricultural vehicles lags behind those of road transport vehicles (Kubsh 2017), current US based Tier-IV regulations (Equivalent to EU based stage IV regulations) for non-road diesel engines used in agriculture, gradually phased in since 2008, have forced manufacturers to achieve a 90% reduction in particulate material and 50% reduction in nitrogen oxides over Tier I levels of the mid-1990s. This was achieved using dedicated control technologies (*e.g.* John Deere 2019a).

In the Agriculture sector, there is currently no cost-effective substitute for diesel power which allows Australian agriculture to produce more output with less energy inputs. New Holland have commercially available tractors (T6.140 and T6.180) using *FTP Industrial* engines that run on methane or biogas, which is most economical where it can be produced on-farm (New Holland Agriculture 2019).

Transmissions

A tractor transmission converts power from the engine into useful tractive effort on the ground, and most R&D efforts have aimed to reduce losses due to friction and heat, and optimise the transmission ratios available in the key implement operating speeds to keep the engine running at peak performance, including minimal fuel consumption.

The main advance in recent years has been in the development of continuously/infinitely variable transmission (CVT, IVT) and hybrid power shift transmissions that provide a much greater (or infinite) choice of ground speed for all field and road operations. In 1995, Fendt introduced the world's first tractor with continuously variable transmission, and this set a benchmark for user control. In 2012, John Deere released its direct-drive transmission which combines the efficiency benefits of a manual shift transmission with the ease of operation of the IVT™ transmission (Figure1).

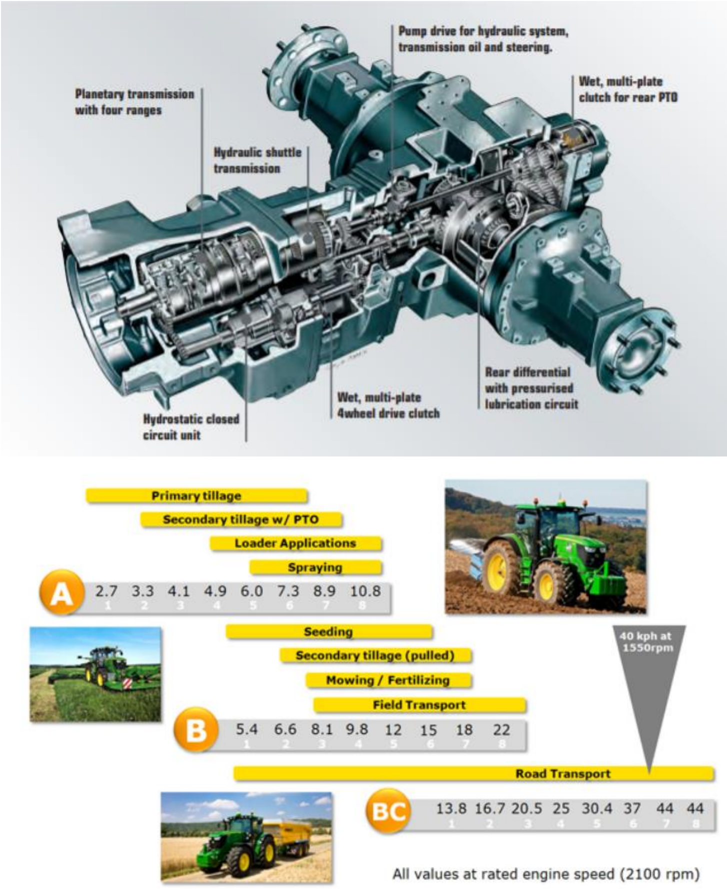


Figure 1. CVT/IVT transmissions have revolutionised tractor operational efficiency:
Top: TTV 610 drive train from ZF/Deutz-Fahr integrating stepless hydrostatic powershuttle offering automatic, PTO and manual driving strategies over 0-50 km/h speed range *(*graphic illustration courtesy of Deutz-Fahr*);*
Bottom: 8 automatic powershift gears over 3 ranges offered by the direct drive IVT from John Deere (diagram courtesy of John Deere)

In addition to improvements in the working gear range, transport speeds have also increased rapidly since the 1980s. With the introduction of the JCB FastTrack which was capable of travel speeds of ≈70 km/h, most tractor manufacturers have now increased their road speeds to 40-50 km/h. Such travel speeds have been accompanied by suspension and braking improvements to meet regulations and safety standards and allow for increased productivity of such activities as spraying and fertiliser application, along with lighter service activities and road carting, indirectly improving the overall tractor use productivity.

The improvements in transmission technology have led to efficiency improvements in the field, allowing either the farmer to intervene with gear change under load, or the tractor to automatically choose the optimum gear ratio to maintain optimum engine performance; the operational speed is kept at its targeted optimum (power or fuel consumption) by a dedicated control system with a user-friendly interface, improving operator comfort.

Tyres and tracks

Critical aspects of a tractor are its tractive performance and ground pressure affecting the extent of traffic-induced compaction, especially in CA systems where compaction removal by tillage is often not an acceptable option. As the size, weight and power of tractors have steadily increased, the need to support this weight and transmit higher power to the ground has amplified. Commonly, the number of tyres per axle can be increased while also reducing their inflation pressure. This increases the overall footprint of the tractor and adds extra load to each axle. An alternative exists in the rubber track system, which was first introduced as the Mobile-Trac System by Caterpillar in 1986. Evaluation of the benefits of tracks over dual wheels sustained strong marketing debates across the tractor industry over the ensuing three decades. In 1996, Case IH introduced their Quadtrac system, for articulated tractors giving more traction and less ground pressure than 12 tyres (x3 per wheel hub) on a 4WD tractor and eliminated power hop to provide a smoother ride. Today, many manufacturers offer competing tracked versions or alternatives, some with narrower profile and footprint adoptable for controlled traffic systems, many of which can now be specified on particular centre spacing to suit a chosen CTF system. The benefits of track systems have also been extended to trailers, air-seeder carts and harvesters, to reduce soil compaction.

In conventional front wheel assist tractor configurations, an alternative to tracks is to reduce the ground pressure under the tractor via a central tyre inflation system (*e.g*. Tigges 2015). Fendt have integrated this technology (VarioGrip) as standard on the latest 1000 Vario series tractors powered with up to 517 HP. In conjunction with Michelin tyre development, PTG launched in 2018 a fully ISOBUS compatible retrofit system that can automatically reduce and increase tyre pressure on the go from 0.4 bar to 2.0 bar suitable for optimum traction and minimum compaction in field operations and for optimum road transport efficiency, respectively (Figure 2).

Figure 2. *Left*: Track suspension technology improving the riding stability in rough terrain (*e.g*. ATI Inc. Power-Flex Trax$^{\text{TM}}$ with Terraform$^{\text{TM}}$ suspension), *Right*: New adaptive tyre technology (*e.g*. Michelin EvoBib) maximising footprint under field setting (0.4 bar) vs optimum road footprint at 1.8 bar via the use of a central tyre inflation system **(**pictures courtesy ATI and Michelin, respectively)

Cabin technology

With cropping areas continuously increasing, the time spent by farmers on tractors has increased the demand for greater cabin comfort. In a similar way that the car industry has increased the comfort and safety of cars over the past 20 years, a similar standard is now expected in tractors, to provide better working conditions and reduce operator fatigue. In 1987, Renault became the first tractor manufacturer to introduce the *hydrostable* cab, a full cabin suspension with coil springs dampers and anti-roll bars; this was a system employed on their trucks and was claimed to reduce cab vibration by 35% (Henley 2017). Cab suspension is now commonplace throughout modern tractors, and front axle suspension is considered standard in front wheel assist tractors. New means of adding suspension comfort to fully tracked tractors is also becoming more common, *e.g.* the Terraform^{TM} suspension, which improves load distribution, uniformly follows ground contours and greatly reduces vibration (Figure 2).

System controls

Electronics have played a significant role to increase the efficiency of CA over the past decade and have been pivotal in many areas of tractor development and improvement. Keys areas such as engines, transmission, hydraulics and linkage control and, most recently, headland management have improved tractor operations. Additionally, the key area of differential global positioning systems (DGPS) guidance with Real Time Kinematic (RTK) accuracy, autosteering control and many other associated precision agricultural functions have added to the tractor ease of functionality. This technology is at a stage where pre-prescribed areas and operations can be pre-programmed by the manager and the tasks completed with minimal input from the operator. The driver is there to monitor and provide redundant safety in case of system error. This is a natural interim step before fully autonomous tractors become common place. A key electronic advancement is embodied in the ISO 11783 Standard (ISOBUS) specifying a serial data network for control and communications between tractor and implement, and the associated message-based protocol for Controller Area Network (CANBUS) applications. This standardised communication protocol into pairing any tractor and implement increases the practical functionality and safety, allows more automated connection, set-up and operation to maximise productivity while minimising the user input.

As the amount of work that needs completing in a timely manner increases at the farm level, the impact of technology breakdown is becoming much greater. The development of telematics and tractor sensing systems allows monitoring of tractors and attached equipment in the field from a remote site or location. This has become more common over recent years for applications such as fleet logistics and scheduling preventive maintenance (*e.g.* John Deere 2019b). In the latter, trends in operating conditions can be logged and predictions of potential failures can be made, reducing the risk of untimely breakdown and optimising the productivity of tractor operations. This means that components and parts that are suspect or near to end-of-life or replacement period can be swapped or replaced preventively during scheduled down-time before the next critical period of work to help guarantee reliability and productivity.

