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Economic Potential of Autonomous Tractor Technology in Australian Cotton Production Systems[1]

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Abstract

Autonomous tractor technology is increasingly viewed as a key factor in changing the paradigm of conventional agriculture, allowing a shift away from ever-increasing crop machinery sizes to swarms of smaller agricultural robots (agbots). The predicted benefits of agbots include improved productivity relating to key inputs such as labour, energy, and chemicals, as well as yield improvements from improved crop and fallow management and reduced compaction. To understand the economic potential of agbots in Australian cotton production, this analysis applied discounted cash flow analysis to compare changes in income and costs associated with investment in an agbot spraying system. The results showed that switching to agbot spraying is economically feasible compared to two conventional spray platforms in a representative cotton farming enterprise. Compared to a self-propelled sprayer, agbot spraying returned an average annual NPV of $95,750 (at a 5 per cent real discount rate) and a MIRR of 16 per cent, while compared to a three-point linkage tractor sprayer, agbot spraying returned an average annual NPV of $178,603 and a MIRR of 13 per cent. Differences in the NPV and MIRR rules were due to variations in the cashflow patterns. For both scenarios, the largest benefit component was increased crop income from yield gain, followed by avoided machinery capital costs, and reduced chemical costs. Sensitivity testing revealed that, for the self-propelled sprayer scenario, the yield change and farm size variables were both individually significant to the results as they both had the capacity to reduce the NPV below $0 at their maximum range. In the tractor sprayer scenario, the yield gain was the only significant variable, reducing the NPV to $0. With the increasing commercial availability of agbots and the widely predicted benefits, it is timely to understand the economic potential for agbot adoption in the Australian cotton industry. From the results we infer that agbot sprayer technology can be a viable economic technology for adoption in a cotton farming system if yield gains can be generated. The economic viability will also be influenced by a number of factors that will differ between farming operations, and as with any decision, farmers should closely review agbots in their own operational context before investment.

Keywords: autonomous tractors; agbot; technology investment; cotton; agriculture, economics, discounted cash-flow.

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Automation in Agriculture

Over the years, the dominant trend in agricultural machinery has been toward the use of larger sizes of conventional equipment in crop production. One of the primary drivers of larger equipment is to take advantage of economies of size. Specifically, farmers can become more economically competitive by substituting capital for labour, thereby reducing per hectare labour costs. The need to compensate for the declining availability of skilled agricultural labour is also a possible explanation for the trend to larger machines. In addition, larger equipment can mitigate the risks associated with untimely operations due to unfavourable weather conditions. However, as the size of agricultural machines continues to increase, this brings about additional complications relating to both the operator and environment. These include issues with manoeuvrability, skilled labour availability, and compaction effects on soil health and yield (Shockley and Dillon, 2018).

In recent decades, autonomous tractor technology has been widely predicted and investigated as a key factor in changing the paradigm of conventional agriculture (Shockley and Dillon, 2018; Lowenberg-DeBoer et al., 2019). Replacing a human operator with automated controls could reduce average labour requirements and associated costs. Autonomous agricultural field operations could occur 24 hours per day and seven days a week during times of favourable field conditions thereby mitigating some of the risk associated with untimely field operations. Furthermore, replacing tractors with small autonomous platforms is seen as an option to support lower chemical and fertilizer applications (due to decreased product overlap), reduced energy usage, and reduced soil compaction with water savings and yield benefits (Pedersen et al., 2008).

The most basic step towards autonomous tractors, from a systems perspective, is the development of technology solutions that bolt-on to conventional tractor platforms. This approach removes the labour requirement of tractor operations but otherwise works within the existing farming system. The major tractor manufacturers are in varying stages of developing autonomous tractor systems (Baillie et al., 2017), some of which are still based on standard tractor dynamics (Fastline, 2018).

Another approach to autonomous tractor development is to fully redesign the platform from the bottom up. This approach recognises that removing human equipment operators will lead to a radical redesign of agricultural mechanization. With no human operator, one of the key economic motivations for the ever-increasing size of farm equipment is largely removed (Pedersen et al., 2008). As a result, smaller, light-weight agricultural robots (agbots) that can operate in swarms and use intelligent controls to perform production operations like seeding, spraying, fertilizing, and even harvesting may prove to be a realistic option for producers in the future (Shockley and Dillon, 2018).

This bottom-up redesign is the approach being taken by Australian agbot manufacturer SwarmFarm, based in Emerald, Queensland. The company's SwarmBots are being designed for a range of agricultural activities and early adopters have begun using the company's SwarmBots in broadacre cropping.

Previous Economic Analyses

International economists have begun investigating the economic potential of integrating agbots into farming operations. However, because of the early stages of development and adoption of the technology there is a recognised lack of suitable economic analysis of agbot systems (Lowenberg-DeBoer et al., 2018; Shockley and Dillon, 2018).

Existing studies include analysis of the costs and potential benefits of agbots in weed spraying and mechanical weeding in European sugar beet, and grass cutting in golf courses (Pedersen et al., 2006). These analyses used budgeting to compare capital costs, operating costs, and chemical input costs (labour and chemicals) between prototype agbots with conventional systems. Shockley and Dillon (2018) evaluated the application of prototype agbots in planting, spraying, fertilising and harvesting corn and soybeans in the United States. A whole farm model was developed to compare ownership costs, repairs and maintenance, chemical use, and yield. The study did not consider incidental labour costs associated with refilling the agbot with chemical or fuel.

In Australia, Perez et al. (2014) undertook an analysis of agbot applications in broadacre agriculture as part of a Queensland Government funded three year research program on Strategic Investment in Farm Robotics (SIFR). As part of the analysis, they quantified the cost per hectare of agbots in comparison to conventional weed spray technology with regard to labour, energy and chemical requirements. The analysis did not consider the different spray requirements for individual crops or fallow land, or maintenance costs, or variations in labour requirements associated with chemical and fuel refill. Furthermore, it did not compare the identified benefits with investment costs to explore the economic viability of investment at a farm level.

Method

This economic analysis evaluates the application of agbot spraying platforms in a representative farming enterprise comprised of cotton production in rotation with grains and legumes in both dryland and irrigation. Two scenarios are examined to determine the economic feasibility of agbot sprayers in comparison with two conventional spraying systems — a self-propelled sprayer (24 m boom), and a three-point linkage tractor sprayer (12 m boom). Given the commercial availability in Australia, where possible, the agbot specifications — including cost structure and system specifications and capabilities — were based off a SwarmBot, produced by SwarmFarm.

Economic Model

The analysis was conducted to represent a decision point for investment in a new spray platform: the farm's previous spray platform has reached the end of its economic life, and the options are to invest in a new conventional spray platform, or change to an agbot spray platform.

