A Nuffield Farming Scholarships Trust Report

Award sponsored by

Elizabeth Creak Charitable Trust

Clyde Higgs Scholarship

Site Specific Weed Management

William Atkinson

July 2018

NUFFIELD UK

NUFFIELD FARMING SCHOLARSHIPS TRUST (UK)

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A

Nuffield (UK) Farming Scholarships Trust Report

"Leading positive change in agriculture. Inspiring passion and potential in people."

Date of report: July 2018

Title	Site Specific Weed Management
Scholar	William Atkinson
Sponsor	Elizabeth Creak Charitable Trust Clyde Higgs Scholarship
Objectives of Study Tour	To capture a glimpse of some of the innovative technology coming into the market for weed control in modern day grain production, looking predominantly at three areas: • Remote Sensing • Inter Row Management • Robotics
Countries Visited	Canada, USA, Australia
Messages	• It is possible to use alternative techniques for weed control in modern day grain production, although it requires a complete change in mind-set from a grower's perspective. • The once reliable means of emptying a can into a sprayer and achieving good and cheap control seems to be a thing of the past. • Now complex and expensive technology looks to fill some of the gaps created by the environmental, social and plant resistance changes anticipated in the modern farming industry. • This report is designed to introduce you to some of the concepts in development.

EXECUTIVE SUMMARY

Weeds, the non-desired species, have been recognised for hundreds of year as a major factor in hindering yields of field-based crops. They are notoriously competitive for nutrients, water, light and space and create an undesirable canopy for modern day food production. They're well-recognised for their ability to shed seed at a prolific rate. They also have no value from a nutritional or medicinal point of view.

Over the past century many different control techniques have been used with varying success. Most recently, chemical herbicides have become the dominant control method for mainstream agriculture (estimated 96 % of European agriculture). The reliance on herbicides became prominent and now, as they begin to fail, controlling weed burdens is again a focus for modern producers in order to remain profitable. Organic systems offer much insight into cultural techniques but some would question sustainability long-term.

The objective of my study was to examine selective techniques, chemical and non-chemical, available and in development, with emphasis on moving away from the "blanket" approach used today. It was also important to try to access some of the financial elements concerned with each technique.

My research focused on three areas;

- Remote Sensing (passive and active)
- Inter Row Management
- Robotics

I visited two continents, looking at research facilities both commercial and educational, choosing countries with ability economically to invest in the technologies whilst being in the forefront of modern grain production:

- Canada and United States of America
- Australia

Each country had its own set of constraints which were led by several factors. It was important to bear some of these in mind as the outlook of each individual, company or country would be slightly different as a result. Examples included:

- Legislation
- Climate
- Markets
- Soils
- Profitability

I found that it is possible that these technologies, both commercially and environmentally, will be viable in the future. Each could often be complementary to another with a high level of precision being required. However, more developments are essential to achieve 'market readiness'. It was

encouraging that there is enough incentive from both commercial and government organisations to sponsor this technology forward. There was an obvious level of investment in certain locations but it wasn't always driven by the need to become more 'sensitive' with herbicide applications. The Australian farmers, I concluded, were the best in the world with their business knowledge, open-eyed and also holistic approach to every aspect of site specific weed management.

DISCLAIMER

The opinions expressed in this report are my own and not necessarily those of the Nuffield Farming Scholarships Trust, or of my sponsor, or of any other sponsoring body.

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1.0. INTRODUCTION


Figure 1: The author, William Atkinson

I was born in Northallerton, North Yorkshire, on the 5th September 1989. I was a heavy baby and I would argue, exceedingly good looking! I spent the early years of my life a keen rugby player, after trying other hobbies such as musical instruments. I found being thrown around a pitch more fun than being a musician. I attended a small school in the local town of Barnard Castle, well regarded for its rugby prowess, and enjoyed a boarding life away from the hustle and bustle of growing up on a farm.

At the end of school, I decided university wasn't for me, as much as I probably wasn't for university, and so I came home to work at what was inevitably going to be my career, farming. I started doing as many young individuals do, sitting on tractors, working long hours and enjoying life. However, after 4 seasons running around between sitting in a silage crew and doing my routine jobs at home, enough was enough and I concentrated my efforts into home farming life.

The farm, a mixed arable and beef farm at the time had been the family business since the 1950's. It became obvious to me almost immediately that stock farming wasn't going to be my future and it didn't take long before I got myself fully involved in the arable side. It is thanks to my agronomist Patrick Stephenson, to whom I owe a lot of my knowledge in this area. The fortnightly walk together is educational if not, at times, comical.

At this point I'd been with my girlfriend, Kirsty, for nine years and much of my current direction is down to her. She excelled at school and then gained a 1st class master's degree in Chemistry from Newcastle University. I particularly enjoyed my weekly visits up to Newcastle to get a small taste of university life. Today, we are engaged and no doubt if I'm left to organise the wedding will still be engaged for many years to come. I have my Nuffield Farming travels to thank for helping me find the location to propose, the edge of a cliff in the Blue Mountains, Australia. A calculated risk!

Today, the business has evolved into a diverse multi-branch business with pigs, cattle, sheep and arable enterprises, with a cropping area of 500 ha which I manage. Crops include wheat, spring barley, canola, fava beans, rye and grass leys. There is inevitably still a lot to learn on rotations, but diversity seems to be the obvious option for me going forward. One of the big challenges we face in the North of England is the short seasons, where the weather will close in on us early in the autumn and open later in the spring than in other parts of the country; this, combined with the exceptionally heavy clay soils we have, leads to several issues, blackgrass being amongst them.

2.0. BACKGROUND TO MY STUDY SUBJECT

As an agricultural business, we need to be aware of all the cost elements to warrant success. Certainly, over the last number of years one of the silently increasing costs has been weed control. Weeds have become a heavy burden on all businesses, absorbing large quantities of cash and hampering yields. It seems almost impossible to pick up an agricultural tabloid anywhere in the world and not find a headline title that mentions the negative impact. Blackgrass is of course our UK version of cancer in agriculture. Over several years, I have seen expenditure on dealing with weeds, particularly blackgrass, increase by as much as 680% whilst overall control has evaporated gradually until a point where it's almost impossible, even with the ideal environment, to maintain a stalemate position with the burden. Along with social pressure and chemical resistance it leaves an unattractive proposition for anyone wishing to produce food in today's markets.

It is, as many growers will say, that simply throwing more money at a failing picture is completely unsustainable and therefore something must give. The typical practice of spraying an area in its entirety resulting in a significant level of spending on herbicides needs to change. Only the location of a weed should dictate the location of spray application.

When the concept of site specific weed management was discussed, there was initially a lot of opposition to the idea, with questions around the accuracy and ability to recognise weeds. Unlike a disease or a nutritional requirement, which commonly may be specific to each square meter of a field, a weed burden can be acknowledged on a spot-by-spot basis where it is present.

Four years ago, whilst driving up and down a field trying to spot spray with glyphosate, it became obvious to me that the operator, no matter how skilled, wouldn't be able to hit the small, spatially spread out targets at the traditional forward speeds required when using a conventional sprayer. Control of weeds on an individual basis requires individual nozzle control by computer with the necessary processing speed to make hitting the target with 100% accuracy realistic.

Recognising this, in 2015 I bought a drone (unmanned aerial vehicle, UAV) and began to investigate the technology required for it to possess the ability to recognise the difference between weed and non-weed species. In the past two years I spent time learning about the good and the bad this technique had to offer, appreciating some major problems along the way. I started to try and understand if there was a way to take site specific weed management to the next level.

In the meantime, social demands have added an additional burden to agriculture with the rise of the 'anti-glyphosate' campaign. I have no intention getting too involved in the arguments either way but the mind-set of the consumer will influence where the future of agriculture may end up. With this in mind, I started to seek opportunities that a closed European market post-glyphosate might produce. It would, of course, mean a complete change in direction for the industry and significant change in the mind-set of the grower as much as anything. I had no experience of any form of non-chemical control beyond rogueing and stubble cultivation techniques. I decided to investigate the culture around the non-chemical technique. Unusually, I turned to gardeners before I investigated the organic sector looking for direction. Imagination throws up some unusual ideas, some of them very questionable but it led me down the avenue of inter-row management; with no understanding of the age-old technique I looked into how it had developed. Not new to the industry, but still commonplace globally, mechanical techniques offer an alternative in lesser economically developed places and where chemical alternatives aren't always readily available.