Look into the future

Although FPT Industrial, the supplier of engines to both CASE and New-Holland tractors, have had methane and biofuel running engines used in trucks throughout Europe since 2016, such technology is unlikely to make a big impact in the Australian sector. EU Stage V certified engine technologies have recently appeared in the tractor markets, ‘kick-started’ by the Deutz TTCD engines in 2017.

In 2016, John Deere introduced its SESAM (Sustainable Energy Supply for Agricultural Machinery) prototype technology in a world first fully battery operated electric high-performance tractor, with 174 HP of continuous power, 400 HP maximum output, and an autonomy of up to 4 hours depending on the operations conducted, including the ability to recharge from restoring energy source (Agri-Machinery News 2017). New Holland Agriculture and Fendt have concepts for electric/hybrid tractors, but this is unlikely to replace completely the power needed for current agricultural practices. If practice change can come about (*e.g.* through automation) then smaller lighter electric tractors may become an attractive proposition. In the short term, markets are not quite ready for this still limited technology (*e.g*. Kanicki 2017), especially in the Australian context of large farms.

Figure 3. *Left***:** DOT autonomous tractor and no-till seeder tested in Canada since 2017; *Right:* CNH industrial autonomous tractor concept (pictures courtesy of Norbert Beaujot, SeedMaster, and CNH respectively)

In 2017, DOT Technology Corp. of SeedMaster in Canada unveiled a U shape, autonomous powered platform concept, designed to slide on and off a range of dedicated implements (DOT 2017). This world-first concept of fully autonomous tractor and implement system was developed as a holistic answer to the future of farming including considerations of reduced field machinery weight. A 163 HP engine powers a standard DOT unit, incorporates safety halting features, relies on remote control by the operator for swapping implements and RTK GPS positional information to follow farmer-approved path-plans for field operations. The operator reviews progress in real time and can manage multiple units to suit the farm size. While it was first equipped with a 9 m wide precision seeder implement for field testing (Figure 3), mainstreaming this concept requires a full suite of DOT-ready implements, yet to be developed with existing manufacturers.

Similarly, in 2016, CNH announced their autonomous tractor concept (CNH Industrial 2016 – see Figure 3) featuring advanced obstacle detection technology. Initially suitable for integrating within existing operator-based machinery fleets, including as autonomous support vehicles, the concept aims to move towards increased autonomy over time, offering full control and optimisation via big data management.

An automated ‘whole of system’ approach, starting with autonomous tractors, and following through the implements, fleets and tendering machines to enable non-stop 24/7 operations with little to no human intervention, are likely to be most beneficial to Australian broad-acre CA systems. The barriers to such autonomous systems currently lie beyond the tractor and with the equipment attached. ISOBUS international standards go some way towards ensuring consistent communication between the implement and the tractor; more sensors and feedback are needed from the implement to the tractor in the absence of a human operator to check the quality and safety of work being carried out. The second barrier will always be the human and industry acceptance, as well as the regulation and legalisation around a completely autonomous farm.

The future of tractor development and functionality is likely to be driven from the main markets to which the manufacturers supply, *i.e.* USA and Europe. In these regions the regulations around emissions, fuel type availability and any autonomy restriction will probably drive the demand and therefore supply of these future technologies.

Evolution of no-till seeder technology

Overview

The crop seeding operation in Australian CA systems has been optimised over the last 40 years, from the early years of 'trash farming', aiming to reduce tillage and promote residual residue cover on the surface. Two of the three key principles of CA have the most direct impacts on seeder technology requirements, namely:

- minimising soil disturbance, via no pre-seeding cultivation and low soil disturbance at seeding; and
- permanent soil cover, including dedicated cover crops, intercrops and/or previous crop residue, with least disturbance or burial occurring at seeding.

The terminology around CA systems was addressed in the mid-1990s by the Western Australian No-Tillage Farmers Association in its early years of activities, leading to the following Australian framework followed to this day, despite not being matched internationally:

- *Direct seeding*: a one pass seeding operation into stubble, using a 'full cut' soil disturbance down to seeding depth;
- *No-till seeding*: a one pass seeding operation using a tyne seeder fitted with narrow openers creating distinct narrow furrows between undisturbed inter-row zones; and
- *Zero-till seeding*: A one pass seeding operation using a disc seeder to minimise furrow disturbance, soil throw and disruption to crop residue.

During this time, the evolution in seeder technology has benefited from an increased momentum of research, dedicated to optimising the performance of the seeding system, gradually recognising the significant impact of machinery on no-till (NT) crop performance. The seeding system is defined by the components of the seeder engaging with soil and residue, and responsible for the optimum delivery of furrow inputs, including seeds and fertiliser. The principles driving its performance have been described as independent of seeder scale (Desbiolles and Kleemann 2003) and commonly, five key functions are considered in a research setting: a) residue handling, b) furrow opening, c) fertiliser placement, d) seed placement, and e) furrow closing/ pressing. Over time, the seeding system technology quickly evolved, reflecting the advance in CA cropping systems, to encompass extra functions, such as: seed pressing, pre-emergence herbicide incorporation by sowing, row placement of other nutrients (*e.g.* trace elements), amendments (*e.g.* soil wetters, soil inoculants) and pesticides (*e.g.* fungicides, insecticides…), enabled in particular by the development of accurate liquid application technology, and stubble row relative positioning via GPS (*e.g.* inter-row and on-row).

Key milestones in seeding system evolution

Initially the need to address the physical context of i) high soil strength and ii) surface residue load drove the early focus of seeder machinery modifications. While the fundamental approach to crop seeding – *i.e.* continuous furrow systems – did not change in the transition from CT to NT, some key milestones of seeder technology development over the last 30 years can be recognised. These steps occurred initially under a process of low-cost upgrades of conventional (combine) seeders under a low risk approach to experiment with NT farming. A persistent process of trial and error, which underpinned the gradual improvements of NT seeder capacity and performance, was a common endeavour for many adopting farmers, who thereby played a key role in machinery innovation contributing to the success of NT farming in Australia. Overseas seeding technologies also underwrote the diversity of choice, most notably from Canada and the USA.

In winter grain cropping, the development in seeding system technology and capabilities included the following step-changes, some introduced in different forms at various times over the last 30 years (Kondinin 1993a, 2000):

- removing tilling tynes and re-distributing seeding tynes on combine drills;
- fitting narrow openers to minimise furrow disturbance;
- increasing the seeding tyne break-out rating;
- modifying the tyne layout by increasing the seed row spacing and the number of tool bars;
- matching seed banding boots to narrow furrow openers;
- maximising opener wear life and wear shape via cast steel, tungsten carbide tile and hardfacing technologies;
- implementing deeper furrows with sub-seed disturbance, to break-up the hard pan and address increasing *Rhizoctonia solani* root disease pressure;
- adapting furrow press-wheels to optimise crop establishment into stored soil moisture, including adaptation to maximise water harvesting potential of furrows;
- optimising tyne design and increasing frame layout clearances to maximise residue handling capacity;
- separating seed and fertiliser banding to enable higher nutrition inputs at seeding;
- hydraulic tyne release systems to improve reliability and longevity in harsh and stony soil conditions;
- adapting paired row and ribbon seeding for higher seedbed utilisation, to compensate for wider row spacing, maintain higher yield potential and greater competition against weeds;
- more accurate seed placement with independent press-wheel regulated seed boots;
- tyne opener adaptation for furrow moisture seeking down to 250 mm depth;
- controlled soil throw to optimise weed control efficacy and crop safety under pre-emergence herbicides incorporated by sowing (IBS);
- increased role of disc seeder technologies for higher quality CA systems;
- development of split banding options for disc seeders;
- technology enhancement for sticky soil conditions, including self-cleaning press-coils;
- mainstreaming of contour-following seeding tynes to ensure row accuracy on increasingly wider seeders;
- liquid application technologies for in-furrow nutrition, amendment and disease/pest management at seeding; and
- high-speed compatible, low soil throw (bentleg) tyne opener technology (Barr *et al*. 2016, 2019).

Evolution in seed and fertiliser dispensing

When initially converting to NT seeding, the seed/fertiliser hoppers on combine drills were raised to accommodate the larger underframe tyne layouts, and splitter cups were adapted to accommodate dual banding arrangements (Kondinin 1993a). However, it is the air-seeding configurations, where seeds and fertiliser were centrally metered, and conveyed by air to furrow openers across the seeding implement, which achieved the necessary capacities required on large farms (Figure 4). Air-seeding technology arose from an Australian invention by Albert Fuss in 1956, who thereafter founded the Gyral Implements company in Dalby, Qld. Today's air-seeder technologies can reach up to 47 m^3 in volume capacity and have the ability to meter up to seven products (*e.g*. seeds, liquid/granular fertilisers, inoculants, amendments), including granular and liquids. The air-carts exist as frame-mounted, tow-between or tow-behind models, while their latest features include auto-section control, GPS controlled variable rate, self-adjusting calibration, fast-fill auger/conveyor system, track-axle option, monitoring cameras, and fast hopper clean-out.