The analysis used discounted cash flow analysis (DCF) to compare changes in income and costs associated with investment in agbot systems. The DCF approach involves comparing farm costs and returns from a base scenario with costs and returns from the adoption scenarios. The base or 'business as usual' scenario is simply the reference farm assuming continued investment in and use of conventional technology. As costs and benefits are incurred over a period of years, all dollar amounts are converted into present value (PV) dollar terms. This conversion process is referred to as discounting. The DCF procedure comprises two main steps. The first is to construct a periodic cash flow series that reflects the investment period. As the purpose of this analysis is to review the current agbot systems available to Australian broadacre farmers, a three year lend-lease agreement was applied for the agbot investment reflecting the SwarmFarm model. In this analysis a nine-year period was used to align the economic life of purchased spray equipment, and the three-year agbot lease period. The second step is to apply a discount rate to the cash flow series, which converts all future cash flows back to equivalent present values.

The discount rate used was a real (inflation adjusted), risk free, pre-tax discount rate of 5 per cent. A real discount rate was appropriate since all costs and benefits were estimated in real (inflation-free) terms. Where a cost-benefit analysis is aimed at assessing a commercial investment with a short to medium-term outlook, a strong argument can be made for using a discount rate that reflects the investor's opportunity cost of capital (AgTrans, 2018). For this reason, commercial investment analysis frequently uses a firm's weighted average cost of capital. A real discount rate of 5 per cent is approximate to an agricultural enterprise real cost of capital (NAB-Agribusiness, 2019), or opportunity cost.

In economic analysis there is often the assumption of a perfect capital market which means borrowing costs equal opportunity costs, and there is the added assumption that the investor can borrow and lend the required sums at the market rate. If this assumption is not held, and an investment and method of finance are closely linked, then financing arrangements can be incorporated explicitly in the economic analysis (Kay et al., 2020). Given this, and as this analysis seeks to reflect commercially-available options for cotton farmers, the agbot has been evaluated on a lend-lease agreement as per the SwarmBot model, while the alternative spray platforms are financed by borrowing and purchasing at the market rate. Given the lease cost structure of the agbot with monthly payments, this cost was discounted at a monthly equivalent discount rate. All other costs and benefit cashflows were assumed to occur at the end of the year.

This analysis assumed a machinery lease for agbot adoption in line with the SwarmFarm model. This has the potential for tax implications; however, the complexity of individual producers' tax situations is such that modelling tax for the representative farm would significantly increase the number of assumptions. As such, the analysis was done on a pre-tax basis, with the exception of GST, which was excluded from all prices, and the Government fuel tax credit, which was incorporated into the diesel fuel price. Tax implications would change the final value of the investment for individual farms, and should therefore be considered on a case-by-case basis.

Data and Assumptions

Farm and equipment data

The following section outlines the farm and equipment characteristics incorporated in the analysis. Given the potential variation in the baseline data values, the results were subsequently tested for sensitivity to changes in all key variables.

Farming system data

This section outlines the specific physical and managerial parameters assumed in the modelling. Many of the farm characteristics were based on a published representative farm by Powell and Scott (2011). A summary of the farming system assumptions can be found in Tables 1 and 2.

Farm location: Farm inputs and management practices can vary from region to region and farm to farm. To maintain, as much as possible, a consistent approach to data, a Lower Namoi Valley mixed-enterprise farm with irrigation and dryland farming was used for baseline data.

Farm size: With a fixed cost per agbot unit, larger farming operations will generate greater cost efficiencies. A farm size of 1203 ha was used, as per (Powell and Scott, 2011). The results were tested for sensitivity to variations in farm size from 500 ha to 2000 ha (Agrifutures, 2017) to investigate the implications of larger cropping operations on the results.

Water availability: The farm had a total water allocation of 2773 ML (Powell and Scott, 2011). This consisted of a 1061 ML groundwater licence, and a 1712 ML regulated surface water licence. Annual water allocations are assumed to be 25 per cent for the baseline. The results were tested for sensitivity to variations in annual water allocation. When testing the results for sensitivity to farm size, the total water allocation was adjusted at a concurrent rate.

Cropped area: It was assumed that 962 ha (80 per cent of total farm area) was used for cropping with the remaining area made up of infrastructure (such as roads, channels, sheds, etc) cattle grazing and native vegetation (Powell and Scott, 2011). The cropped area included 782 ha (65 per cent of total farm area) of land developed for irrigated cropping and 180 ha (15 per cent of total farm area) for dryland cropping.

Rotation system: The rotation system, in conjunction with the cropped area, is relevant in determining annual ground-spray requirements, and therefore annual usage of the agbot technology. Rotation systems vary from farm to farm and season to season depending on climate, water availability, pest and disease pressures, soil type, commodity prices, cash flow requirements and available resources. The rotations used for irrigated and dryland cropping are summarised in Table 2.

While there is no 'typical' cotton crop rotation system, they often include green manure legume crops as well as pulse and cereal crops (Hulugalle and Scott, 2008). For the purposes of this analysis, the model included a 3-year rotation of irrigated crops between cotton, wheat/short-fallow, and chickpea/short-fallow. No crop was planted over more than one third of irrigation area to minimise risk, with any land unable to be grown to cotton (due to water restrictions) left fallow to maintain the rotation.

The dryland rotation followed the irrigated rotation, with one third of dryland planted to opportunistic dryland cotton in rotation with wheat/short-fallow, chickpea/short-fallow. There is a 25–30 per cent chance of meeting sowing conditions by mid-October, which is the optimum month for sowing in northern NSW (Baird et al., 2018). As such, this analysis included only one dryland cotton crop every three years, with the allocated cotton land remaining fallow in two out of three years.

Spray requirements: All crop and fallow spray requirements were taken from relevant industry gross margins. Irrigated and dryland cotton and refuge spray requirements were taken from the Ag Econ cotton industry gross margins (Powell et al., 2019). Cereal and pulse crop spray requirements are taken from NSW DPI (2012), and fallow spray requirements are taken from Powell and Scott (2011).

Conventional spray system: This analysis compared a new agbot sprayer to two conventional spraying systems that may be in place on cotton farming enterprises. The first scenario compared an agbot sprayer to a new self-propelled (SP) sprayer modelled off a 129 kW John Deere 4023, with a 24 m boom and 2300 L spray tank. The SP sprayer undertook all crop and fallow herbicide, pesticide, fungicide sprays, and defoliations sprays in dryland double-skip cotton. Defoliation of irrigated solid configuration cotton was done with contracted aerial spraying (CottonInfo, 2018). The second scenario compared an agbot sprayer to a new three-point linkage tractor modelled off a 217 kW John Deere 8295R with a 12 m spray boom and 1200 L spray tank. Due to a lower clearance of 60 cm, the tractor sprayer undertook all early crop and fallow herbicide, pesticide, and fungicide sprays, with late crop and defoliations sprays in dryland double-skip cotton done by an external contractor. Defoliation of irrigated solid configuration cotton was done with contracted aerial spraying. For both scenarios the baseline analysis assumed that the conventional spraying systems did not include precision spraying technology, reflecting the 86 per cent of cotton growers, and 92 per cent of grain growers, who do not use variable rate application technology for chemicals and other crop inputs (ABS, 2017). The results were sensitivity tested for changes in the baseline use of precision spraying.