Over the last years of my farming career there have been some great technical advances with the introduction of the Global Positioning System being one of the most important. What is always mentioned at any 'blue sky' discussion is the use of robotics and the inevitable part that they must play in the future of agriculture. Again, I had no experience of robotics but was equally excited to see what they had to offer the industry going forward with the possibility of 'third generation' technology removing the requirements for herbicides altogether. Today, there is little alternative to the applications of chemicals along with the vicious circle of renewing high cost machinery. There's a gap for new, smaller innovators to disrupt this along with a willingness from the industry to drive them to the market.

3.0. STUDY TOUR

The decision-making process around where to visit was a simple one for me, the criteria had to consist of five key elements:

- Access to funding
- Need for change because of financial pressures
- Social pressures
- Cropping limits
- Herbicide resistance

Having never spent any time in agriculture outside Europe, my eyes were sure to be opened on how the wider world systems compared. Whilst planning the trip I knew I was heading out at the wrong time of year to be seeing activities in the field but the opportunity to meet and talk to the people implementing developments wouldn't be hampered. I would learn about some of the crops not traditionally grown in the UK such as soybeans, corn (maize) and high value crops such as lettuce or tomatoes and wild blueberries,

It became obvious that the wide range of cropping systems out there, whether they were root or grain-orientated had a similar set of problems and this presented the option for technological advances for the industry as a whole, and innovation wasn't forced to be one-sector oriented. This opened up the breadth of my research further, bringing into my focus some of the high value crops such as carrots and lettuce and the larger scope for investment that these crops offered over small grains. However, it was important to me the impact that the technology could have should include small grain crops more commonly grown in the UK. It was also crucial that the main markets dominating global agricultural commodities of corn (maize) and soya beans were considered, as it would be easy to assume that advances in technology would most likely be concentrated where there was established access to global market share. It was also apparent that there could easily be a language barrier for communicating with some of the more technical details. Table 1 summarizes my study tour.

Table 1: Showing study tour and dates

Early November 2017	Canada (Nova Scotia)
Mid November 2017	USA (North Carolina, Ohio ,Indiana, Illinois, Iowa, Minnesota, California)
December – January 2018	Australia (Queensland, Victoria, New South Wales, South Australia)

4.0. TECHNOLOGICAL ADVANCES

In the history of weeding technology great advancement came with the start of the mechanised revolution was in the 1920's. Before this the arduous task of weeding involved a large proportion of hand hoeing and, although important, is not relevant in the context of this report. Post the development of the first combustible engine in the early 1900's the mind-set changed from a labour-intensive way of management to that of a highly mechanised system with pressures on both food commodities and, later, availability of workforce. The initial years saw the replacement of the horse by mechanical pulling of the plough. However, post emergence of crops saw the development of the first inter-row hoe. The concept, which still exists today, used a shallow, manually-guided point running through the topsoil pulling weeds from their rooting area.

Figure 2: Mechanical inter-row management

Of course, the quality of the job would depend on several variables, such as:

1. Condition of soil
2. Weed population
3. Density of intended crop
4. Driver ability

Regardless of effectiveness this was a huge progressive step forward from manual weeding. It wasn't until the introduction of the first commercial herbicide, 24-D in 1946 that the next revolution happened - the rapid evolution of the agro-chemical industry. It's estimated that 99.1 % of modern farmland in more economically developed countries is non-organic and therefore using herbicides in one capacity or another. The effectiveness of herbicides was incomparable and mechanical techniques soon died out, leaving a generation without the knowledge of alternative methods. Even today, with widespread individual herbicide resistances, it still seems hard to find a non-chemical solution that can compete with the now traditional methods of applying herbicides. Nevertheless, what is becoming evident is that the economic, social and environmental impact that herbicides and other agro-chemicals are having is becoming unsustainable. Change in agriculture has been accelerated in recent years as the industry comes under new forms of pressure.

Now the evolution of new technology is leading us into a position where we appear to be developing the next two generations of weed control: i.e. non-chemical options and robotics, (discussed later in this report) before we've fully conquered the potential of the first i.e. remote sensing (GPS, drones and cameras) . We are now seeing the hype around robotics being more prevalent than interest in the fine-tuned traditional techniques of herbicides. It would be fair to say that a degree of this is down to the insecurity that the industry feels right now. The most recent form of destabilisation has been the social pressure around glyphosate and, whilst I grit my teeth in writing this, it seems a foregone conclusion that the most commonly used herbicide in the world will soon fall by the wayside under the social propaganda of lobbyists. Rightly or wrongly!

During the past 36 months, we've seen the huge social push against use of many pesticide products which has directed study towards analysis of "non-chemical" alternatives. The shortage of new and young entrants to agriculture has also limited industry progression - it's estimated that the average age of the primary producer in the UK industry is now over 60. It's hoped that the rise of the autonomous era will reinvigorate the younger generation back into agriculture. Whilst this is undoubtedly going to be vital for the future success of food production it shouldn't be forgotten that with every change comes a loss of knowledge as has been seen through the latest generational change on my family farm.

5.0. REASON BEHIND LACK OF INNOVATION

5.1. ACCESS TO FUNDING

Some of the greatest challenges that are yet to be overcome are those of financing new techniques and research. Certainly, the most far-reaching innovation which comes to the agricultural market is often a spin off from developments in the medical, automotive and the military sectors. The latter often proving to be the silent conquer of global security, ironic when you consider that the very reasons for military expenditure is often to develop weapons to destroy vast areas but they can result in a solution offering world security by adaptation to modernise food production. Undoubtedly, when any new idea needs lifting off the ground it requires huge sums of money and with agricultural margins much tighter than those of the automotive or aggregate industries for example, there is comparatively less space for innovation. It seems that any form of investment is either coming from the large agro-tech companies, for example John Deere, or the large agrochemical companies such as Bayer, BASF. This inevitably limits the market and the future development of some of the more intuitive ideas that are often thought of in the primary production areas. Ideas thought of on farm can be disruptive for the major manufacturers. However, one thing that has become apparent on my travels is that this has become a well-recognised problem for some nations and we've seen an increase in countries now investing government funds in the technology sector.

5.2. EDUCATIONAL COLLABORATIONS

There are government funded development programmes, sometimes running in collaboration with educational arenas (universities and other institutions) to develop new techniques. These logical collaborative advances are important with tightening budgets for future educational funding and are becoming more prominent. It might be argued that some of the historic research at this level has been, at times, irrelevant and questions hang over the applicability of it in the industry. Though, as my partner often reminds me, there's no such thing as a failed result: you always learn something from any result. Still the opportunity for collaboration seems right in today's market.

One of the best examples of collaborations was in Australia with the Grain Research Development Corporation. Here the farmer pays a levy on every unit of produce delivered or sold to market and a small percentage is then distributed to research organisations whether they are educational or otherwise. All this research is then led by farmers with a voting system put forward on projects that the industry feels is relevant to them.

Below is a table of how the funding structure may look.

Table 2: Example scenario of voting mechanism with farmers: Grains Research Development Corporation

Project 1	18%
Project 2	52%
Project 3	7%
Project 4	23%

In this scenario if there were $100,000 available, projects would get the funding proportioned out as:

1) A$18000
2) A$52000
3) A$7000
4) A$23000

Funding rises and falls with farmers' productivity, so negative results impact the researcher in equal measure with the farmer. This concentrates all involved on producing positive, relevant research.

The other great example I saw of collaborations between industry and education was at the University of Prince Edward Island, Canada. Here all the research is funded equally by both industry and government with extra as required from the university. In a typical scenario, an industrial company would enter into an agreement with the university for a full schooling year, with three students dedicating 33% of their time to the project. Often the students would be expected to have a weekly conference call with the sponsor to ensure that the project was running smoothly on target. The students also had the advantage of being able to call on other departments in the organisations to help with development outside of their parameters and on completion the product would be handed on to the industrial partner. The graduates would remain in ownership of the intellectual property with some examples being given of students going on to begin full production of their educational project and turning it into a business. The entry fee for such a project is US$7,000 of industrial sponsorship with equal amount of government backing and the University making up the remainder.