The centralised metering of air seeders requires splitting in multiple stages to reach individual seeding rows, leading to variable splitting accuracies. In contrast, fast metering seed-row specific roller technology has been extended to air seeders to improve the delivery rate uniformity across seed rows and also contribute to more uniform distribution along the seed row when combined with low speed downslope air-assist delivery to row openers (*e.g.* Ultra-Pro II metering system, SeedMaster 2017). The row by row control of metering technology has recently taken a new dimension with the CX6 Smart

Figure 4. Large scale air seeder CA equipment for broadacre crops are commonly 12-24 m wide, set at 220-300 mm seed row spacing and can sustain effective work rates in the range of 15-25 ha/hr (picture by Jack Desbiolles)

Seeder, launched in 2017 by Canadian innovation company *Clean Seed Capital Group*. It offers simultaneous electronic metering of up to 6 products above each opener, GPS based corrections for overlap and curve sowing compensation. The 45 tonne, 18.7 m wide air-seeder bar also features an innovative triple shoot opener and offers a unique flexibility to deliver a wide range of furrow configurations under high resolution prescriptions row by row across the paddock (Clean Seed Capital Group 2019).

In parallel, the development of CA seeder bar implements has continually increased in width, reaching up to 27 m with double fold option for transport, and up to 65 m with end-tow transport mode. Various implement features, such as floating hitch, flexible sectional frames, parallel lift, fixed frames with rising openers, and centralised depth adjustment provide a range of specific benefits able to improve the efficacy and efficiency of crop seeding operations, such as improved contour following, high floatation, adjustable furrow till depth ‘on the go’, and swapping versatility between single/double row spacing. The scale of Australian seeders is perhaps best illustrated by the Guinness world record achieved in 2010 by the John Coggan Family in Meandarra, Qld, using a 36 m wide Multi-Planter to sow 905.5 ha of wheat in 24 hours.

Tyne versus disc seeding systems

In the Australian context, the dominant seeder technology over the last 30 years has remained the tyne seeders, whereby the ‘narrow point + press-wheel’ system (*e.g*. Figure 5a) has been widely acknowledged as the cornerstone of Australian NT farming. Its key features include the ability to till below the seed zone and separate seeds from fertiliser within the furrow to improve seedling vigour and control risks of fertiliser toxicity (GRDC 2011). The tyne-press wheel system has also been adapted to maximise the water harvesting capabilities of NT furrows, to achieve deeper moisture seeking and to increase the seedbed utilisation by the use of paired row or band sowing attachments (Moodie and Desbiolles 2016). Tyne-press wheel systems have enabled the safe application of pre-emergence herbicides immediately prior to sowing and mechanically incorporated by the seeding system. This technique developed in Australia requires physical separation of the herbicide from the seed zone to be successful, which is commonly achieved in the process of furrow opening from the associated lateral soil throw over the inter-row under a controlled speed (Haskins 2012). Such requirements emphasise the need to control the furrow opener soil disturbance characteristics in order to achieve uniform incorporation for reliable weed control and maintain high levels of crop safety.

Figure 5. (a) A majority of CA seeders in Australia use tyne seeding systems, (b) Recent interest in disc seeding systems is especially increasing among long term CA farmers (pictures from Jack Desbiolles)

In contrast, the interest in zero-till (ZT) disc seeders (*e.g.* Figure 5b) has resulted in a period of significant development over the last 12-15 years, mainly in line with a focus on reduced soil disturbance to improve CA 'quality'. Disc seeding systems include single, double and/or triple disc blade assemblies as well as hybrid disc-blade systems, and their benefits relative to tyne systems have been reviewed by Ashworth *et al.* (2010). Incentives to adopt ZT include the ability to reduce soil and residue disturbance, maximise work rates and facilitate full crop residue retention (Desbiolles 2011). The fundamental differences in furrow opening process between a narrow point and a disc blade means crop safety is not easily achieved with pre-emergence herbicides, most of which are not registered for use with disc seeders. Research has demonstrated that crop safety is highest with triple disc seeders or when using row cleaners to remove herbicide contaminated surface soil over a narrow band ahead of the seeding disc blade (Kleemann *et al*. 2014).

RTK auto-steering: A significant tool assisting CA

Tractor GPS guidance with RTK differential correction delivers repeatable 2 cm auto-steering accuracy across the farm, season after season, and enables several 'precise row sowing' strategies, such as:

- *Inter-row sowing* (Figure 6a): sowing centrally between existing stubble rows to solve implement blockage (tyne seeder) and residue hair-pinning (disc seeder) issues. This technique also provides several valuable agronomic benefits such as improved crop establishment and grain yield, lower crown rot disease (*Fusarium* pathogens) incidence, better harvestability of low-lying pulses and greater efficacy of pre-emergence herbicides (McCallum 2007); and
- *Edge row sowing* (Figure 6b): close to the side of existing stubble rows to benefit from the improved soil moisture, nutrition and biology present within the old furrow, while keeping the standing stubble intact. This technique ideally uses side-banding seeding systems with a row-based guidance system, but is often practiced with paired-row sowing under GPS guidance for ease of adoption. Edge row sowing is critical for establishing uniform CA crops in low fertility, water repellent sands.
- *On-row sowing:* is an alternative technique to edge row sowing, easier to implement at the paddock level with mainstream seeding systems and GPS guidance, but with the key drawback of uprooting and bunching existing standing stubble.

Research is currently investigating the impact of cumulative edge row sowing within a permanent row zone, as a way to enhance the seed row fertility and productivity on deep sands (Desbiolles *et al*. 2017). Where the seeder tracking behind the tractor is not sufficiently stable, some passive and active implement steering options exist to guide the implement more precisely onto the intended path (Desbiolles 2017).

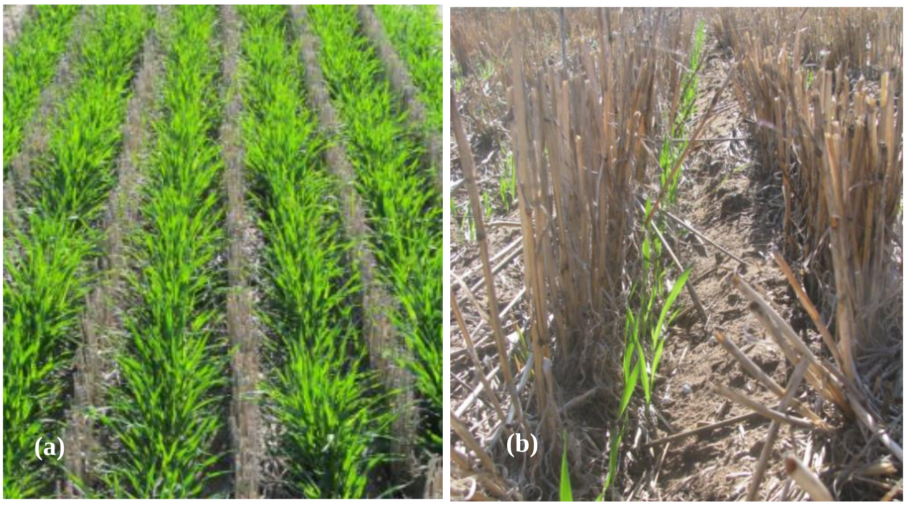


Figure 6. Example inter-row sowing (a) and 'edge row' sowing (b) of barley crops into wheat stubble. Both techniques require GPS autosteer guidance with RTK accuracy, and may benefit from additional GPS steering of the implement *(*pictures from Jack Desbiolles*)*

Innovation in residue cutting technology

A novel approach to crop residue handling at sowing has been the commercial development, led by the South Australian No-Till Farmers Association, of the *Aqua-Till*^{TM} 'liquid coulter' (Figure 7), which uses ultra-high pressure (UHP) waterjet cutting technology to slice very large amounts of surface residue ahead of a disc or tyne seeding system. Recent evaluation by Taki *et al*. (2018) showed residue cutting was most effective under wet and compressed conditions. Liquid herbicides have also been successfully applied under the *Jetacide*^{TM} adaptation of the technology for the termination of cotton ratoons after harvest (Butler 2018), enabling rapid NT establishment of follow-up winter grain crops. A current research adaptation of UHP liquid-jet technology focusses on the banding of amendments (*e.g*. gypsum, lime, and nano-carbon liquids) below furrow depth in order to mitigate specific constraints at the furrow scale.