A summary of the farming system assumptions is shown in Tables 1 and 2.

Table 1. Baseline farming system assumptions

Parameter	Value	Source
Farm location	Lower Namoi valley	Assumption
Farm size	1203 ha	Powell and Scott 2011
Water	1061 ML groundwater (100% allocation) 1712 ML surface water (25% allocation)	
Non-cropped area	120 ha	
Cropped area	962 ha	
Irrigated area	782 ha	
Dryland area	180 ha	
Conventional spray system to be replaced	Scenario 1: 129 kW SP sprayer with 24 m boom and 2300 L spray tank. No precision spraying. Scenario 2: 217 kW Tractor sprayer with 12 m boom and 1200 L spray tank. No precision spraying.	Assumption

Table 2. Crop rotations

Irrigation land		
Year 1	Year 2	Year 3
Irrigated cotton	Dryland wheat (short fallow)	Dryland chickpeas (short fallow)
Dryland wheat (short fallow)	Dryland chickpeas (short fallow)	Irrigated cotton
Dryland chickpeas (short fallow)	Irrigated cotton	Dryland wheat (short fallow)
Dryland		
Year 1	Year 2	Year 3
Dryland cotton	Dryland wheat (short fallow)	Dryland chickpeas (short fallow)
Dryland wheat (short fallow)	Dryland chickpeas (short fallow)	Fallow
Dryland chickpeas (short fallow)	Fallow	Dryland wheat (short fallow)

Agbot spray system data

This section discusses assumptions relating to the agbot sprayer costs and operational data. Given the commercial availability in Australia, where possible, the agbot specifications were based off a SwarmBot, produced by SwarmFarm. The agbot data are presented in comparison with the SP sprayer and tractor sprayer for costs (Table 3) and operational specifications (Table 4).

Agbot cost: The agbot was financed on a 3-year lease agreement of $5,800 plus GST in advance, per month. The lease agreement included system support and major servicing for the period of the lease, with a new model agbot provided for each new lease. To align to the spray boom life of equipment (nine years) the agbot was leased for three lease periods.

Agbot spray system cost: The agbot used Cat 2.3 linkage to fit most implements. For spraying, the agbot connected to a 12 m boom and 1000 L tank. The agbot boom was assumed to be custom built including a weed precision spraying system for a combined price of $110,000 (SwarmFarm, 2020), with an assumed equipment life of nine years and salvage value of 35 per cent. One boom was required per agbot.

Number of agbots — rationale: Managing crop pests in a timely manner is a critical factor in minimising any yield loss. Similarly, timely weed management in fallow fields has yield implications through the preservation of soil moisture. In addition, timeliness is also affected by the ability to react to favourable spraying weather conditions that minimise compaction after rainfall events and minimise chemical drift. In order to avoid any negative impacts from reduced spray application timeliness, sufficient agbots were leased to complete the spray tasks in an approximately equivalent time as the conventional spray machinery. On average, given a slower spray rate, one agbot sprayer took 2.4 times as many hours as the SP sprayer across all spray tasks, and 1.3 times as many hours as the tractor sprayer. Slightly mitigating this was an assumed 15 per cent increase in spray hours achieved per day given the agbots ability to immediately react to appropriate spraying weather conditions. This was achieved through an on-board weather station (SwarmFarm, 2020), as well as the reduced agbot sprayer weight (less than 4 t fully loaded) (SwarmFarm, 2020) compared to more than 10 t for the conventional systems (John-Deere, 2019a; John-Deere, 2019b), thereby allowing early spraying after rainfall. As a result, in the model two agbots were leased to replace the SP sprayer and one agbot was leased to replace the tractor spray tasks, resulting in a 30 per cent and 20 per cent increase in respective spray time across all tasks. The results were tested for sensitivity to an increase in agbot numbers to enable spray tasks to be completed at least as fast as the conventional spray machinery.

Weed detection and precision spraying technology cost: There were multiple commercially available weed spot spraying technologies that could be installed onto a spray boom, including WEEDit® and WeedSeeker®, both of which have been shown to be compatible with agbots (McCarthy, 2016). Spot spraying technology costs approximately $4,000 per metre (Schaefer and Trengove, 2016). The precision spraying technology was assumed to be included in the pricing of the custom built boom for $110,000 (SwarmFarm, 2020). The system was assumed to be capable of precision spraying in both a fallow and in-crop situation. In-crop precision spraying may be achieved through the use of a shielded sprayer (Gordron, 2017) or by adjusting sensors, or spray nozzles to block out the crop rows (SwarmFarm, 2020).

Data connectivity cost: The agbot used RTK GPS while operating in the field (SwarmFarm, 2020). RTK is a form of correction signal to improve accuracy in GPS systems. It uses a ground based single reference point to provide real-time corrections and enable centimetre level accuracy. It requires a base station to be located within no more than 20 km to ensure sufficient accuracy for the agbot. Most farms already have access to an RTK GPS network (AllDayRTK, 2020), which require an initial annual subscription of around $500–$1,500 per year (Kondinin-Group, 2018; SST-GPS, 2020), with a reduced fee for additional receivers or machines connected. If there is no base station within range of the farm, one can be installed for a cost of up to $20,000 (SST-GPS, 2020) after which no ongoing network access costs are required (Neale, 2017). For the purposes of this analysis, the representative farm already accessed an RTK GPS network for farm operations (bed-forming, planting, controlled traffic spraying). As such, there was no additional RTK GPS cost for the first agbot replacing the SP Sprayer, with additional agbots incurring a $500/yr access fee. As the tractor sprayer was retained for non-spraying operations, the agbot requires an additional connection at $500/yr.