One of the highlights of my Nuffield Farming study tour was hosting a lecture to the second-year engineering students at University of Prince Edward Island (Figure 3). After setting them some tasks on weed management, we spent time going around the room discussing their ideas. Impressively some of the ideas from a group of non-agricultural students were actually right on target with where the industry seems to be heading and it was encouraging to see how students connected with the problems of food production.

I was once told that at 2 years old the brain is 98% imaginative and by the time you reach 58 is only 2% imaginative; possibly some of the answers out there now need to come from the younger unclouded minds.

Figure 3: University of Prince Edward Island engineering students talking alternative options for weed control

5.3. INDUSTRY RELUCTANCE

It seems apparent that one of the biggest issues is the reluctance of the industry itself to take on innovative ideas. However, I did not find any one targeted system of weed control that was 100 % satisfactory. Rightly so, the industry has been somewhat reluctant to suggest that it is an easy move to go from the blanket approach to a more targeted one. We know that even the smallest failure with certain weeds can have a devastating long-term effect on managing populations. I've seen it myself how one plant can go from a small innocent aberration to a significant 'out of control' infestation within a short period of time. The question remains of how we change this going forward. The simple answer would of course be to prove the technology: 99% accuracy has got to be a realistic target for any technology company wishing to enter the market with any success. Farmers need a high degree of assurance of success if they are to invest to change their farming system.

Over the last decade, however, farmers have increased sprayer width and forward speeds to increase work rates but have lowered efficiency since nozzle design has not kept pace. Farmers need to balance nozzle capability and sprayer output speeds.

5.4. PROTECTING INTELLECTUAL PROPERTY

One of the obvious reasons for seeing developments in technology is the financial returns that should be available. Innovative ideas that are feasible and effective seem few and far between and require huge sums of money to develop. To this extent often the initial ideas that start either in a laboratory or on a workshop floor need protecting - to see them through to offer a financial incentive for the original inventor - hence the need for intellectual property protection. One example of this failing was in North Carolina: a farmer who carried a reputation of being an innovator had found himself with a lawsuit trying to protect his product and all the developments he'd done with a thermal weed destruction technique. As a result of this he was unwilling to share details of his product with me.

6.0. RESEARCH

6.1. UNDERSTANDING REMOTE SENSING

The principle of remote sensing is to use an external image acquisition source to capture data, not in contact with the target but passing over the area of interest. The acquisition tool, most commonly a camera with high-precision focal lenses, detects a wide range of colours and energy wave variation, not limited to our own visual wavelengths, and gives the growers and data analysts the ability to see the 'unseeable'. When the full Electro Magnetic Spectrum is considered, the human ability to see colours is highly limited within a very narrow visual range. We use our brain capacity to recognise variations in leaf shape and to a lesser extent the colour variations. In a plant interactions between reflected, transmitted and absorbed energy differ according to species and condition. This gives spectral signatures unique to each plant and growing condition at the time of measurement. Thus identification of species and health of weeds or crop can be achieved.

It was historically recognised whilst shining a white light into a prism, results were recorded of distributed light outside of the visual range and when a thermal reading was recognised the principle of the invisible light was acknowledged.

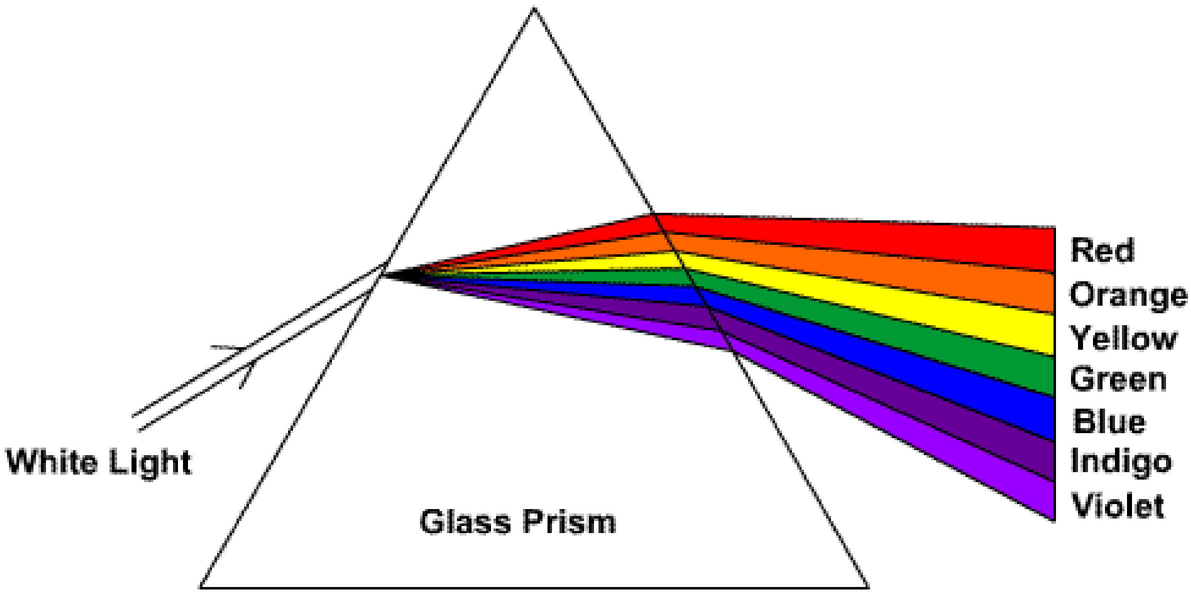


Figure 4: Illustration of white light shining into a prism before separation into various elements of the visible spectrum.

The importance that this offers agriculture is significant because we know that plants, through the process of photosynthesis, absorb and reflect light in different proportions. Through the palisade and spongy mesophyll cells within the plant structure light is reflected in variations and consequently can be measured with the use of modified cameras. The light reflected off wheat and blackgrass, as an example, is similar in the visual wavelengths; however in 'non-visible' wavelengths it becomes more varied.

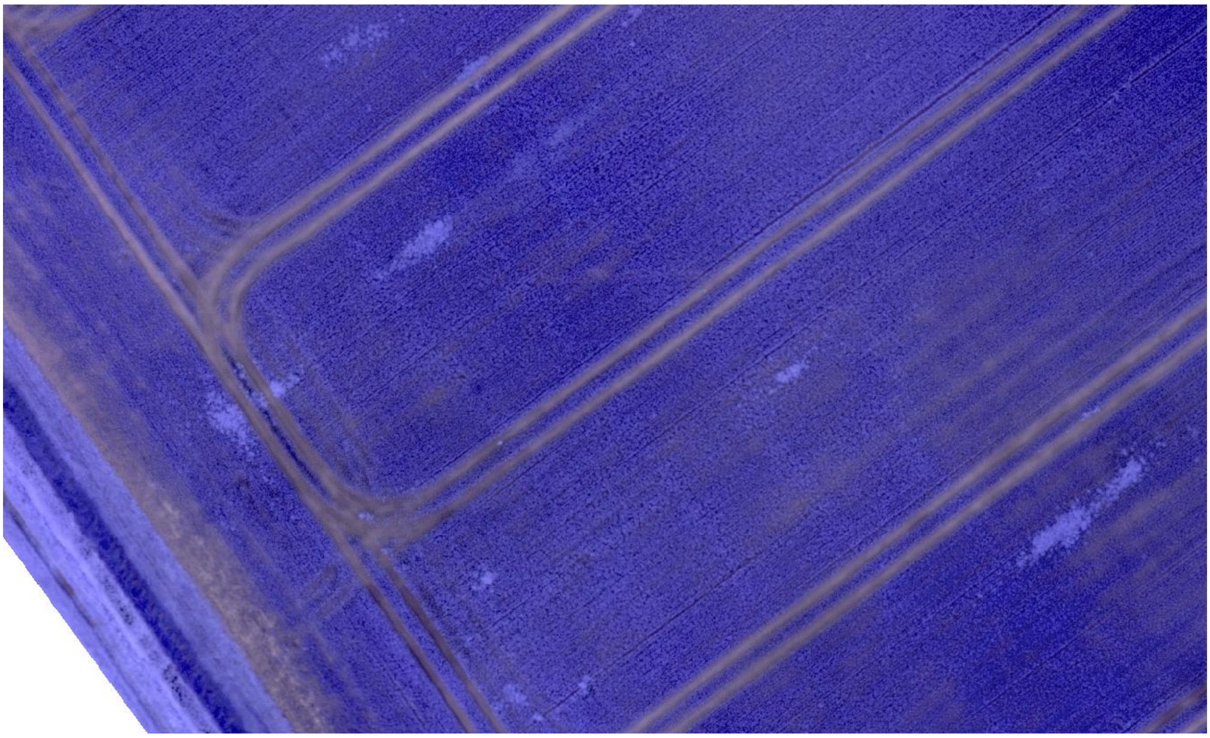


Figure 5: The author's drone image showing blackgrass within a field of wheat in NIR.