Figure 7. Recent research showed the Aqua-Till^{TM} waterjet cutting capacity of wheat residue is proportional to the nozzle orifice area, and exceeds 35 t/ha with a 0.3 mm nozzle size *(*picture from Greg Butler*)*

Precision planter technologies

Precision planters used for summer grain crops on up to 1 m row spacing have evolved significantly since the 1980s, when mechanical singulation technology was still competing with early versions of single row vacuum pick-up plate and pressurised drums, and mechanical ground drives combined sprocket ratios with plate hole numbers to adjust seed population per ha (Kepner *et al*. 1986). While double disc openers have remained the common basis of most planter row units, today's technology incorporates many innovations which play an active role to maximise performance and efficiency of wide row crop planting in CA systems. These include:

- High speed capable, vacuum or pressure-assist seed singulation systems, coupled with assisted delivery into the furrow to achieve consistent plant-to-plant spacing on every row;
- Singulation plates optimised for many seed types and sizes, increasingly including winter grain crops;
- Hydraulic over mechanical drive upgrade with GPS based control systems enabling ground drive equivalence, variable rate by prescription zone and row level swath control via individual clutches, for row auto shut-off to cancel overlap over headlands;
- Electric drive on individual row units enabling similar row by row variable rate control GPS-based, with additional benefits such as self-adjusting individual feed rate to maintain constant plant spacing when planting on curves;
- Controlled down pressure to achieve constant furrow depth across variable strength soil types, and ensure consistent seed placement;
- Controlled down force over furrow closing to tailor to the seed agronomic requirements in soil specific conditions; and
- Most recently, 'on-the-go' sensing of in-furrow data (*e.g. Smart Firmer*^{TM}, Precision Planting 2019) such as organic matter, moisture, temperature, cation exchange capacity and residue content to optimise – in true-time – furrow uniformity (via adjustable residue managers), seed placement depth into moisture (via self-adjusting gauge wheels) and seed/fertiliser rates matched to soil zone potential.

The precision management of seeding operations for winter grain crops is a recent innovation, which involves extending and adapting precision planter technologies (Figure 8) in particular to suit narrower spacing down to the 25-38 cm spacing range. The resulting uniform crop establishment at a consistent plant spacing on the row, combined with precision placement within the furrow, allows significant seed cost savings, especially when using high vigour graded (hybrid) seeds (*e.g*. 40-60% seed savings per ha achievable with hybrid canola). For the narrower row spacing broadacre applications, various bulk fill systems have been developed to integrate a centralised high capacity seed hopper, designed to continuously recharge the buffering mini-hoppers within each row singulation unit.

Figure 8. Precision planting technology adapted for winter grain crop sowing is the new frontier of CA mechanisation in Australia (picture from Jack Desbiolles)

Look into the future

The mechanisation of crop seeding continues to evolve in line with the expanding knowledge of successful CA cropping systems in Australia, and the ability to improve operational and agronomic efficiencies via greater integration of real time sensing and automation, in a precision agriculture framework. The current trends point to providing each individual seed (of calibrated vigour and potential) with an optimised furrow environment, row by row, with a view to maximise the yield performance of each individual plant across the whole paddock.

Innovation in sprayer technology

Without tillage, CA remains dependent on chemical applications to control weeds and pests. For weed control alone, farmers typically spray weeds before seeding as a non-selective ‘knock down’, immediately prior to seeding with soil applied pre-emergence chemicals, and during the season with multiple post-emergence sprays. The constant battle to conserve moisture in Australian conditions has also led to summer weed spraying becoming standard practice, with entire farms being sprayed (often multiple times) after major summer rainfall events. In addition, in-season pesticide, fungicide and foliar fertiliser applications, as well as end-of-season spray topping, make the sprayer arguably the most used implement in CA. The evolution of sprayer technology over the last 30 years was driven by the following requirements (GRDC 2017):

- Need for *timely applications* and therefore higher work rates (exacerbated by increased cropping area);
- *Minimise crop damage* leading to yield loss, especially from over-application due to overlaps, cross contamination of chemical mixtures between sprays and trafficking damage during in-season sprays;
- *Maximise application efficacy*, whereby the issue of herbicide resistance has become severe in Australian CA and any under-application or poor application quality can accelerate the selection for herbicide resistant weeds (Broster *et al*. 2019, see also Chapter 10);
- *More sophisticated chemistries*, providing a toolbox for selecting weeds in crop, and managing the development of herbicide resistance. However, with this sophistication came cost and as such, now every litre of chemical is monitored closely;
- *Sensitive cropping areas* (such as vineyards and cotton fields) in proximity to urban areas and organically grown farms requiring even more effectively controlled spray drift, especially during night-time spraying (enabled by tractor autosteer guidance and required by ever more demanding spraying programs), when high risk of surface temperature inversion occurs; and
- *Operator safety*, particularly with the handling of chemicals in the mixing processes.

Modern sprayer technology offers drastic improvements in work rates from a typical 30-40 ha/hr in the early 1990s to 80-90 ha/hr today; improved efficacy to minimise both under and over-application; high clearance machines, safe chemical handling processes and better controlled droplet size. Technology advances are summarised below by major components of a sprayer.

Trailed vs self-propelled

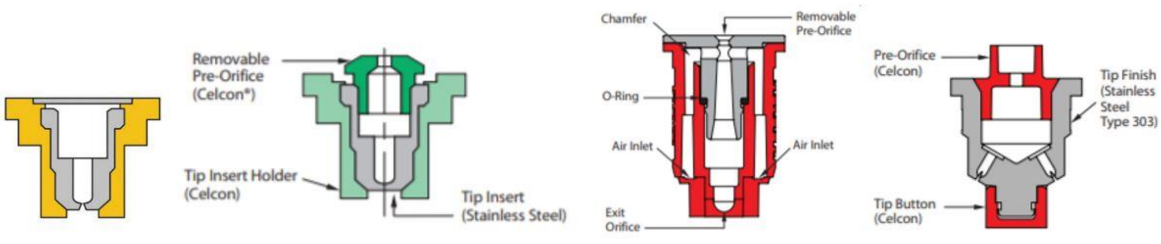
As little as 15 years ago, trailed boom sprayers dominated the Australian market, and a range of tanks and boom sizes were available to suit different farms. Self-propelled (SP) sprayers have now taken a major share in sales of the large farm-scale market, with growers chasing specific benefits including high work rates associated with larger tanks, wider booms, high effective speed through dedicated suspension systems, and minimised crop damage with high clearance chassis design. The 2017 estimated sales of SP sprayers alone in Australia was over $250 M or 12% of the total major new machinery sales (TMA 2017). However, the significantly higher cost of self-propelled units currently limits their adoption on low to mid-scale farms.

Nozzle technologies

The nozzle function on a sprayer is to control liquid flow, convert (via atomisation) the spray liquid into suitable size droplets, and disperse the droplets in a specific pattern for the target application. Conventional *flat fan nozzles* (Figure 9a) with a spray angle between 80-110 degrees have been the most commonly used nozzles in CA and ISO standards (ISO 1984-2018) have been in place since the 1980s linking recommended flow rates, operating pressures and droplet sizes with standardised nozzle colours and physical dimensions. Recent developments in flat fan nozzles has seen the pressure range increase, enabling lower pressures to generate coarser droplets and reduce drift. Reductions in spray drift risk has best been achieved with *pre-orifice* 'low-drift' nozzles and *air induction nozzles*. Pre-orifice nozzles (Figure 9b) contain a relatively large exit orifice compared with conventional flat fan nozzles and a smaller metering orifice close to inlet of the nozzle which causes a pressure drop and pre-atomisation. The combination of a pressure drop and large exit orifice minimise the atomisation of smaller droplets and therefore narrow the range of droplet sizes created to a coarser range. Air induction nozzles (Figure 9c) additionally draw air into a mixing chamber via a venturi effect. This creates larger air filled droplets, less prone to spray drift, which shatter on impact with the target to create smaller droplets. Nozzle orientation can also have an impact on spray drift and coverage. *Twinjet* (Figure 9d) and *dual pattern* nozzles, and fore/aft nozzle arrangements (Figure 10), improve coverage on vertical surfaces within the canopy, through standing rows of stubble and on rough surfaces.

The vast majority of spray nozzles come in fixed sizes, where pressure adjustments vary the flow rate to account for speed variations in the field. This can be achieved through the spray control unit, although droplet size and nozzle performance are very sensitive to pressure. Low pressures cause inconsistent spray patterns resulting in poor coverage. High pressures increase the proportion of fine particles, increasing the risk of spray drift (GRDC 2017).

Multi-tier nozzles (double, triple and quad – *e.g*. Figure 10) have been developed and paired with electronic control systems to swap automatically between nozzles, increasing the effective range and providing a level of optimisation to suit the impact of variable operating speed on desired droplet size. *Pulse-width modulation* (PWD) is an alternative approach to control flow rate at the nozzle (Giles *et al*. 1996). PWD technology pulses a solenoid to actuate a diaphragm, closing flow from the nozzle based on an inputted duty cycle. The duty cycle typically can close the nozzle up to 10 times per second limiting the flow to between 20-100% of its full capacity and providing the ability to limit the rate of chemical application 'on-the-go' as speed varies. Importantly this can be achieved with minimal change to the pressure, providing a consistent droplet size and spray pattern. Having such sophistication at the nozzle level increases cost but enables variable rates for site specific management, or the ability to shut off nozzles for a high resolution section control.



(a) (b) (c) (d)

Figure 9. Example flat fan nozzle technologies: conventional (a), pre-orifice low-drift (b), air-induction (c), twin-jet (d) (diagrams courtesy of Teejet Technologies).

Figure 10. Fore/aft dual (left) and multi-tier (right) nozzle arrangements (pictures courtesy of Teejet Technologies*)*

Boom design and height control

Boom stability while cornering and navigating across the paddock is critical for spray accuracy. Height movements in the boom from vertical movement or a rolling action reduces spray quality – in the worse cases leaving unsprayed strips, concentrating chemicals in hot spots, generating boom damage from ground strikes, or increasing the risk of spray drift (Heidary *et al*. 2014). The acceleration of the boom tips while turning can induce yaw in the boom and cause speed differentiations over the boom length, therein reducing spray quality. With the demand for higher work rates driving boom widths up to 54 m and operating speeds in excess of 30 km/h, maintaining a stable boom is a challenge. Modelling research by Langenakens *et al*. (1999) showed spray deposits could vary between 0-760% under large sprayer boom rolling motion and vertical deformations, due to excessive speed.