Field capacity. The field capacity measures the hectares sprayed per hour. The field capacity influences the potential savings associated with labour (spraying and refilling), fuel and maintenance costs. While theoretical field capacity (TFC) is derived from in-field spraying capacity, the actual effective field capacity (EFC) includes time spent spraying, turning, refilling, and travelling.

$$EFC\ (ha/h) = 1\ /\ (spray\ time\ (h/ha) + turn\ time\ (h/ha) + refill\ travel\ time\ (h/ha) + refill\ time\ (h/ha))$$

Where:

$$Spray\ time\ (h/ha) = 10\ /\ (width\ (m) x\ speed\ (km/h)\ )$$

$$Turn\ time\ (h/ha) = turn\ freqency\ (\#/ha)\ x\ turn\ speed\ (h/turn)$$

$$Turn\ frequency\ (\#/ha) = 10000\ /\ (field\ row\ length\ (m)\ x\ boom\ width\ (m)\ )$$

$$Refill\ travel\ time\ (h/ha)$$
$$= refill\ rate\ (\#/ha)\ x\ road\ distance\ (km)\ x\ road\ speed\ (km/h)\ x\ 2$$
$$Refill\ frequency\ (\#/ha)$$
$$= water\ equivalent\ application\ rate\ (L/ha)\ /\ spray\ tank\ capacity\ (L)$$
$$Refill\ time\ (h/ha) = refill\ frequency\ (\#/ha)\ x\ tank\ size\ (L)\ /\ refill\ speed (L/h)$$

The water equivalent application volume is different depending on the type of spray being applied and decreases with weed detection technology (depending on weed density).

The field capacity for the agbot and conventional systems is calculated in Table 4.

Table 3. Baseline spray system cost data

Parameter	Agbot sprayer	SP sprayer	Tractor sprayer
Machine capital cost	NA	$258,671	$315,106
Machine lease cost per month	$5,800	NA	NA
Machine life of equipment	3 year lease	4000 h	3500 h
Machine trade-in value (% of new)	NA	40%	40%
Boom cost	$62,000	Included	$62,000
Boom life of equipment	9 years	Included	9 years
Boom trade-in value (% of new)	35%	Included	35%
Precision spraying cost	$48,000	Not used	Not used
Life of precision spray equipment	9 years	Not used	Not used
Precision spraying trade-in value (% of new)	0%	NA	NA
RTK GPS network subscription	$500/y	$500/y	$500/y

Table 4. Baseline sprayer operational data

	Agbot sprayer		SP sprayer		Tractor sprayer	
	Herbicide	Insecticide / fungicide / defoliation	Herbicide	Insecticide / fungicide / defoliation	Herbicide	Insecticide / fungicide / defoliation
Boom width	12 m		24 m		12 m	
Spray speed	10 km/h	10 km/h	18 km/h	10 km/h	15 km/h	10 km/h
Theoretical field capacity	12 ha/h	12 ha/h	43 ha/h	24 ha/h	18 ha/h	12 ha/h
Spray tank	1000 L		2300 L		1200 L	
Application volume	50 L	80 L	50 L	80 L	50 L	80 L
Refill pump speed	9000 L/h					
Distance to refill	2 km					
Road speed	12 km/h		40 km/h		30 km/h	
Row length	625 m					
Turn speed	10 sec					
Ectual field capacity	10 ha/h	7 ha/h	29 ha/h	19 ha/h	13 ha/h	10 ha/h
In-field time	84%	62%	73%	74%	75%	74%
Refill and travel time	16%	38%	27%	26%	25%	26%

Agbot Adoption Impacts

This section discusses the potential impacts of adopting an agbot sprayer when compared to the baseline scenarios. Potential adoption impacts were identified through industry consultation, including current SwarmBot adopters, and a literature review of related technologies. A summary of the agbot adoption impact assumptions can be found in Table 5. Given the potential variation in the baseline impact values, the results were tested for sensitivity to changes in all key variables.

Machinery costs

This analysis assumed the current farm spray machinery was at the end of its useful life and in need of replacement. Moving forward, the options were to 1) re-purchase a conventional spray system, or 2) switch to an agbot spray system. To understand this management decision, this analysis compared the costs and benefits of a new agbot spray system with a new conventional spray system. The agbot sprayer was compared against two different conventional spray systems: a SP sprayer, and a tractor sprayer.

In the first scenario, it was assumed the agbot sprayer undertook all ground-based spray tasks, negating the need to purchase a SP sprayer, and thereby generating an avoided capital cost. This was been calculated based on the SP sprayer machinery purchase price, life of equipment, and resale value as per Table 3.

In the second scenario it was assumed the agbot sprayer undertook all ground-based spray tasks, negating the need for the tractor sprayer or contract ground-sprayer to undertake these tasks. The tractor sprayer was, however, still required for other crop and fallow operations. While the tractor sprayer was not replaced by the agbot sprayer, the reduction in operating hours extended the life of the tractor. Based on the gross margin operational requirements, the tractor reduced its operational hours from 854 ha/yr to 368 ha/yr with agbot adoption. With an assumed tractor economic life of 3,500 hours, agbot use delayed the need to trade-in the tractor by nearly seven months for every year of agbot use, up to an assumed maximum of 10 years, while maintaining the resale value of 40 per cent.

Labour use

Automation has the potential to dramatically increase efficiencies from a labour productivity perspective. While agbots present the potential for long-term reductions in farm labour when considered in line with broader historical machinery efficiency trends, in the short-term fixed full-time farm labour is likely to be redirected to other tasks. A key labour impact of agbots is to remove the need for in-field labour, which is the major component of spray time (see Table 4) and therefore labour in conventional spraying. Unless agbots have the ability to automatically refill fuel and chemicals, which is yet to be developed, this task will continue to require manual labour. The total labour saved per hectare will differ depending on the type of spray being undertaken (i.e. blanket application vs spot-spray, herbicide vs insecticide / fungicide / defoliation) and the use of weed detection technology for spot spraying (as per Table 4), and also the spray requirements of each crop. Labour was valued at $30/hr, with the results tested for sensitivity to variations in labour costs. While labour saved had the potential to be redirected to more productive tasks, this was not factored into the model, and could provide additional benefits.

Chemical use

The average weed cover in fallow fields in northern NSW is as low as 20 per cent of the total area (McCarthy, 2016). For those not using variable rate application technology for contact herbicides, 80 per cent of the chemical is potentially being applied and wasted on bare soil. The WEEDit® system identifies a potential chemical saving of 90 per cent (WEED-IT, 2019). The WeedSeeker® system identifies a similar chemical saving (McCarthy, 2016). Separate studies have shown a potential saving of between 10 and 80 per cent (Heap and Trengove, 2009; McCallum et al., 2012), and an average 54 per cent savings (Timmermann et al., 2003). This analysis assumed that the farm did not previously use precision spraying technology and can therefore realise a chemical saving of 50 per cent for the baseline spray applications. To support a potential yield benefit from improved weed management, additional spray passes were assumed, requiring additional chemical use and therefore partially offsetting the first pass savings. These subsequent passes were assumed to target earlier stages of weed development with lower weed coverage. The assumed weed coverage (and proportion of blanket spray chemical use) was 12.5 per cent. These net chemical savings only applied to contact weed herbicide applications, with residual (pre-emergent) herbicides, insecticides, fungicides and defoliation chemicals all applied using blanket-spray. The results were tested for sensitivity to variations in weed density, and related net chemical savings.