Image 5 above shows how the plant absorbs the blue and red proportion of the visual wavelength and reflects red and NIR (near infrared) light. The important element to note is how the level of NIR light reflected varies depending on the health of the plant. It would be unfair to say that it's easy to measure the difference between the desired and undesired specie simply on the measurement of NIR light, it is only possible with the assistance of highly complex computer analysis systems.

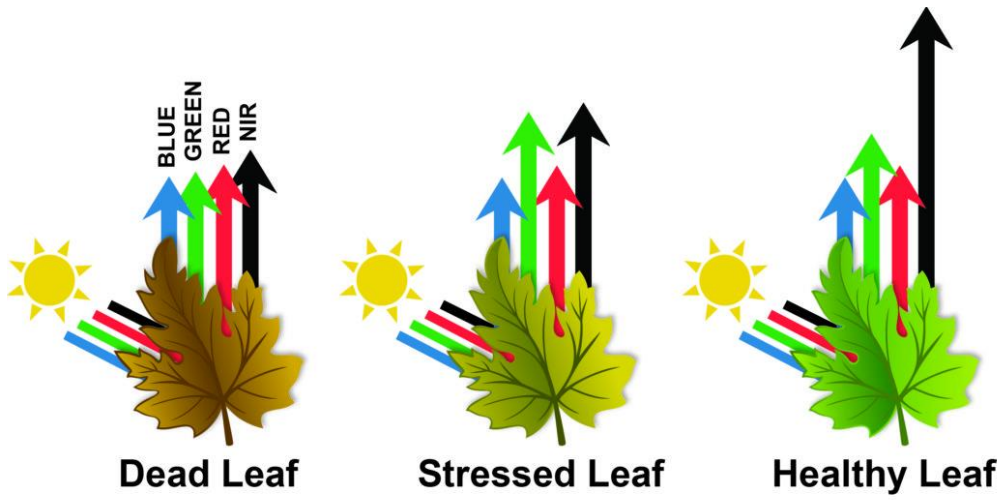
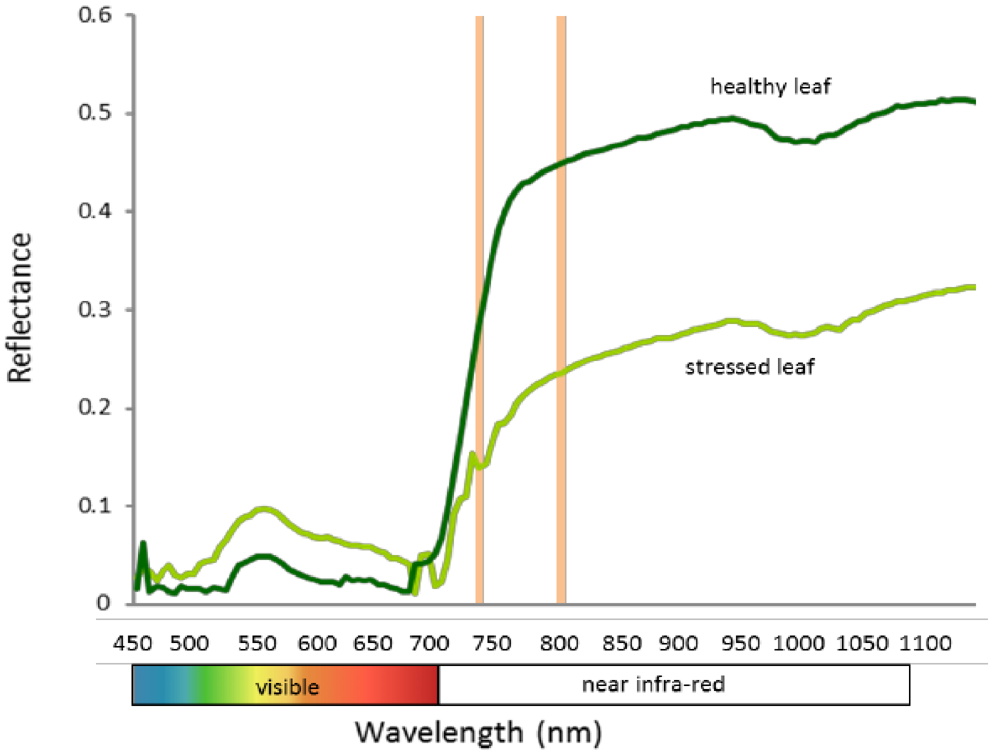


Figure 6: Image showing how leaves absorb and reflect light based on their health.

The other consideration should be that the EM spectrum doesn't acknowledge the huge variation within each light individually. For example, the colour blue isn't a simple one-digit anomaly and thus is made up of hundreds of blues all slightly different to the next but acknowledged as blue nonetheless when we acknowledge them. The unit used to measure these variants is nanometres, a nanometre is one billionth of a meter and when put into context a strand of hair is a hundred thousand nanometres wide. Significantly huge when comparing the variants between the human recognisable light is 390 nm (blue) and 700 nm (red) but the full spectrum of light extends beyond 3,000 nm into the further infer-red



proportion.

Figure 7: Spectrum of light from ultraviolet through to near – infrared.

The problems that are faced when trying to capture the incremental variants, when they're so acute, are that the cameras typically capture the dataset in an individual wavelength, 810 nm (NIR) as an example, and can't always therefore capture the full variants that present themselves in the field. There are however more and more technical cameras entering the market such as multispectral cameras that carry four or six different wavelength capabilities. There are top spec hyperspectral cameras that carry the capability to acquire datasets with up to a thousand variants, with an entry price into the market of around US$100,000. The question remains around which platform is the most efficient to acquire the dataset and how to actually use the data once it's been captured.

In summary

- Understanding the Electromagnetic spectrum is important
- Light ranges hugely between what we can and can't see
- Cost-feasible cameras carry limited capabilities
- Expensive cameras may carry the required technology to achieve the end goal

6.2. ACQUISITION TOOLS

6.2.i. Satellite

The longest standing method of acquiring data has been satellites; they have the lowest cost entry point onto the market due to their massive scalability and they remain set to be a dominant feature in the marketplace. However, it was impossible to find a company around the world that would offer any form of assurance that they could guarantee accurate identification of weeds because satellite imagery has the lowest spatial resolution (size of the pixilation on the imagery) and was so poor that there could be no guarantees that recognition would be at all possible unless used on a massive infestation of the target weed. It should be pointed out that that over the last 20 years spatial resolution has gone from an average of over 20 m^2 down to 60 cm^2 and we can only expect that this will inevitably continue to get better with time.

Satellite data collection remains low cost with the added positive that nobody operates the acquisition tool at any stage: this along with its wide range of cameras allows it to capture data in many different formats and correlate things such as thermal imagery data alongside hyperspectral data. It is important to note that although they may not be using the technology yet, every company I spoke to was keeping one eye open on when it will offer the resolution necessary to make reliable identification possible. As was explained to me by several companies, one of the biggest issues with any collection of multiple satellite images involving variations in light over the time of capture, which are then used to make up a single dataset, is difficult and as a result it requires many hours of 'smoothing out'. This isn't however a big issue where each image covers many square kilometres 'smoothing out' is a small process. It is the detailed space analysis which is problematic.

Maverick in San Francisco had built a business where a small group of individuals processed satellite data from day to day which covered in excess of 400,000 hectares; they offered fast 'Up To Date' imagery for the client, they showed me how small recurring themes were seen and alerts were sent to the farmer. This data could aid the day-to-day decision making on farm, however they remained unconvinced that the data could be used for any weed decisions today.

Recently there has been a big push in the media extolling the value of data acquired from satellites and to date the acquiring and handling the data has been put to good use, but we should always be cautious that the real value in this data may yet transition into the larger companies holding the monopoly over the industry.