Boom stability has been greatly improved by isolating its movement relative to the chassis. This has been achieved by minimising total chassis movement via improved axle suspension and through height control systems. Passive boom height control has been achieved with flexible boom centres in the form of fully supported, suspended and semi-suspended designs which have been available in the market for years (Kondinin 2001). Active boom height control is now being widely adopted, taking measurements of downforce on boom gauge wheels or, more commonly, through ultrasonic sensors to provide real time control over boom height uniformity. Unlike ground wheels, ultrasonic sensors cause no crop damage and are able to sense an often variable crop canopy height – a key advantage for in-season applications. Initial adoption of active boom height control was slow due to cost and the sampling frequency and response of the booms limiting performance at speeds above 20 km/h. However, these issues have largely been addressed and such sensors are almost a standard feature on newly purchased sprayers. The design of wider booms, more heavily loaded with nozzles, control units and sensors has forced manufacturers to investigate lighter and stronger materials to maintain structural integrity and boom stability. As a result, manufacturers are opting to move to aluminium truss booms – reducing boom weight by as much as 50%, and adopting the light, stiff and strong carbon fibre mast technology from the yachting industry.

Transfer systems

Mixing, pouring and loading chemicals onto the sprayer traditionally places the operator at risk. Closed loop transfer systems, which use suction to pump chemical from the commercial drum and mix into the main spray tank (sometimes via an induction hopper) safely isolate the operator from chemical exposure (Kondinin 2001). Chemical suppliers have adapted to safer operations by supplying re-fillable drums with quick fit attachments and measurement scales printed on the side. Re-fillable drums also save time in the cleaning process and eliminate environmental risks associated with disposal of non-refillable chemical drums.

Pumps and plumbing

At the heart of the spray technology is the pump which is used to pressurise and draw liquid from a tank. The liquid is pumped in two paths, to the boom section and nozzles, and back to tank to provide agitation and bypass return when the boom section is turned off. In its basic principle, the spray pump technology has not changed in decades, although the capacity has grown to match increasing work rates. Rather, the technology advancements have come from the plumbing quality and functionality between tanks, pumps and nozzles – offering a range of options to control the flow of liquid and output at the nozzles, and options to mitigate the risk of contamination between mixes.

Sprayers now split wide booms into many sections, with liquid feeding centrally into each section reducing the extent of internal pressure drop. When paired with solenoid control valves and GPS technologies, this arrangement enables sectional shut off to reduce overlap in headlands: more sections, down to single nozzle level, increase the resolution and further minimise overlap. Flushing and rinsing between spray mixtures is typically achieved by opening a valve at the end of each spray section. Clean water flush tanks and recirculating booms have also been incorporated onto sprays booms to streamline this process for efficiency and efficacy.

Direct injection (DI) systems mix chemical and clean water in-line and enable the primary tank to contain water alone. This results in faster more efficient mixing, less chemical waste and a quicker cleaning process after spraying (Figure 11). The popularity of these systems is growing, driven primarily by the need to minimise cross contamination between chemical mixtures. However the cost, particularly when multiple products are commonly used, the inability to mix granular formulas, and the risk of exposure to concentrated chemicals during maintenance continue to limit adoption on a broad scale.

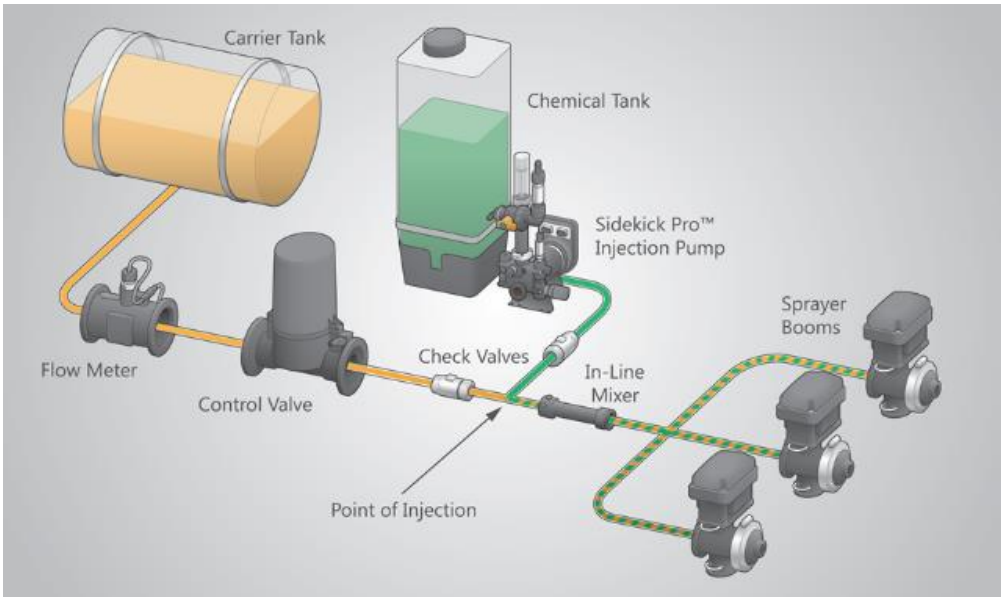


Figure 11. Example direct injection concept in sprayers – *Diagram courtesy of Teejet Technologies*

Weather Stations

The weather, in particular the temperature, water evaporation rate (delta T) and wind speed, has a major influence on spray drift risk and application efficacy. Many product labels, and state or territory legislation, require operators to record wind speed, wind direction, temperature and humidity at the site of application for accountability and traceability. Hand-held weather stations are common place for this application, with more and more on farm weather stations, and tractor mounted weather stations being adopted. Regional weather station networks are being established within the farm community to record weather conditions at ground level, but also at a 10 m height for predicting temperature inversions, which drastically increase the risk of long-distance (2 km+) spray drift. These farmer-initiated infrastructures have been established with the intent to stay ahead of their duty-of-care to neighbouring industries and communities, and therefore reduce the risk of important chemistries becoming banned (PIRSA 2018).

Sensing

In an attempt to cut down the high chemical costs in blanket applications, sensors have been, and continue to be, developed for targeted weed spraying applications. The *WEEDit* (Figure 12) and WeedSeeker sensors, which use electro-optical sensors to detect plant chlorophyll and activate individual spray nozzles via electrical solenoids, have found commercial success and are currently being used in spot spraying applications of summer weeds. Major benefits for the CA systems are significantly reduced chemical use and the possibility to afford higher chemical dose improving the weed control efficacy and lowering the risk of weeds evolving herbicide resistance. Weed sensing technology can similarly be paired with actuators and mechanical weeding devices (rather than solenoids and spray nozzles), offering a chemical-free alternative (*e.g. Weed Chipper*) for 'spot' weed control (GRDC 2019).

A greater challenge is to detect weeds in the growing crop and to selectively apply chemicals. New sensor developments, such as the H-sensor by Agricon are combining red, near infrared and plant shape factors to achieve this. This technology has been tested in Australian conditions (Dimos *et al*. 2018) and can identify grasses within broadleaf species, but identifying individual species remains a challenge. Further, as the detection algorithms use shape factors, its field of view also limits performance and detection is only viable prior to canopy closure. The "green on green" sensor fitted as a limited release on the Agrifac 48 m sprayer is also being developed and uses a RGB camera and artificial intelligence with deep learning to target broadleaf weeds in cereal crops (Jourdain 2019). Despite the current issues, the importance of such technology should not be understated. With growing herbicide resistance issues and the diversity of effective herbicide mixes dwindling, the significance of in-crop weed sensing applications is becoming increasingly important.

Figure 12. *WEEDit* sensing light footprint under sprayer boom during night spraying of summer weeds (picture courtesy of Bulla Burra farm)

Harvester technology

Older harvesters in Australia tended to have a comb or closed front, which left long straw protecting the soil from wind and water erosion. This concept originated from the original stripper design pulled by horses where the crop heads were taken off between long extended fingers, which were ideal for low yielding crops (Quick and Buchele 1978). A 1986 Kondinin Group survey (Kondinin 1993b) conducted across all of Australia's grain cropping areas with a 24% response rate highlighted that 51% of the 1692 recorded harvesters were closed front type, and 49% open front type. Today, modern harvesters in Australia use open fronts and are principally manufactured in the USA or Europe, where much higher crop biomass levels are common. The open front can cut the crop close to the ground and get weed seeds into the harvester for treatment as part of an integrated weed management system, increasingly valuable in modern CA cropping systems (see Chapter 10).

Harvester power, front width, grain tank capacity and weight have increased significantly over the last 30 years. Modern harvesters are currently categorised into a class system which is broadly based on engine power (Eckelkamp 2011), namely Class 4 up to 160 kW; Class 5, 161kW to 199kW; class 6, 200kW to 240kW; class 7, 241kW to 279kW; class 8, 280kW to 300kW; class 9, above 345kW; and class 10, above 373kW.