Fuel use

The agbot had an in-field fuel use of 4.2 L/hr (SwarmFarm, 2020) compared to the SP sprayer fuel usage of approximately 17.5 L/hr (John-Deere, 2019a) and the tractor sprayer fuel usage of 12 L/hr (John-Deere, 2019b). Net fuel savings depend on the EFC (ha/hr) and the number of agbots employed. With higher EFCs, the SP sprayer and tractor sprayer required less operational time per hectare, which partially offset the lower fuel usage of an agbot. The use of two agbots to replace the SP sprayer further offset the agbot fuel use advantage. The national average diesel fuel price at the time of writing was $0.97/L, well below the 5-year average daily price of $1.26/L (AIP, 2020). For this analysis, a baseline diesel fuel price of $0.84/L was used based off the 5-year average daily price minus the Government fuel tax credit (ATO, 2020), with the results tested for sensitivity to changes in this figure.

Machinery maintenance

Machinery maintenance included servicing costs such as oil, filters, tyres, batteries, and repairs. Total maintenance costs were estimated at $29.9/hr for the SP sprayer, $14.5/hr for the tractor sprayer, and $2.0/hr for the agbot. As part of the three year lease agreement the agbot was assumed to be fully warranted (SwarmFarm, 2020) and serviced at all levels other than general maintenance, which includes oil, filters, tyres and batteries. Total maintenance savings depend on the EFC (ha/hr) and the number of agbots employed. With higher EFCs, the SP sprayer and tractor sprayer required less operational time per hectare, which partially offset the lower maintenance cost of an agbot. The use of two agbots to replace the SP sprayer further offset the agbot maintenance cost advantage.

Yield

Crop yield is impacted by soil, climate, sowing dates, planting density and cultivar, tillage practices, fallow management, cropping sequences, and the impact of pests and diseases. This analysis identified three potential impacts of agbot use on crop yield. Variations in the potential yield impacts were tested in sensitivity analysis.

Improved weed control: An agbot provides the opportunity for more persistent and responsive weed control. For dryland crops, soil water stored before sowing is as equally important as in crop rainfall (CWFS, 2018). Trials have shown dryland fallow weed reduction has the potential to provide a reduction in the water limited yield gap of 38 per cent for wheat (Hunt et al., 2013; CSIRO and GRDC, 2019). For the Namoi Valley this equates to 0.68 t/ha. While there was no identified information on the impact of fallow management in cotton production, in-crop weeds have been shown to reduce yields by 90 per cent with the critical period being in early plant development and particularly prior to canopy closure (Manalil et al., 2017). A yield benefit from improved weed control was assumed to require additional spray passes (Schaefer and Trengove, 2016), which offset some of the savings in labour, chemical, and maintenance. A baseline figure of the agbot performing one extra pass for each individual spray application of contact herbicide was used in the analysis.

Compaction: Compaction impacts crop yield both directly and indirectly (Antille et al., 2016). Direct effects relate to changes in water and nutrient uptake, and physical impedance to root growth. Indirect effects relate to the time and resources required to remediate soil compaction. Research (Håkansson and Reeder, 1994) has indicated that deep compaction can take more than five years to ameliorate, if at all. Reduced compaction has been shown to increase irrigated cotton yield by 12 per cent, dryland cotton yield by 28 per cent, and winter cereals and legumes by 35 per cent (Antille et al., 2016). With a fully loaded weight of less than 4 t (SwarmFarm, 2020), compared to a SP sprayer and tractor sprayer at more than 10 t (John-Deere, 2019a; John-Deere, 2019b), an agbot sprayer would generate significantly less soil compaction per pass. However, while the weight of machinery influences subsoil compaction, repeated passes with lighter equipment can result in compaction equal to or greater than with fewer passes with heavier equipment (Jorajuria et al., 1997; Botta et al., 2004). This suggests that if agbots are to be used for a more persistent weed pest control program, using multiple passes, then the compaction benefits could be reduced. Furthermore, the continued use of heavy machinery for other crop operations (such as planting and harvesting) would potentially limit the compaction benefit of a lighter spraying platform.

Reduced phytotoxicity effects: Herbicide chemicals accumulate in the soils from year to year and can cause a reduction in crop yield of 5–10 per cent (Reddy et al., 1990; Heap and Trengove, 2009). By reducing unnecessary chemical application, spot spraying technology can improve overall yields by minimising herbicide build-up and the associated phytotoxic effects on crop plant growth.

Given the above, implementing agbot spraying is assumed to support improved crop yields through a combination of improved weed control, reduced compaction and reduced phytotoxicity effects. Increased yield is calculated as a reduction in the yield gap for each crop. Yield gaps reflect the difference between actual yields and potential yields. Actual yields and potential yields were taken from a range of sources as per Table 5. Based on the above research, this analysis has included a yield gap reduction by 25 per cent for all dryland crops, and 12.5 per cent for irrigated cotton. Variations in the potential yield impacts were tested in sensitivity analysis.

Table 5. Baseline yield and yield change data

Parameter		Value	Source
Baseline (and potential yield)	Irrigated cotton	10.7 bales/ha (15.4)	Lower Namoi Valley 10y average yield potential (GreenMount), yield potential (Constable and Bange, 2015)
	Dryland cotton	3.4 bales/ha (4.6)	(Bange et al., 2005)
	Dryland wheat	2.1 t/ha (4.4)	(CSIRO and GRDC, 2019)
	Dryland chickpeas	1.2 t/ha (3.2)	(CSIRO and GRDC, 2019)
Yield change	Irrigated cotton All other crops	+13% of yield gap +25% of yield gap	(Hunt et al., 2013; Antille et al., 2016; CSIRO and GRDC, 2019)
Commodity prices	Cotton lint	$532/bale	5-year average daily cotton futures (Powell et al., 2019)
	Dryland cotton lint discount	5%	(Powell et al., 2019)
	Cotton seed	$400/t	(Powell et al., 2019)
	Wheat PH	$210/t	5-year average delivered to port minus $100 cartage (ABARES, 2020)
	Chickpeas	$741/t	5-year average delivered to port minus $100 cartage (ABARES, 2020)

Results

From the above data and assumptions, the results showed that switching to agbot spraying was economically feasible for both scenarios. For the SP sprayer scenario, adoption of agbot spraying generated an average annual net present value (NPV) of $95,750 (at a 5 per cent real discount rate) with a modified internal rate of return (MIRR) of 16 per cent. For the tractor sprayer scenario, adoption of agbot spraying generated an average annual NPV of $178,603 with a MIRR of 13 per cent. Differences in the NPV and MIRR rules between the two scenarios were due to variations in the cashflow patterns. The results are summarised in Table 6 and Figure 1.