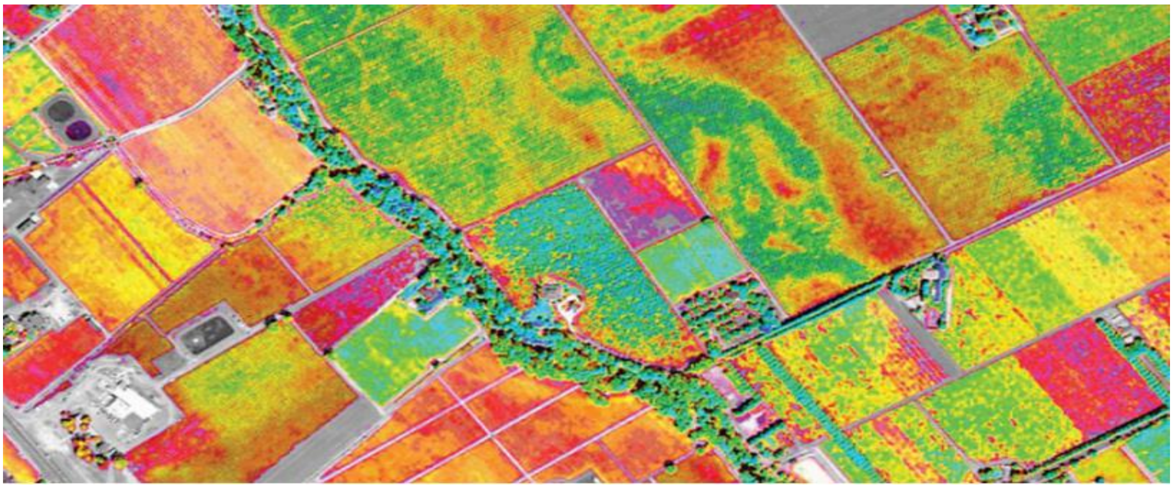


Figure 8: A Satellite image showing field variations through a Normalised Differential Vegetation Index map but showing also the intensity of detail.

Summary

- Level of resolution not good enough for weed recognition
- Easiest means of acquiring data
- Many types of cameras at a low entry point into the market
- One for the future

6.2.ii. UAV/Manned Aircraft

It seems the big push in the industry for everyone to own a UAV (drone) has come and gone. The high resolution that these aircraft offer has come with an expensive operating cost that makes the system uncompetitive; their resolution is still too big. My own experience of using such an item has forced me to reconsider the future of drone machines. James Lambert, a PhD student from the University of Sheffield, has done some extensive work with the use of drones for weeding purposes. His conclusions were as follows, "*Our main finding was that aerial images collected with a low-cost UAS (<€1000) have the potential to be used to map populations of A. myosuroides Blackgrass). However, our results indicate that if this technology is to be applied at a large scale in an automated way, then there are several issues that need to be addressed. Secondly, our analyses of within-field variation using simple statistical models show that it is possible in principle to capture the variation in weed densities. However, models developed in* *one field rarely perform well when applied elsewhere, indicating that locally they were over-fitting the relationship between density state and the spectral signal. This means that currently the interpretation of such imagery is limited without supporting ground-truthed data; the ultimate objective of our research is to be able to generate estimates of densities from imagery without the need for detailed ecological surveys. Year-on-year transferability is currently being assessed. We have highlighted that there are challenges in generating robust predictive models that relate variation within images to weed densities within fields yet are applicable across multiple sites. Our work has revealed areas that need to be streamlined for the methodology to become more of a tool for management applications."*

To summarise, the ability to cover large areas is therefore important when considering this system. However, the requirements for follow up by 'ground truthing' is time-consuming and negates a desired outcome and this shouldn't be underestimated.

The price of the equipment has moved dramatically in recent years. At first entry to the market the average UAV would cost more than £20,000 but with this technology becoming more widely available across multiple industries the entry cost would now be less than £2,000. Many different platforms are available with fixed wings or rotary type platforms becoming easily accessible. The big decision on which is the better depends on what the requirements from the platform are. A fixed wing has the ability to cover significantly more ground in a single flight, but their operating height is much higher leading to poorer quality datasets. They do carry a stronger ability to withstand higher wind speeds allowing for more flying days when compared to their rotary counterparts. The rotary-based platform can offer significantly higher quality datasets due to their ability to fly lower and being able to hover over an area of interest, such as a trial plot. I met Jerome Leroy in Goondiwindi, Queensland; he showed me some trial imagery that he'd developed with his background in geology and gave some good examples of what the market was looking for. The ability to recognise a developed weed from more than 300m meant that the weed would need to be of a certain size, possibly beyond what the market would accept but with further processing it could be highly possible to fine tune this to an acceptable level. But he also remained concerned as to how a UAV would offer him a reliable source for acquiring the data in a timely enough manner going forward.

I also met Ryan Smart in Keith, Southern Australia. He showed me how flying a drone remotely from his office to a paddock more than 2km away, flying the mission and returning fully autonomously before processing the data all in less than 45 minutes, was helping them manage nitrogen applications and irrigation gates. It was a good system that required almost no input from him once the mission had been set. Rules around the flying of such like aircraft have been a hot topic in recent years with horror stories a-plenty on the internet. In the UK anyone wishing to use a UAV for commercial purposes is required to attain a Permission for Commercial Operations (PfCO) certificate from the Civil Aviation Authority, to undertake a two-day course with exams and flight tests along with annual checks on current flying experience and have necessary insurance. This forces the professional flyers to be precise and accountable but these additional costs make it expensive.

Figure 9: An example of an unmanned aerial vehicle (UAV).

Summary

- UAV's present themselves as a low-cost entry point to the market for farmers
- High operating costs make them expensive to justify
- Quality of imagery still not good enough for single plant recognition

6.2.iii. On-board sensing

The basic principle of a camera being mounted to a sprayer boom (or something similar) without doubt represents the most feasible option going forward. The ability for a camera to take an image at the desired rate is possible today with many modern cameras having a shutter speed of hundreds of frames a second which eliminates the problems that are commonly associated with similar sensing formats. The big questions remain about how to process these datasets at the required speed. A single image is often more than a kilobyte and a typical processor on an agricultural platform is 40Mhz. put into context in today's processing capabilities.

See Table 2 on next page: guide to show the relationship between processors, data analysis speeds and year of introduction

Table 3: Guide to show the relationship between processors, data analysis speeds and year of introduction

Processor	Analysis per second of data	Year of technological introduction
10 MHz	0.25	1982
16 MHz	0.303	1984
40 MHz	1.1	1990
300 MHz	1.41	1996
400 MHz	1.9	2000
3.3 GHz	53.38	2011
3.6 GHz	84.6	2017

A typical image can take up to 2.5 MB of computer space leading to larger-than-acceptable datasets to process when you consider multiple images are required per second for forward motion multiplied by the number of nozzles on a boom which often number 48 or more. Data compression tools have developed significantly and can 'crunch megawatts' down to more manageable quantities in minutes or less. Commonly companies are now looking to build in a 'lower spec' camera to reduce the intensity of the image and in turn reduce the size of the dataset for processing.

One of the most proactive research facilities in this field was University Southern Queensland in Toowoomba. Dr. Cheryl McCarthy, and Dr. Steve Rees have been integral in designing and building a prototype machine for a large manufacturer. A camera based on each nozzle or a camera managing a cluster of nozzles meant that the required spatial resolution was achieved with booms commonly running at no more than 50cm above the canopy. With this set up the resolution can get down to the sub-centimetre level. The biggest issue was the speeds at which modern sprayers are required to operate. Often a sprayer will have a forward speed of more than 12kph or 3.336m/s giving milliseconds to identify if a weed was present or not. A common means of resolving this is to place the cameras further forward from the application method or nozzle giving a longer lead time.

The interest that on-board sensing is receiving from major manufacturers is evident as, prior to leaving for my travels, an innovative company in California was bought for a significant sum of money by arguably the biggest of all the manufacturers. Blue River Technology has been doing a lot of testing over the years on several different technologies. Today it has developed a thinning machine for high value crops such as lettuce. The ability to recognise plants and weeds on a plant-by-plant basis and act on them is nothing short of impressive. They have used a hooded cover to control the variable light and create a dark environment thus aiding the ability of the machine to recognise weeds from non-weeds as well as counting plants and plant-spacing to enable achievement of an optimum plant count in the field.