Traditional open fronts use a screw auger to move material sideways towards the centre feeder house which takes the crop into the harvester for threshing and separation. To use the full capacity of the larger headers in lower rainfall zones, open front widths now commonly reach 11-12 m, with up to 18 m available. These fronts commonly rely on air-bag floatation systems to float along, aiming to keep the cutting height constant across the paddock, while wide front stability at speed is improved by the use of adjustable, spring-loaded side gauge wheels. Draper belt fronts are now the most common alternative as they feed the crop more evenly, are lighter weight and can cut the crop even closer to the ground. Flexing draper fronts (e.g. Figure 13) are a recent development for harvesting very low crops such as lentils whereby the cutting knife can additionally flex to better follow ground contours across the width and maximise crop harvestability.

Harvester front technology

Figure 13. Flexi-belt fronts can follow ground contours across their width with a 225 mm flex range (*e.g.* Claas Convio Flex front, picture by Jack Desbiolles*)*

Stripper fronts were first commercialised in 1989 in the UK and are increasingly popular in Australia as a way to maximise the quantity of anchored stubble in CA systems. They use rows of stripping fingers fitted on a counter-rotating barrel over the full width of the front. They are designed to remove the grain heads from the crop, which is achieved most efficiently on thick and even crops (Figure 14). They have the advantage of increased capacity and efficiency, as well as improved performance in high moisture and weed infested crops, since mostly pre-threshed grain and chaff with only limited straw material are taken into the harvester, while the bulk of the straw remains as anchored stubble. Stripper fronts integrate best with disc seeders due to the straw length, while there is some evidence that the long straw may also reduce summer weed problems. Stripper fronts generally are limited in width due to their weight, and efficiently picking up lodged crops can be a problem.

Figure 14. Stripper fronts use multiple rows of stripping fingers (inset) and help maximise the proportion of anchored residue retained in CA systems, *e.g.* Shelbourne Reynolds (picture by Glen Riethmuller)

Crop threshing and separating components

Conventional harvesters have a rotating drum located transverse to the direction of travel and threshing the grain against a stationery and adjustable concave, followed by a separation process, commonly over alternating straw walkers or multi-separation rotors. While add-on drums can improve both feed and threshing efficiency, this concept tends to limit throughput but can handle damp straw very well. A majority of current harvesters in Australia use single or twin rotors oriented in the same direction as travel, first introduced in 1977 by International Harvesters as the *Axial Flow* concept, which offers the advantage of gentler threshing over a larger concave area and a more efficient straw-grain separation further along the rotor. These rotary harvesters tend to break the straw more, due to the longer processing path around the rotor, which reduce its quality for baling and handling but makes sowing into stubble with tyne seeders easier. Hybrid systems also exist to combine the relative benefits of transverse drum threshing with efficient rotary separation.

Technologies for integrated weed management

When the maturity of weed and crop coincide well, weed seeds can be collected effectively during the crop harvesting process, so harvest weed seed control (HWSC) methods have been developed (Walsh *et al*. 2013, see also Chapter 10) to assist with herbicide resistant weeds. Their success depends largely on how successful the weed seeds can enter the harvester and be streamlined on exit. The various harvester modification options (Weed Smart 2019) include the following:

- *Windrow burning* became common for weed seed control by simply taking the straw spreaders off to allow careful burning of harvested windrows. Beside the high labour intensity, this method has the risk of the field catching fire, especially in high residue crops such as cereals.
- *Chaff carts* are towed behind the harvester to catch the material off the sieves. When carts are full the material can be dumped in the paddock for either later burning, grazed by stock or removed for disposal or use.
- *Chaff lining* is a low-cost approach where a chute is added to the back of the harvester to concentrate the chaff material into a thin band, usually onto a wheel track, that can rot down with rainfall. Even if some weed seeds survive, the resulting weeds are concentrated in area and therefore can be targeted with herbicide. At best, the chaff lines are kept permanent across seasons, to reinforce the effect. In a controlled traffic system, the chaff is best dropped onto the wheel tracks (using a *chaff deck*), where vehicle traffic additionally contributes to weed control. This option also helps reduce soil dust in summer spraying operations.
- *The Glenvar Bale Direct^{TM} system* has a straw baler attached behind the harvester to capture all material residues coming out of the harvester into bales. These bales have a high string number to

help hold the fine material in the bale and then can be removed for uses such as stock feed (as there is some grain in it) or pelletised with other ingredients for confined stock feeding.

- *Weed Seed Destruction Mills* (Figure 14). The *Harrington Seed Destructor* (HSD) was initially a trailed machine behind the harvester with its own power source. It was designed to mill the chaff and weed seed material off the sieves using a cage mill. Dedicated research underpinning later designs developed by the University of South Australia (Berry *et al*. 2014, 2015), suited to high class harvesters, have impact destruction mills integrated into the back of, and powered by, the harvester, and were commercialised as the *iHSD*. One drawback was measuring sieve losses as all the material goes through the mill. The later designs developed by De-Bruin Engineering (SA) and McIntosh Distribution (WA) have two vertical mills at the ends with an auger taking material into them; this auger has a removable floor so grain loss can be assessed and foreign objects can be captured and removed. They are also powered directly from the harvester shafts via belts which are more energy efficient than hydraulic motors. The *Seed Terminator* is an alternate design which first introduced a mechanical drive solution and uses a multistage hammer mill. Major harvester manufacturers are now also working on different weed seed destruction mechanisms, which will further advance the technology and aid CA. On-going R&D for all of these systems is focussed on reducing power usage while maintaining high levels of weed seed kill. The benefit with such systems is that the pulverised material is returned to the paddock and not burnt or nutrients removed, but a side effect is that the fine dust can become a harvester fire risk if not carefully managed.

Figure 15. Weed seed destruction at harvest is a recent Australian innovation that is a game changer for sustainable weed management in CA systems . *Left*: close-up view of *iHSD* early prototype with hydraulic drive (picture by Chris Saunders*) Right*: Seed Terminator unit in operation below a conventional straw chopper (picture courtesy of Seed Terminator*)*

Controlled traffic farming (CTF) is increasing Australia-wide (Tullberg *et al*. 2007) but spreading the straw evenly is a problem for wide fronts – now out to 18 m width. Nufab have developed a limited release of a double conveyor and spinner system to help spread the straw to 18 m but more work needs to focus in this area. Modern straw chopper/spreaders claim spreading capabilities up to 12-15 m wide (Kondinin 2018).

A Global Positioning System (GPS) for automatic steering and crop output mapping is now commonly used on harvesters and this reduces overlap for greater field efficiency and is also required for CTF. Yield mapping is common on most harvesters, where the grain flow is monitored and recorded along with GPS position. Grain moisture is measured on the go together with yield, and increasingly with protein level, which can guide the next season nitrogen input using variable rate application.

Chaser bins pulled by tractors increase harvester field efficiency and many now have a system where the harvester controls the tractor speed to facilitate easier unloading 'on the go'.

Adaptation to manage snails in crops

Snail contamination of grain is a continuing problem in southern areas of Australia, exacerbated by residue retention, and some management options have extended to harvester modifications (Leonard *et al*. 2003). These include *dislodger bars*, mechanically knocking snails off the crop ahead of the harvester front, and *fixed aperture screens* for separating snails from grain within the harvester. Field research showed the stripper fronts are able to minimise the intake of snails into the harvester.

Machinery integration into CTF systems

History

In Australia, Adem and Tisdall (1984) demonstrated the benefits of 'permanent bed' cropping systems. Tullberg (1988) confirmed the energy effects of controlling traffic, noting that a few Queensland grain growers were also doing this with conventional tractors modified to 3-m track gauge to match the harvester. Controlled Traffic Farming (CTF) was developed and defined as a package in a participatory research, development and extension program in the 1990s (Yule *et al.* 2000). Large-scale adoption followed. The Australian Controlled Traffic Farming Association Inc. (ACTFA, www.actfa.net/) has defined as the fundamentals of CTF:

- All machinery has the same or modular working and track gauge width, which allows establishment of permanent traffic lanes;
- All machinery is capable of precise guidance along the permanent traffic lanes; and
- Farm, paddock and permanent traffic layout arranged to optimise surface drainage and logistics.

In practice, it is usually combined with RT or NT, greater surface residue retention, opportunity cropping, and more precise placement of inputs. Over the past 25 years, the percentage of Australian grain cropping land under CTF increased to 15% in 2008 and 29% in 2016. It has also been adopted by an unknown, but substantial number of cotton and sugarcane growers, and some horticultural producers. Adoption is driven by grower perceptions of the benefits, which vary with region, soil type and cropping system, but can be grouped into those related directly to the management of soil compaction, and those which might be described as 'system' benefits. The latter includes the environmental benefits associated with the perceived overall improvements in soil health and function. Although significant, these benefits are more difficult to quantify than the soil and agronomic benefits that result in improved yield, and water and fertiliser use efficiency.