Table 6. Baseline results

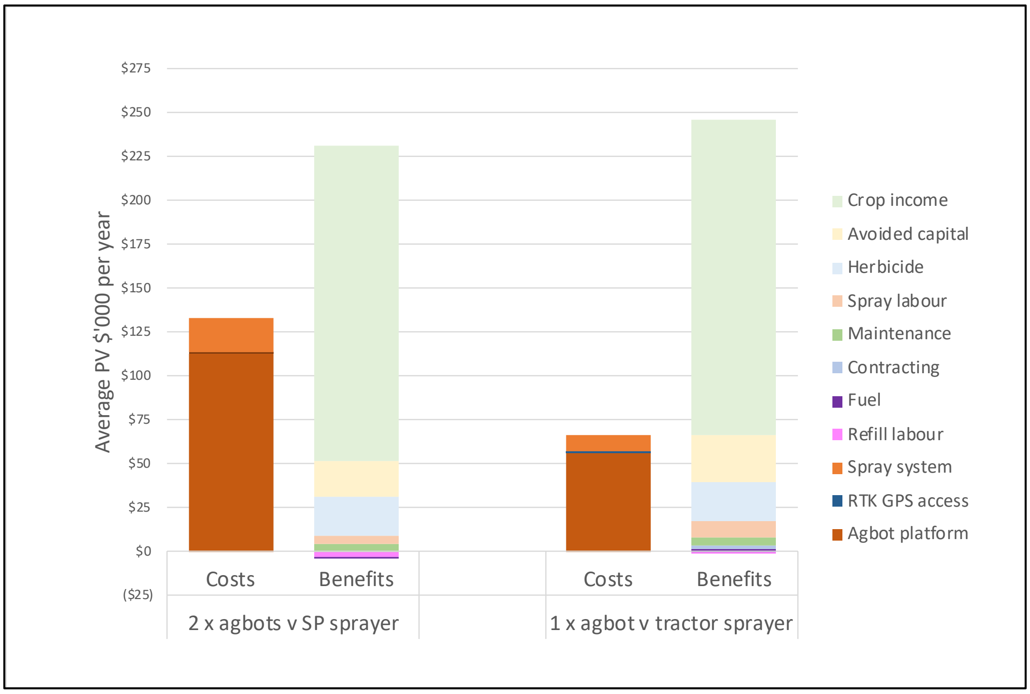
Costs and benefits	Agbot Sprayer v SP Sprayer	Share of total	Agbot Sprayer v Tractor Sprayer	Share of total
COST				
Agbot	$112,890	85%	$56,445	85%
RTK GPS access	$901	1%	$450	1%
Spray system	$18,929	14%	$9,465	14%
Total capital cost	**$132,720**		**$66,360**	
BENEFITS				
Machinery capital cost	$20,476	9%	$26,657	11%
Fuel cost	($20)	0%	$1,271	1%
Maintenance cost	$4,077	2%	$4,284	2%
Spray labour cost	$4,466	2%	$9,516	4%
Refill labour cost	($2,769)	-1%	($1,189)	0%
Herbicide cost	$22,123	10%	$22,123	9%
Crop income	$180,117	79%	$180,117	74%
Contracting costs	$0	0%	$2,182	1%
Total benefits	**$228,470**		**$244,963**	
IMPACT				
NPV	$95,750		$178,603	
BCR	1.72		3.69	
MIRR	16%		13%	

For both scenarios, the largest benefit component was increased crop income from yield gain, followed by avoided machinery capital costs, and reduced chemical costs.

While the yield benefits and chemical savings were identical between the two scenarios, agbot spraying generated greater operational benefits (relating to labour, maintenance, fuel, and avoided contracting) when replacing the tractor sprayer tasks than it did when replacing the SP sprayer. The additional benefits in the tractor sprayer scenario were reflective of the lower field capacity of the tractor sprayer compared to the SP sprayer, and also the need for more expensive contracting sprays due to the lower tractor clearance compared to the SP sprayer.

Despite increased refill labour requirements due to the more frequent spray tank refills and the additional spray tasks, for both scenarios, there was a net decrease in total spray labour costs. The additional spray tasks also led to an increase in overall fuel use for the agbots compared to the SP sprayer which had the highest fuel efficiency per hectare of the three systems. In contrast, even with additional spray passes, agbot spraying generated fuel savings compared to the tractor sprayer which had the lowest fuel efficiency per hectare of all three systems.

Figure 1. Baseline results



Sensitivity Analysis

Sensitivity analysis was undertaken for 26 input variables to test the implications on the results. The input variables were tested at plus and minus 10 per cent from the baseline value, and also a maximum and minimum value. For maximum and minimum values, data on the different variables was obtained from published data (where available), otherwise a range of plus and minus 25 per cent was used. The full list of variables and ranges are shown in Table 7.

The input variables were tested at plus or minus 10 per cent of their baseline value to understand which variables individually have the greatest relative impact in the economic results (Figures 2 and 3). A 10 per cent change in variables relating to farm size, yield, and commodity prices had the largest impacts on the results for both scenarios. The agbot lease price had a larger impact in the SP sprayer scenario due to the lease of two agbots. Other variables showed significantly less impact on the economic outcome. No variables were individually significant for either scenario at the 10 per cent range as the variables did not reduce the NPV to below the breakeven value of NPV=$0.