Figure 10: Blue River Technologies automated thinning machine

Summary

- Real time data analysis is becoming achievable
- Forward speeds may be limited
- Technology will be expensive
- No extra man power or processing required between entering and exiting the field

6.3. APPLICATION TECHNOLOGY

Undoubtedly the story of recognition technology isn't complete without the application technology carrying similar levels of innovation. The industry has made huge progress in recent years, with the historic means of simply turning a boom of nozzles on and off now a distant memory. Today the industry is accustomed to having a Global Positioning System controlling a group of nozzles but this has been limited to a minimum capacity of 2m sections (typically 4 nozzles). The limiting factor is the capacity at which the processors can work. This remains a significant problem for the speeds at which we can require to control a nozzle at the desired rate.

Typically, with modern sprayers travelling at 12 kph or 3.336 m/s, an 'on and off signal' can represent an area of over 1.668 m^2. This represents a huge overspray of the area of an individual target weed. Undoubtedly demand from farmers is pushing application technology developers to invest in this area with several companies currently trying to enter the market with individual nozzle control technology. In Southern Australia I saw an Agricfac Sprayer working with a new system, due to market shortly. The system didn't use the typical controller that turned each section or nozzle on and off but, instead, used a means of applying the product in microbursts, so the application could be set between anywhere from 0 to 100 applications a second with each burst giving an application set by the operator. I witnessed an external source prescribing widely varying individual nozzle application rates on a machine and, after placing some water-sensitive paper at random, I recorded how the system applied these prescribed rates very accurately; rates ranging from a zero through to areas the full rate, all individually controlled within a matter of metres.

See photograph on next page

Figure 11: An image of applied rates of 0%, 25%, 50% and 100% of prescribed rate applied to water sensitive paper at random points across the boom. (Top papers only).

Summary

- Application technology is catching up fast
- It is possible to spray a varied rate from each individual nozzle

6.4. WHERE NOW FOR THE SYSTEM

Undoubtedly for the traditional sprayer to continue to dominate the market the hardware must be backed up by successful chemistry. Without this the spraying technology will fall at its first hurdle; however it still seems difficult to imagine a world completely without pesticides over the next decade.

7.0. INTER-ROW MANAGEMENT

7.1. UNDERSTANDING THE PRINCIPLE

The fundamental principle of this technique is to control an area between two rows of cash crop with an holistic destruction method whilst no contact is made with the intended crop being grown. Traditional row widths of 150mm make it difficult for row segregation year-round and so wider rows are often required to allow openness to be maintained. Typically row widths of over 180mm are used but up to 250mm are not unheard of in small grains crops. Once a defined row width has been established it creates an avenue of 'clean space' to manage. In recent years there has been a push for manufacturers to produce narrower row spacing on planters to aid weed control through more crop competitiveness. This method of percentage gain on combatting weeds leaves no opportunity for cultural management practices to ensue and thus is reliant on herbicides. One of the big drivers behind researching inter- row management has been the overhanging threat to the industry of restrictions on Glyphosate use and other products suffering from a build-up of resistance or under the threat of being withdrawn. Whilst the ability to simply turn the tap off with weed burdens is a distant dream, managing weed seed return is critical and some of the technologies below look encouraging.

The inter-row weeding technique is undoubtedly more intensive in terms of management requirements and commonly machine working widths are significantly reduced, to the more humble size of 12metres.

The percentage of ground covered by crops varies based on the chosen row width; the wider the row spacing the larger the area of "clean ground available for inter row management". Below Table 4 shows the potential areas as percentages of the total area.

Table 4: Effect of Row Width on percentage of ground cropped and uncropped

Row width, mm	% of cropped ground, %	% of uncropped ground, %
150	33	66
180	27	73
200	25	75
220	22	78
250	20	80
300	16	84

Note that all these values are based on a maximum digression of no more than 2.5cm either side of the cash crop; each row of cash crop will be within a 5cm band of controlled area.

7.2. NON-CHEMICAL OPTIONS

Although non-chemical techniques of killing plants would seem simple, scaling the procedure to field size comes with significant challenges. Accuracy of application onto target plants only is a huge challenge. The biggest cost associated with this option is not the cost of buying technology or the products used but the energy consumed. Michael Walsh from the University of Sydney explained that energy usage comes in many forms:

- Direct Energy - defined as the energy directly applied to perform the weeding treatment.
- Draft Energy – the requirement for energy through exerting drag force via a mechanical implement.
- Power Take-off Energy (PTO) – force created by the initial source, e.g. tractor engine that in turn creates an opportunity to drive a secondary energy e.g. rotary tiller.
- Chemical Energy – the use of sourced products e.g. propane gas to create a heat source

Each of these is important when considering what the requirements of the main drive source will be.

7.2.i. Mechanical hoes

The most traditional and historic means of inter row management consists of a steel hoe acting like a large knife scraping just below the surface level and uprooting or cutting the plant at ground level. A well proven system for lighter soils, this technique relies on soil water content to be optimum in heavier soil. In heavily infested ground cleaning the knife and prevention of dragging on the blade can be problematic.

This technique requires the lowest energy level, and should result in the cheapest means of non-chemical techniques.

7.2.ii. Flame throwing

This technique involves the exposure to large volumes of propane gas burning at approximately 2000°C causing singeing of the leaf. It is essential that the plant is exposed to sufficient burning time to ensure that full destruction is achieved. Care needs to be taken to avoid simply burning the leaf mass and not destroying the nervous system resulting in not killing the plant.

Although the initial reaction to witnessing this is frightening, the exposure to bright orange flames hurtling through a crop is striking to say the very least. One of the initial concerns when witnessing this system working is the volume of gas been burnt. In fact, the system is currently rated the cheapest means of proven thermal destruction. Typically, applications of propane are 20-25kg/ha. The system works better in taller crops such as corn (maize) that has a higher temperature threshold. Soybeans or wheat have a much lower heat exposure threshold and are both more exposed to the treatment due to being a smaller plant.

Figure 12: Showing a hooded inter row flaming machine complete with fuel supply tank

7.2.iii. Ultraviolet radiation

This is a new technique that hasn't yet been proven on a field scale, although initial testing on the concept has been on-going for several years. I struggled to find any companies that had developed a product or testing rig. I did manage to contact a start-up company in the state of Indiana; however they were unwilling to expose their product. The basic concept of exposing leaf tissue to damaging light is a simple and potentially effective idea but, as was explained to me, levels of exposure would need to be long and sustained to have the desired outcome and variability in success occurs, depending hugely on plant biomass area which dictates how much radiation is absorbed. The light effects chlorophyll and consequently the plant's ability to photosynthesise.

7.2.iv. Steam – hot water

One concept I particularly liked was the water boiler and applicators being developed by Weedtechnics, Sydney. Here Jeremy Winer showed me some of the technology he'd created and was probably the closest of all to having a boiler ready for the agricultural market. The concept consists of heating water from ambient temperature to approximately 80°C. Then through a complex process of compression the water is exposed to the plant at about 140°. However, unlike light where retention time is minimal, steam, when compressed, holds its temperature for minutes which is critical when trying to apply to larger areas, both from the point of view of application and of exposure. The tank took very little time to be ready for application; however tank sizes are limited and the volume water required on a field scale is huge, so massive volumes need to be in the preparation process within the applicator. The upside to this technique is of course logistically many businesses already have the water infrastructure in place to make this technique a possibility.

Figure 13: Weedtechnics handheld applicator

Figure 14: Weedtechnics small scale rig for handheld applications along with the applicator.

University College Davis, California has been doing work on reducing the seed bank with the use of pressurised steam below the surface. Dr. Richard Smith had designed and manufactured a test machine that was used in the high value rooting crops in the region. Initial results were “promising” with weed levels recorded in subsequent crops significantly reduced. However, it was acknowledged that the economics of doing this meant that it was only cost-feasible for high value crops. It was also recognised that through the application of steam sub-surface a reduction in fungal build up helped alleviate some of the consequential pressures in the following crop.