Compaction-related benefits of CTF

Compaction damage occurs almost instantly under traffic on relatively soft soil conditions, and one pass of a farm vehicle may cause up to 90 % of the maximum compaction. Compaction is probably endemic in Australian systems where each crop involves traffic on more than 40% of field area by 10-35 t machines. Compaction reduces porosity and increases soil strength, impeding root exploration of the profile, and increasing the risk of run-off and soil erosion, and therefore nutrient losses to the environment and watercourse pollution. It adversely affects soil biota, water and fertiliser use efficiency, constraining yield and irrigation intervals (Antille *et al.* 2015). Mechanical amelioration of compaction is energy-demanding and expensive, and soil recovery through natural processes is slow or non-existent in some soils (Pollard and Webster 1978, see Chapter 8). CTF restricts all heavy traffic to permanent traffic lanes, occupying 10-25% of crop area, allowing most crop production to occur in soil unaffected by wheel compaction. Direct effects of CTF compared with non-CTF systems have been demonstrated in a wide variety of soils and cropping systems:

- Increased water infiltration into the soil (Li *et al.* 2007);
- Increased plant available water capacity (McHugh *et al*. 2009);
- Increased soil biological activity (Pangnakorn *et al*. 2003);
- Reduced run-off and nutrient loss (Rohde and Yule 1995); and
- Reduced risk of denitrification and soil emissions of greenhouse gases (Tullberg *et al*. 2018).

These effects all facilitate more sustainable and productive cropping, and CTF is usually associated with reduced production costs and improved yields (Chamen *et al*. 2015).

Indirect 'system' benefits of CTF

A significant proportion of equipment power (and fuel) is used to create compaction. This power to overcome motion resistance can be very large in soft, cultivated soils in 'seedable' condition, and smaller on hard, dry soil. Motion resistance reductions of 20-40% have been reported for travel on permanent lanes, instead of crop beds. This improved trafficability enhances timeliness allowing more rapid start (or resumption of work) after rainfall events, an important effect noted by McPhee *et al*. (1995). There is also a significant energy penalty involved in mechanical disturbance of wheeled soil (Luhaib *et al*. 2017). Other indirect benefits of CTF are matters of grower observation, such as:

- A slow improvement in paddock, and consequently crop, uniformity is often noted from the elimination of traffic-induced soil variability developing from random field traffic;
- Greater precision is possible in the more uniform soil conditions of CTF, facilitating more precise placement of seeds, fertilisers and crop chemicals; and
- CTF growers note the convenience of having only two soil, crop and weed conditions to manage (crop beds and permanent traffic lanes), with both in a consistent spatial relationship with their equipment.

Machinery integration into CTF systems

Most grain growers have been able to develop compatible CTF systems by integrating the modification of some units with their normal equipment replacement cycle, often at little additional cost. Conversion from a conventional mechanisation system, with unmatched machinery and track gauge widths, to CTF should consider the steps listed below. Decision support systems (*e.g*. CTF Calculator, www.ctfcalculator.org/) have been developed to calculate and illustrate the relative footprint of a given mechanisation system, and to assist growers with CTF designs as they transition from a conventional system to CTF. By providing information on the machinery modifications required, an economic evaluation can then be undertaken to assist decision-making. Such decision support systems can also be used to assess compaction management options (*e.g*. deep tillage) based on estimates of field cropped area affected by traffic. Similarly, tools are available to plan the layout of CTF systems such as aerial photogrammetry coupled with digital elevation models used in combination with soil type and historic yield maps (Antille *et al*. 2019). The key components of CTF systems are (Isbister *et al.* 2013):

- *Guidance system*: global navigation satellite systems with real-time kinematic (RTK) ±0.02 m correction;
- *Machinery matching*: decide on imperial or metric system, select the operating width (*e.g*. 3:1 or 2:1 ratio sprayer-combine harvester and planter), match wheel track spacing (*e.g*. 3 m);
- *Design of permanent traffic lanes*: cropped or bare, and width; and
- *Layout considerations*: optimisation of in-field routing and orientation to minimise risk of erosion and runoff.

CTF adoption can be more challenging in other (non-grain) cropping systems, but there are many successful examples in cotton (Antille *et al*. 2016), sugarcane (Braunack and McGarry 2006) and horticulture (McPhee and Aird 2013). The one common theme of almost all successful CTF adoption has been careful, long-term planning (see grower Case Studies, Chapter 4).

Conclusions

Over the last 30 years, the evolution of cropping machinery for CA systems has been remarkable, leading to major steps in field productivity improvements, machine reliability, energy efficiency, ergonomics and operator safety. A fundamental contributor has been the standardisation of communication protocols via ISOBUS and CANBUS, mainstreamed over the last 15 years. This has improved user-friendliness, integration, compatibility and functionality of plug-and-play control system technologies. In the highly mechanised, large cropping farm context of Australia, the integration of GPS geolocation into mapping and control systems has perhaps made the most notable difference to the adoption of controlled traffic farming and the development of precision agriculture, underpinning the successful implementation of effective and efficient CA systems. The logical progression in machinery evolution lies in further innovation around powering technology, real-time sensing within soil-plant-machine systems, machine to machine wireless communication, data management platforms and automation of machine tasks removing operator control, with a focus maintained on improving the productivity of both the operator and the grain producing plant. While cropping system and operator productivity will continue to be a major focus, we can also expect an increased emphasis on minimising the environmental impacts – both on and off-farm – of equipment system operation.

References

ABARES (2018) Australian Farm Surveys and Analysis: Report of the Farm Physical Characteristics for the Grains Industry 2015-17 (ABARES, Department of Agriculture and Water Resources: Canberra) www.agriculture.gov.au/abares/research-topics/surveys

ABS (2017) Australian Bureau of Statistics Land Management and Farming in Australia2015-16. Catalogue no. 4627.0 www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02015-16?OpenDocument

Adem H H, Tisdall JM (1984) Management of tillage and crop residues for double-cropping in a fragile soil. *Soil and Tillage Research* **4,** 577-589

Agri-Machinery News (2017) John Deere SESAM Electric Tractor www.youtube.com/watch?v=kxLm2XnQixk

Antille DL, Bennett JMcL, Jensen TA (2016) Soil compaction and controlled traffic considerations in Australian cotton-farming systems. *Crop and Pasture Science* **67**, 1-28

Antille DL, Chamen T, Tullberg JN *et al.* (2019) Controlled traffic farming in precision agriculture. In (Ed. JV Stafford) "Precision Agriculture for Sustainability, Part 2: Delivery Systems" Chapter 10 pp 239-270, Burleigh Dodds Series in Agricultural Science No.52 (Burleigh Dodds Science Publishing Limited: Cambridge, UK)

Antille DL, Chamen WCT, Tullberg JN, Lal R (2015) The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. *Transactions of the ASABE* **58**, 707-731

Ashworth M, Desbiolles J, Tola E (2010) Disc seeding in zero-till farming systems: A review of technology and paddock issues (West Australian No-Tillage Farmers Association: Northam, Western Australia)

Barr JB, Desbiolles J, Fielke J (2016) Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers. *Biosystems Engineering* **151,** 53-64

Barr JB, Desbiolles JMA, Fielke JM, Ucgul M (2019) Development and field evaluation of a high speed no-till seeding system. *Soil and Tillage Research* (in press)

Berry NK, Fielke JM, Saunders C (2014) Determination of impact energy to devitalise annual ryegrass (*Lolium rigidum*) seed from one impact using double and single sided impacts. *Biosystems Engineering* **118,** 138-146

Berry NK, Fielke JM, Saunders C (2015) A Mastercurve to predict annual ryegrass (*Lolium rigidum*) seed devitalisation when exposed to multiple single sided impacts. *Biosystems Engineering* **133** 56-63

Braunack MV, McGarry D (2006) Traffic control and tillage strategies for harvesting and planting of sugarcane (*Saccharum officinarum*) in Australia. *Soil and Tillage Research*, **89**, 86-102

Broster JC, Pratley JE, Ip RHL *et al.* (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Crop and Pasture Science* **70**, 283-293

Butler G (2018) Cotton ratoon termination with AquaTill injecticide. *The Australian Cottongrower*, Dec 2018/Jan 2019, 20-22

Chamen WCT, Moxey AP, Towers W *et al.* (2015) Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil and Tillage Research* **146**, 10-25

Clean Seed Capital Group (2019) CX-6 Smart Seeder http://www.cx6smartseeder.com

CNH Industrial (2016) The CNH Industrial Autonomous Tractor Concept www.youtube.com/watch?v=T7Os5Okf3OQ

Desbiolles J and Kleemann S (2003) Seeding system factors influence no-till cropping results. *Proceedings of 16th Triennial International Soil Tillage Research Organisation Conference*, University of Queensland, Brisbane pp 364-372

Desbiolles J (2011) Disc seeders in Australian Agriculture: An Australian survey. *Proceedings of 5th World Congress on Conservation Agriculture* Brisbane, Australia

Desbiolles J (2017) Seeder Tracker and guidance for precise row sowing. *Ag Contractor and Large Scale Farmer*, **99,** 16-18

Desbiolles J, McBeath T, MacDonald L *et al*. (2017) Testing the concept of fertility strips to increase productivity on deep sand. (Mallee Sustainable Farming) www.msfp.org.au/testing-concept-fertility-strips-increase-productivity-deep-sand

Dimos N, Trengrove S, Sherriff S *et al*. (2018) The H Sensor: a weed ID and mapping system, SAGIT Research Summary, SPAA114

DOT (2017) Meet the Future of Agriculture. www.seedotrun.com/index.php

Eckelkamp M (2011) What gives a combine its class? *AgWeb Farm Journal*, 30 September www.agweb.com/article/what_gives_a_combine_its_class