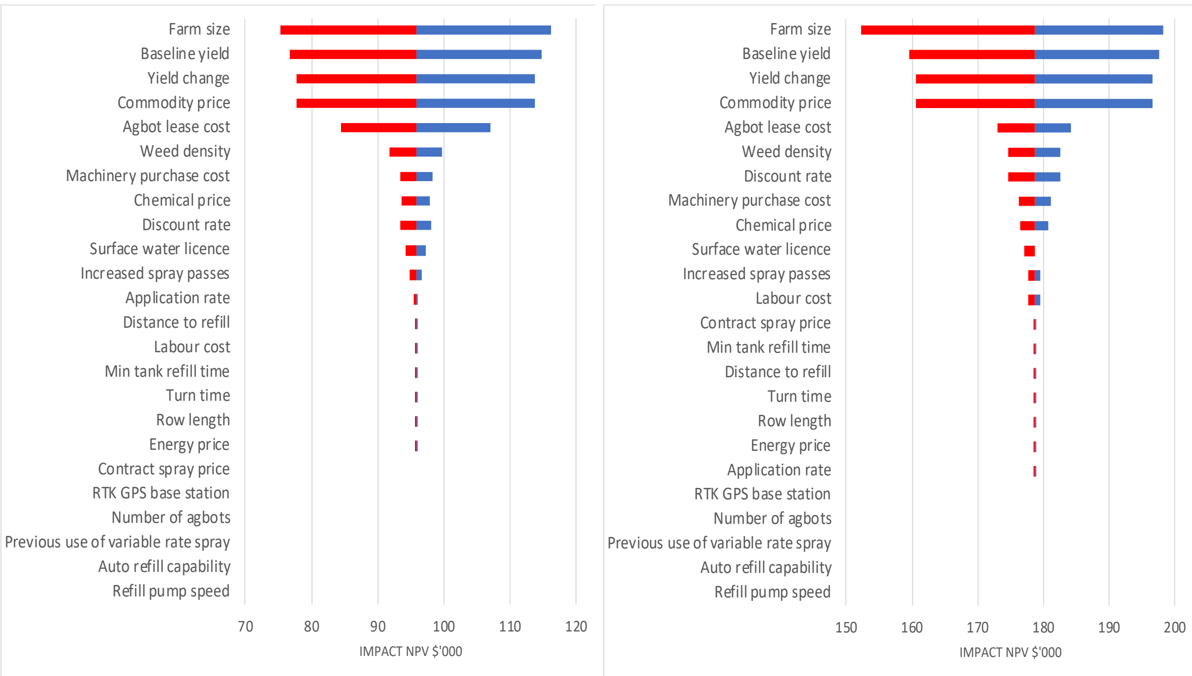
The input variables were also tested at their full assumed range to understand which variables individually have the greatest potential impact in the economic results (Figures 4 and 5). A maximum change in yield, farm size, and number of agbots had the largest impacts on the results for both scenarios. In the tractor sprayer scenario, there is only a downside for the number of agbots, as the minimum number of agbots (one) is already being leased.

In the SP sprayer scenario, the yield change and farm size variables were both individually significant to the results as they both had the capacity to reduce the NPV to below the breakeven value of NPV=$0 at their maximum range. For yield change, the breakeven value was an average 12 per cent reduction in the yield gap across all dryland crops, and a 6 per cent reduction in the yield gap for irrigated cotton. In the SP spray scenario, the minimum viable size was a farm area of 530 ha.

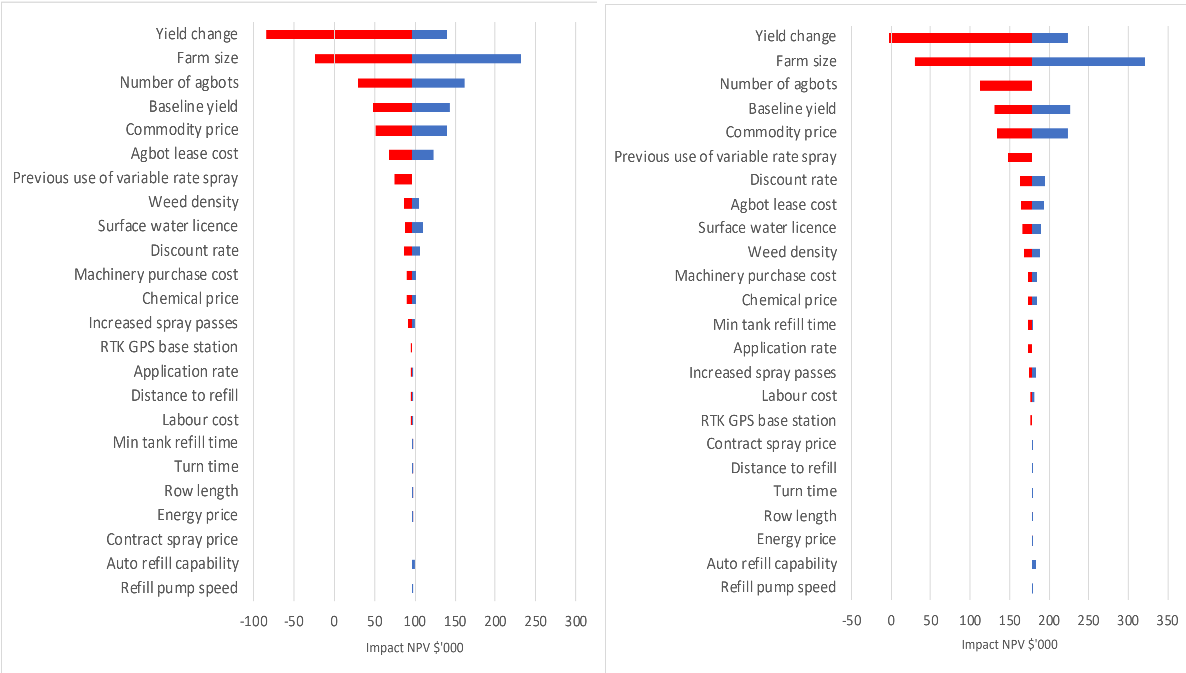
Table 7. Sensitivity testing values

Model input variable	Minimum	-10%	Baseline	+10%	Maximum
Discount rate (%)	3%	4.5%	**5%**	5.5%	7%
Farm size (ha)	500	1,083	**1,203**	1,323	2,000
Surface water allocation (%)	13%	23%	**25%**	28%	50%
Additional spray passes (#)	0.5	0.9	**1.0**	1.1	1.5
Chemical price (% of baseline)	75%	90%	**100%**	110%	125%
Spray application rate (% of baseline)	75%	90%	**100%**	110%	125%
Previous use of variable rate spray	Yes	NA	**No**	NA	No
Weed density first pass (% of area)	38%	45%	**50%**	55%	63%
Min tank refill time (min)	6	18	**20**	22	25
Turn time (sec)	8	9	**10**	11	13
Refill pump speed (L/h)	6750	8100	**9000**	9900	11,250
Distance to refill (km)	1.5	1.8	**2.0**	2.2	2.5
Row length (m)	469	563	**625**	688	781
Labour cost ($/h)	23	27	**30**	33	38
Counterfactual yield (% of baseline)	75%	90%	**100%**	110%	125%
Energy price (% of baseline)	75%	90%	**100%**	110%	125%
Yield change (% of baseline yield gap)	0%	90%	**100%**	110%	125%
Commodity price	75%	90%	**100%**	110%	125%
Contract spray price	8	9	**10**	11	13
Auto refill capability	NA	NA	**No**	NA	Yes
SP Sprayer purchase cost	$194,003	$232,804	**$258,671**	$284,538	$323,339
Tractor purchase cost	$236,330	$283,595	**$315,106**	$346,617	$393,883
Agbot lease cost	$52,200	$62,640	**$69,600**	$76,560	$87,000
# Agbots to replace SP sprayer	1	NA	**2**	NA	3
# Agbots to replace tractor sprayer	NA	NA	**1**	NA	2
RTK GPS installation	Yes	NA	**No**	NA	NA

Figures 2 and 3. Sensitivity of results (NPV) to 10% variable range for SP sprayer (left) and tractor sprayer (right). Note different range of the x-axes



Figures 4 and 5. Sensitivity of results (NPV) to full variable range for SP sprayer (left) and tractor sprayer (right). Note different range of the x-axes



In the tractor sprayer scenario, yield change was the only individually significant variable at the maximum variable range; however, this was marginal, requiring less than 1 per cent reduction in the yield gap to be economically viable according to the NPV rule. Of note, a much higher yield change would likely be required to meet individual farmers acceptable hurdle rates. In the tractor sprayer scenario, the minimum viable size was a farm area of 350 ha.