7.2.v. Microwave technology

Probably the most complex form of creating thermal mass is a microwave. I'd heard several years ago of the concept of using a microwave to expose living tissue to an invisible heating source but always had a degree of scepticism towards it. It was a pleasure to be hosted by a Dr Ian Graham Brodie of the University of Melbourne. Here I was shown a working prototype that had been designed for small scale trials and as proof of concept. The design consisted of four microwave applicators each with a 2kw generator. The magnetron heats the molecules in the plant causing rapid movement and in turn the molecules begin to clash creating heat. When the heat reaches a critical point cell walls rupture thus killing the plant. The question remains as to how you scale the system up to a commercial level. I met the microwave department of Nottingham University to talk through the challenges; Dr. Chris Dodds explained that to achieve something comparable on a larger scale, the sheer volume of energy required would make it almost impossible to heat the volume of living plant mass on average +72 thermal degrees with an exposure time of less than two seconds. Unlike some other technologies where a physical product can be left to expose the target to residual heat, with microwave radiation residual properties don't exist. The laws of thermodynamics dictate that this technology will come with its own set of challenges. To achieve a machine 12m wide would require an energy source the size of Rotherham power station -56 megawatts.

Figure 15: The back of the prototype microwave machine complete with 4 applicators.

Figure 16: Area exposed to treatment after 2 hours (strip in centre)

Figure 17: Area exposed to treatment after 24 hours (strip in centre)

7.2.vi. Other options on the market or in development

Other concepts are available - here are a few examples,

- Sandblasting
- High pressure water cutting
- Rotary hoe
- Mowing or mulching
- Freezing

7.3. TECHNOLOGY REQUIRED TO MAKE IT WORK

It is critical when using a complete desiccation technique between rows of cash crop that risks of contamination of the crop are kept to a minimum. In recent years GPS technology has brought much greater accuracy to straight oriented rows up and down fields. In the last two years we've seen several companies offering implement steering using GPS but, although the accuracy of these systems is impressive, the ability is not comparable to that of 'row sensing technology'. Row sensing consists of a camera, typically in an elevated position with a pitch down into the crop. The camera relays the live feed to a computer processor evaluating the correct position of the row and feeding a signal to a hydraulic valve block which uses a pressurised circuit to shift the implement laterally. The technology is well proven in open rows with concerns coming when canopy closure happens in the later stages. At this point it is possible to use a 'finger switch' - this is a physical means that relies on the crop having sufficient resistance in the stalks to manage the fingers, directing the implement back onto the right position within the canopy. UK Researchers Nick Tillett and colleague Tony Hauge have been using this technology for multiple applications.

7.4. THE BIGGER PICTURE OF INTER ROW MANAGEMENT

Whilst the concept offers initial benefits from the point of view of not using pesticides within the cash crop rows, the real advantage may not be proven. However, the technique appears to be gaining impetus.

The use of inter row legumes as an alternative means of sourcing nitrogen is worth mention, as is the ability to then integrate alternative flowering species. It is worth noting that recent Nuffield Farming Scholars have carried out research in this area.

One system that that is gaining traction today is 'Relay' cropping in the USA: in areas where wheat is a minor player it is still occasionally grown as a break from the rigorous rotation of corn (maize), soybeans, corn, soybeans. I met Jason Mauk who is growing wheat between the rows of soybeans. The different maturation times is used to give two harvests of two crops in the same calendar year. Another grower I met, Lorcan Steinglidge, was looking at growing low competitive species in the base of his corn, both as a means of reducing soil erosion post-harvest and as a means of adding value to his area financially and nutritionally.

7.5. CONCLUSION INTER ROW MANAGEMENT

Inter row management does present possibilities going forward to provide a 'greener' alternative to herbicide use which is under pressure. Non-chemical techniques have been a forgotten option in the quest of fighting back weeds. A quick search on the internet will show that there are many inter-row options although some of them remain questionable and a long way from being possible on a field scale. However, these options allow ideas to take shape and for research to prove that the concept has merit before considering economic feasibility.

Limitations around soil types and soil movement mean that predominantly thermal techniques should prevail. It shouldn't be underestimated that the levels of energy required to make thermal techniques work are substantial when compared to traditional techniques such as hoeing, but they do allow for a higher volume of killing in the desired areas. Intra row management is also important when aiming to achieve minimum weed seed return but very few inter row options exist on densely populated grain crops. When examining the table showing row widths on page 33, it clearly demonstrates that the percentage of uncropped land in a field allows for significant gains to be made for inter row management. In high value root crops intra-row technology is becoming an established method for weed control.

8.0. ROBOTICS

Robotics must be the future of the industry: they present exciting possibilities, creating much attention. The introduction of unmanned vehicles is sure to be the biggest shake up of the industry since the introduction of the tractor many decades ago. The technology I have seen has varied, with slight variation from modern practices to complete redesigned machinery, looking almost unrecognisable. As yet the technology outside of a controlled arena is unproven in agriculture and undoubtedly some of the biggest questions remain over how the technology will react in an unpredictable position such as a telegraph pole or a wet spot. The failsafe is being designed but animal or human interactions in the field will be completely unpredictable and will present a considerable design challenge for robotic developers.

The biggest challenge I see is the high level of operator training required to control the robotic implement in use. The quality of a job commonly comes down to the ability of an operator to change 'set-ups' based on the view of what is happening from the seat. I can think of many a time when I've had to 'step in' to alter things to allow for irregularity in performance: such as to prevent a build-up on the knife when harvesting or slowing down to allow a build-up of trash to clear from the cultivators. Some of the benefits of robotics may not be fully used for years to come as we learn and realign ourselves with what the new limits might be. For any industry to get the full value out of the platform, we must be willing to think outside the box. A simple example may be finding advantage by orientating rows across fields to suit the orientation of the sun and managing crop rows in fields based on their length.

8.1. THE PLATFORM (big vs small)

The robotic debate of big vs small may be decided on geographical location and not necessarily be based on farm size as is the norm today. It was interesting to notice, on the small amount of travelling that I've done, how people's attitude towards size was based more on field practices. For example, farmers with 120 ft. planters were thinking of one 600 hp robot in isolation - unlike those with 10 ft. planters who were thinking of a 'swarm' of smaller 3 hp robots working together. In recent years the trend towards heavier vehicles seems to have taken its toll. Andrew Baits, founder and CEO of Swarm Farms, pointed out that, "*We've been ego driven*," in creating the biggest machines possible when all we need is something small to do the same job more accurately. *"We're trying to pull a little splinter out of our finger with a huge pair of pliers when we should have been using a pair of tweezers."*

When we think of robotic weeding technology one of the first hurdles that we must address is to understand exactly what we're applying. If simple chemical application will suffice then possibly we don't need anything more than a simple adjustment of the traditional applicator we have today. However, if we consider a complex system using lasers in crops then perhaps a complete redesign is required. There are undoubtedly going to be advantages to a complete redesign when using some of the new technologies but I can't help but wonder if the levels of investment that would be required would simply incur additional costs being added - to be shouldered by both the farmer and ultimately the consumer.

Figure 18: Swarm Farms' fully autonomous spraying platform.

8.2. NON-CHEMICAL OPTIONS

Fast application speeds limit the capacity to use certain alternative non-chemical technology options. However, the ability to remove the human element by the use of multiple robotic platforms promotes the possibility of the robot concept use with non-chemical options becoming reality.

Non-chemical weed destruction methods employing inter-row management with robotic platforms include:

8.2.i. Lasers

A number of companies and research facilities have been working on this area, most noticeably Harper Adams University College and the University of Sydney. The theory is to apply an exceptionally large volume of heat in a very short period of time precisely to the meristem (growing point of the plant). The minimum dose application of 35 Joules is sufficient to cause mortality. This means that the energy requirement is minimal: it equates to less than 0.000001 kWh. However, the low requirement for energy is offset by the requirement for accuracy, with a miss on application resulting in scorching of the leaf at best. Of course, the advantage to this system is that build-up of resistance is unlikely to be a consideration and that multiple laser 'treatments' would be possible. Recognition systems, however, need to guarantee accuracy and adaptability to accommodate the constantly changing growth pattern and plant characteristics which occur over the growing season. This is possibly the biggest hurdle to overcome.

8.2.ii. Mechanical destruction

When the constraints of speed restrictions are removed the ability to use multiple modes of mechanical weed removal are increased. Some of the examples I saw included traditional pulling or dragging techniques but with the ability to 'punch' weeds into the ground. This required huge downward force from the platform but it does enable the physical characteristics of the platform to be used to advantage, as was explained to me by Nathan Dorn of Food Origins. Unlike when using a sideward action that puts huge stresses on the machine, the action of vertical pressure enables weeds to be forced to such a depth that recovery would be almost impossible.