GRDC (2011) Fertiliser toxicity factsheet: Care with fertiliser and seed placement (Grains Research and Development Corporation: Canberra) : www,grdc.com.au/__data/assets/pdf_file/0019/203635/fertiliser-toxicity.pdf.pdf

GRDC (2017) Grow Notes: Spray application manual for grain growers (Grain Research and Development Corporation: Canberra) www.grdc.com.au/resources-and-publications/grownotes/technical-manuals/spray-application-manual

GRDC (2019) Mechanical chipper added to weeds arsenal. *Groundcover* **138**, p3

Giles DK, Henderson GW, Funk K (1996) Digital control of flow rate and spray droplet size from agricultural nozzles for precision chemical application. In (Eds. PC Robert, RH Rust, WE Larson) "Precision Agriculture" pp 729-738 (American Society of Agronomy, Crop Science Society of America, Soil Science Society of America: Madison WI, USA)

Haskin B (2012) Using pre-emergent herbicides in conservation farming systems. Weed Management Report (NSW Department of Primary Industries: Orange) 20pp https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf

Heidary M, Al Douzals JP, Sinfort C, Vallet A (2014) Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review. *Crop Protection* **63,** 120-130

Henley S (2017) NOSTALGIA: A look back at the tractor 'legends' of the 1990s. *Farmers Guardian*, Insights 25 July www.fginsight.com/vip/vip/nostalgia-a-look-back-at-the-tractor-legends-of-the-1990s-23400

Isbister B, Blackwell P, Riethmuller G, Davies S, Whitlock A, Neale T (2013) Controlled traffic farming technical manual (Northern Agricultural Catchments Council: Geraldton, Western Australia) www.nacc.com.au/wpcontent/uploads/2015/05/NACC_Controlled_Traffic_Farming_Technical_Manual.pdf

ISO (1984-2018) Standards catalogue 65.060.40 – Plant care equipment. International Organisation for Standardization www.iso.org/ics/65.060.40/x/

Langenakens JJ, Clijmans L, Ramon H, De Baerdemaeker J (1999) The effects of vertical sprayer boom movements on the uniformity of spray distribution. *Journal of Agricultural Engineering Research* **74**, 281-291

John Deere (2019a) Making history by leaving little behind – A powerful story of diesel innovation www.deere.com.au/en/campaigns/engines-and-drivetrain/diesel-engine-technology

John Deere (2019b) Telematics: smart machines for increased productivity www.deere.com/en/electronic-solutions/telematics/

Jourdain G (2019) Green on green camera spraying – a game changer on our doorstep? *Grains Research Updates*, Perth www.giwa.org.au/2019researchupdates

Kanicki D (2017) Which has more potential, autonomous or electric tractors? *Ag-Equipment Intelligence*, March

Kassam A, Friedrich T, Derpsch R, Kienzle J (2015) Overview of worldwide spread of conservation agriculture. *Field Action Science Reports* **8** (on-line) www.journals.openedition.org/factsreports/3966

Kepner RA, Bainer R, Barger EL (1982) "Principles of Farm Machinery" 3rd edition (AVI Publishing Company, Inc.: Wesport CT, USA) 527pp

Kleemann S, Desbiolles J, Preston C, Gill GS (2014). Influence of disc seeding systems on pre-emergence herbicide control of annual ryegrass (*Lolium rigidum*) in wheat. *Proceedings of 19th Australasian Weeds Conference* Hobart, Tasmania

Kondinin (1993a) "The seeding edge – The Australian seeding and tillage manual" Revised edition (Eds. M Casey, S Boyle) 376pp (Kondinin Group: Belmont, Western Australia)

Kondinin (1993b) "The reapers digest – The essential harvesting manual" Revised edition (Eds. M Casey and S Boyle) 384pp (Kondinin Group: Belmont, Western Australia)

Kondinin (2000) "Min-Till Drill – A guide to minimum tillage cropping systems" (Ed. S. Wallwork) 340pp (Kondinin Group: Belmont, Western Australia)

Kondinin (2001) "Spraying Solutions" (Ed. T Nugent) 240pp (Kondinin Group: Belmont, Western Australia)

Kondinin (2011) Chemical transfer systems. Issue Report. *Farming Ahead Magazine* **228** 15-28.

Kondinin (2018) Residue management at harvest. Research Report No 097, *Farming Ahead*, February 23pp

Kubsh J (2017) Managing emissions from non-road vehicles. Report prepared for the International Council on Clean Transportation. 24pp www.theicct.org/publications/managing-emissions-non-road-vehicles

Leonard E, Baker G, Hopkins D (2003) Bash'em burn'em bait'em: Integrated snail management in crops and pastures. (GRDC: Canberra) www.grdc.com.au/GRDC-Snails-BashBurnBait

Li YX, Tullberg JN, Freebairn DM (2007) Wheel traffic and tillage effects on runoff and crop yield. *Soil and Tillage Research* **97** (2), 282-292

Llewellyn RS, FH D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212

Luhaib AAA, Antille DL, Tullberg JN *et al*. (2017) Effect of controlled traffic farming on energy saving in Australian grain cropping systems. Paper 1700583 *ASABE Annual International Meeting*, American Society of Agricultural and Biological Engineers St. Joseph, MI doi: 10.13031/aim.201700583

McCallum M (2007) Multiple benefits from Inter-row sowing with 2cm RTK GPS. *Proceedings 5th Controlled Traffic Farming Conference*, Perth WA www.actfa.net/actfa-conferences/ctf07-conference/

McHugh AD, Tullberg JN, Freebairn DM (2009) Controlled traffic farming restores soil structure. *Soil and Tillage Research* **104**, 164-172

McPhee J, Aird E (2013) Controlled traffic for vegetable production: part 1. Machinery challenges and options in a diversified vegetable industry. *Biosystems Engineering* **116,** 144-154

McPhee JE, Braunack MV, Garside AL *et al*. (1995). Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 3, Timeliness and trafficability. *Journal of Agricultural Engineering Research* **60**, 191-199

Moodie M, Desbiolles J (2016) Seeding systems for variable Mallee soils. FarmTalk factsheet No 45. Mallee Sustainable Farming www.msfp.org.au/farmtalk-45-seeding-systems-variable-mallee-soils

New Holland Agriculture (2019) New Holland T6 methane power tractor prototype makes a statement at SIMA 2017 www.agriculture.newholland.com/eu/en-uk/about-us/whats-on/news-events/2017/t6-methane-power

Nossal K, Lim K (2011) Innovation and productivity in the Australian grains industry. ABARES research report 11.06, Canberra

Pangnakorn U, George DL, Tullberg JN, Gupta ML (2003) Effect of tillage and traffic on earthworm populations in a Vertosol in Southeast Queensland. *Proceedings of 16th ISTRO Conference* Brisbane pp 881-885

PIRSA (2018) Reducing spray drift with Mid North Mesonet. *PIRSA News*, Edition 1, p26 www.pir.sa.gov.au/__data/assets/pdf_file/0015/332061/PIRSA_News_-_Edition_1_-_2018.pdf

Pollard F, Webster R (1978) The persistence of the effects of simulated tractor wheeling on sandy loam subsoil. *Journal of Agricultural Engineering Research* **23**, 217-220

Precision planting (2019) www.precisionplanting.com/products/all-products

Quick G, Buchele W (1978) The Grain Harvesters (American Society of Agricultural Engineers: St. Joseph, MI, USA) 269pp

Rohde K, Yule D (1995) Land management systems including controlled traffic, erosion control and crop rotations for dryland cotton. *Proceedings of 1st ACTFA Conference*, Yeppoon, Qld www.actfa.net/actfa-conferences/1995-ctf-conference

SeedMaster (2017) www.seedmaster.ca/ultrapro.php

Taki O, Desbiolles J, Butler G (2018) Waterjet cutting of crop residue using the Aqua-Till liquid coulter – A laboratory evaluation. Paper 207, *Proceedings of 21st International Conference of the International Soil Tillage Research Organisation* 2017, Paris, France

Tigges M (2015) Central tire inflation systems for agricultural vehicles. *Proceedings of 2015 Agricultural Equipment Technology Conference* Louisville, KY USA

TMA (2017) Agriculture tractors and equipment – The state of the industry. July (Tractor and Machinery Association of Australia)

Tullberg J N (1988) Controlled traffic in subtropical grain production. *Proceedings of 11th ISTRO Conference*, Edinburgh, UK **1**, 323-326 www.istro.org/index.php/publications/proceedings

Tullberg JN, Antille DL, Bluett C *et al.*(2018) Controlled traffic farming effects on soil emissions of nitrous oxide and methane. *Soil and Tillage Research* **176**, 18-25

Tullberg JN, Yule DF, McGarry D (2007) Controlled traffic farming – From research to adoption in Australia. *Soil and Tillage Research* **97**, 272-281

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology*, **27**, 431-436

Weed Smart (2019) Harvest Weed Seed Control Tools. www.weedsmart.org.au/resources/hwsc

Yule DF, Cannon RS, Chapman WP (2000) Controlled traffic farming – Technology for sustainability. *Proceedings of 15th Conference*, Fort Worth, Texas www.istro.org/index.php/publications/proceedings