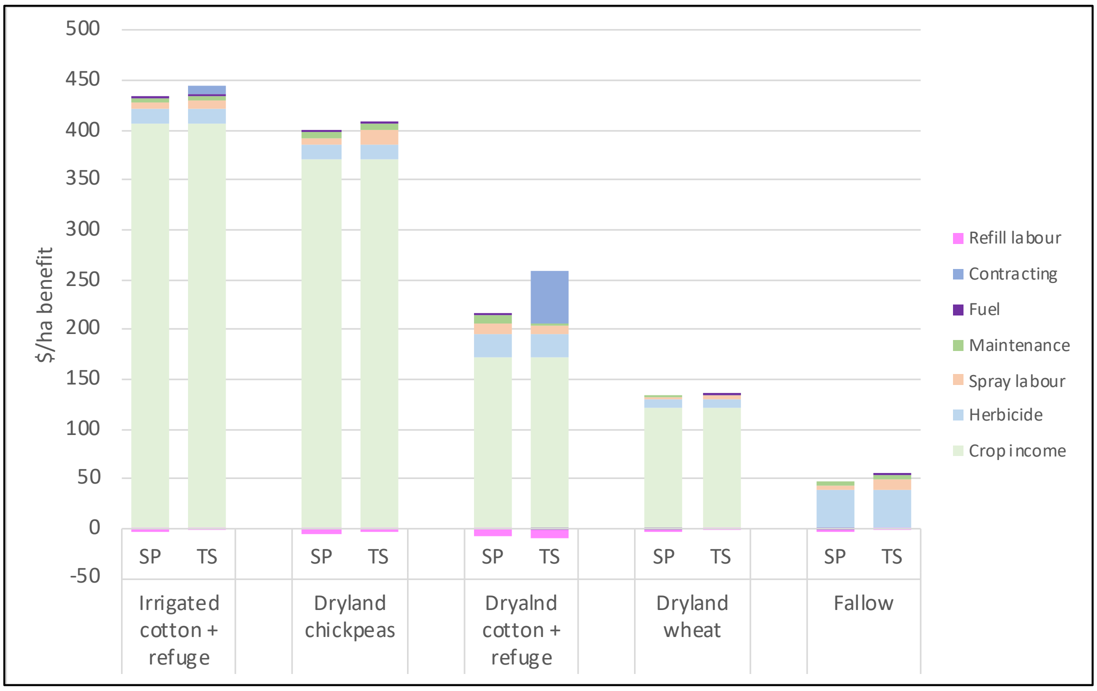
Crop mix is also key driver of the potential impact. Figure 6 shows the benefits associated with agbot adoption for each crop. As avoided capital costs cannot be allocated to a single crop they were excluded from this graph. Of note, while Figure 6 shows the yield benefit aligned with the relevant crop, some of the yield benefits associated with agbot spraying are derived from fallow operations. While yield benefits dominated, the operational cost changes (labour, fuel, maintenance, and herbicide) were highest for fallow, followed by dryland cotton, dryland chickpeas, irrigated cotton, and dryland wheat. The differences between the crop and fallow operational costs were reflective of the different number sprays required for each crop or fallow (to generate machine operational savings), and the proportion of herbicide sprays (to generate chemical savings). Consistent with the overall farm results, the tractor sprayer scenario generates the greatest benefits due to its lower field capacity.

Conclusions and Recommendations

This analysis developed a farm level economic framework to evaluate the economic potential for adopting agbot sprayers in a cotton production system. The analysis used a representative farm with mixed irrigated and dryland cropping including cotton, wheat and chickpeas. The adoption of the agbot was compared to the existing farm spraying equipment based on two scenarios—a SP sprayer, and a tractor sprayer.

In order to avoid any negative impacts from reduced spray application timeliness, sufficient agbots were leased to complete the spray tasks in an approximately equivalent time as the conventional

Figure 6. In-crop benefits for both scenarios and all crops. SP=SP sprayer scenario and TS=Tractor sprayer scenario



spray machinery. As a result, in the model two agbots were leased in the SP sprayer scenario and one agbot was leased in the tractor sprayer scenario. The agbots undertook all ground-based spray tasks, negating the need to invest in a SP sprayer, or extending the operational life of the tractor sprayer.

The analysis showed that, given the data and assumptions, adoption of agbots for spraying was economically feasible for both scenarios, with the primary benefit coming from yield gains, avoided machinery capital costs, and chemical savings. The implementation of agbot spraying to replace tractor spraying generated a greater farm economic impact due the tractor sprayer's lower field capacity. The results reflect the underlying assumptions that will differ between farming operations.

While yield gains generated the largest benefit for both scenarios, this was also the most uncertain variable given the complex interaction of factors affecting crop yield. In particular, the continued use of heavy conventional machinery for other field operations such as planting and harvesting may reduce the potential yield benefit derived from agbot use. While this analysis only evaluated agbot spraying to reflect current commercial agbot attachments and systems, the use of agbots for other field operations would not only increase the operational benefits (avoided capital cost, fuel, labour, maintenance), but also provide greater support for yield benefits by removing additional heavy axle load machinery. This longer-term scenario fits in with the overall vision of agbot developers and proponents to redefine the current farming system.

Sensitivity analysis showed that there was potential for a large variation in the results given the assumed range of the input variables, with yield gains and farm size being the primary drivers of the results.

While irrigated cotton and dryland chickpeas showed the largest crop benefits, this was primarily due to the yield benefit. The greatest operational benefits were delivered in fallow spraying due to the relatively high number of sprays per hectare (generating machine operation savings), and the high proportion of herbicide sprays (generating chemical savings).

With the increasing commercial availability of agbots and the widely predicted benefits, it is timely to understand the economic potential for agbot adoption in the Australian cotton industry. From the results we inferred that agbot sprayer technology can be a viable economic technology for adoption in a cotton farming system if yield gains can be generated. The economic viability will also be influenced by a number of factors that will differ between farming operations, and as with any decision, farmers should closely review agbots in their own operational context before investment.

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