8.3 CHEMICAL OPTION AND ADVANTAGES (Micro Dot Applications)

This is the ability to apply a 'microdot' or minute quantity of liquid to a leaf, often less than 1 microlitre. This requires an ability to recognise, through artificial intelligence, the difference between crop and non-crop. Once successful identification has taken place a robotic arm applies the desired herbicides through one of a multiplicity of means, each of which carry their own merits. Application may be by:

1) Physical exchange through contact with the leaf
2) Firing a dot of product to the leaf through under pressure
3) Applying a short stream of product on the leaf

Wind, intensity of infestation and thickness of canopy are example factors which will affect choice of the best method to use..

Unlike full boom application of herbicides, micro dot applications carry the ability to guarantee that only chemicals contact weed leaf tissues. The environmental concerns associated with broad spraying would in theory diminish, possibly paving the way for historic plant protection products that have been banned, to be brought back into the frame. It remains unclear if the social frenzy around ‘pesticides’ would see guaranteed application as acceptable, or if the public opposition is too strong today.

8.4. WHO WILL SEE THE REAL BENEFIT: THE FARMER OR THE INNOVATOR?

One of the many discussions I had on robotics concerned how to fund development to bring them to market. One of the recurring themes that was been mentioned was to offer robotics not as a purchasable item but as a serviceable item. The model would work based on working alongside the current system of applying herbicides in the initial years, whilst training on the robots improved. Once the robots could reliably replace the chemical options the cost of using chemicals would simply be replaced by the cost of the service. All the developers were adamant that the farmer should never own the equipment to enable them (the developers) to remain in control of how the systems are managed and serviced. I’ve erred on the side of caution throughout these discussions as, until the system is fully implemented, we won’t really know how the change will play out. However, farmers I spoke to shared my concerns on this marketing structure. One of the most-discussed issues was that control was again being lost from the primary producer’s hand and the ability to manage cost was again slipping. As this technology becomes more prominent it seems difficult to imagine that the cost of production would in any way reduce leaving producers again more exposed.

9.0. CONCLUSIONS

1. The future of weeding technology has yet to develop beyond our current understanding. Historic change from intensive manual weed management to the standard chemical format has helped shape and more importantly fed the world over the last 50 years. Today we are on the cusp of a new revolutionary curve that will hopefully deliver a better future for weed management and one with which in general society is more comfortable. Social requirements are undoubtedly changing fast and the industry needs to catch up if not get ahead of the game.
2. The technology promises results, but the overall direction of the technology may yet be set by the willingness or desperation for change from the farmers themselves. As weed resistance develops the investment required from the famer to control weeds will rise. A reoccurring driver for the non-chemical innovation companies has been the banning of the mainstream chemicals alongside the social frenzy around the health questions of such products. It may become apparent that the uptake of the technology is too slow and expensive for the companies leading the way. Therefore, it could be argued that they might recognise their reliance on the banning of such products to make their systems economically feasible. This is not a negative comment but simply a reality. While pesticides are the most available cost-effective method for weed control the chemicals industry will stay the dominant force.
3. Universities seem to be the non-biased innovative hubs of the research world and may be the future of the creative thinking required to move us forward. The funding questions around these institutions needs to be addressed and their future protected
4. Whilst, for the farmer, there remains little or no doubt that the future looks different it isn't necessarily one that should be shied away from.
5. Large companies will continue to develop and invest in the future. It may be that small companies that do the heavy work of research and development may simply move into a position of pursuing a saleable business for the large companies to swallow.
6. From the grower's point of view, there is a danger that we will be manipulated into a direction and future that will continue to evolve faster than we can afford. Robotics may not offer a cheaper alternative but will undoubtedly solve some of the issues associated with herbicide resistance and will help control the yield sapping weed burden. Chemicals will continue to dominate in the short term but with a greater assistance from non-chemical alternatives. Simple options such as hoeing may be the first point of call whilst further research continues to find a more effective alternative, but I believe that alternative weed management be the next progressive

10.0. RECOMMENDATIONS

1. By working with the research facilities to achieve positive results farmers will ultimately hold the key to the future of such technology. However, the lack of cash available will require a ‘prop up’ from the state to develop innovative weed management ideas to the point of commercial viability. We, as an industry, tend to hide away from getting involved with the further development of technology, although this shouldn’t be the case. So often the researchers are desperate to do exactly what their names suggest - research - but need guidance from the farmer. Sometimes their lack of direction leads me to think that a closer relationship would answer a lot of the problems. The added complexity of changing crops, seasons and indeed weeds will undoubtedly force innovation to happen; multiple spheres and a ‘one size fits all’ attitude won’t work.
2. Being open minded and open to change will help problems to be solved, but an industry change of direction must be directed by farmers. Simply allowing the generations of knowledge to be lost to a computer programme with a number-crunching algorithm won’t offer the sixth sense that has fed the world over recent centuries. Embrace change but let it happen as we require and determine.
3. Extend the thoughts beyond that of the excitement of shiny new equipment! All too often the promises made of the capabilities some new equipment do not materialise, and it is often sold more on the capabilities of the salesman than the merits of the machine itself. Whilst this hasn’t discouraged me, it has led me now to better analyse and understand my end goal before I set out to achieve it. Too often I’ve completely underestimated the bigger picture and how change can lead to unintended consequences elsewhere.
4. But above all else, we can’t lead ourselves down a route of thinking that something is impossible just because nobody else is doing it. There seems to be a stalemate position within our own psyche; the limit of possibility should not be based on looking over the fence, or reading the papers, and not making our own informed decision as to what is and isn’t possible.

11.0. AFTER MY STUDY TOUR

Initially, I returned with a concept in mind. I spent time listening to many opinions from researchers through to successfully operating companies, cherry-picking snippets of information that I thought were applicable my subject. I now believe that inter-row weed management is a viable option and I am interested to try and better understand the elements that are required to make it work e.g. what the optimum row width is, what is the balance between optimising solar space versus setting a system up that's too wide and losing yield?. I'm interested to learn how species can interact in a positive way without competing with each other and becoming competitors for yield. I don't believe we can achieve a double cropping in an annual calendar year in the same way as in the USA, but I do believe we can mitigate some of the risks associated with time-critical farming. If I can gain a week or two at either end of the life of a crop we might not only increase yields but also reduce some of our operating costs and at the same time, it might enable us to become more resilient with our farming methods for weed management.

Whilst I'm excited to see what the future holds with robotics I'm also fully aware that to innovate in this area requires huge sums of investment and vast levels of technological advance, most of which will be beyond me and leaves me unable to push this personally but I would be encouraged to see a small fleet of robots working between rows of growing crops in the years to come.

On return from my Nuffield Farming travels the spring work on the farm was waiting for me. Spring seems to have been the longest I can remember with the extreme conditions in March 2018 continuing to cause havoc. I have to acknowledge, however, having spent nine consecutive weeks traveling in what were at times 'extreme conditions', our climate isn't too bad. The 49 °C recorded in Penrith, NSW was nothing short of unbearable.

My travels have helped me become more attentive to detail when making decisions. After writing this report I will be giving several presentations in the coming months including one at the National Advisors' Summit in December 2018 in North America.

William Atkinson

12.0. ACKNOWLEDGEMENT AND THANKS

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13.0. REFERENCES

Figure 3: Illustration of white light shining into a prism before separation into various elements of the visible spectrum. https://images.tutorvista.com/cms/images/38/dispersion-of-white-light.gif

Figure 5: Image showing how leaves absorb and reflect light based on their health. https://zalarieunique.ru/images/crops-clipart-healthy-plant-8.jpg

Figure 6: Spectrum of light from ultraviolet through to near – infrared. https://www.researchgate.net/profile/Miles_Grafton/publication/276062000/figure/fig1/AS:294459788021760@1447216092059/Reflectance-of-healthy-and-stressed-plants-across-the-visible-and-infrared.png

Figure 7: A Satellite image showing field variations through a Normalised Differential Vegetation Index map but showing also the intensity of detail.
https://spacecareers.uk/public/images//uploads/cketest_20180720160736.png

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