Closing the Yield Gap

Measuring plant available water in Australian soils

A report for

By John Stevenson

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Executive Summary

Australian grain production is dynamic and leading edge, supplying large quantities of cereals for milling, feed and oilseed grains and pulses to the international export trade. Australia's climate poses a challenge to the production of these introduced crops, with water being the main yield limiting influence.

Price volatility and the threat of climate instability has focused the attention of the Australian grain producer on the profitability of grain production. Understanding when, where and how soil moisture will be available to a crop has a big influence on crop choice and the nutrition required to optimise yield at harvest without eroding profitability.

With the development of technologies which can economically measure stored soil water in real time, the industry's ability to remain internationally competitive should improve. Matching expensive inputs to available soil moisture should drive both profitability and productivity.

This report provides some insights into the techniques available to map the Plant Available Water Capacity (PAWC) of soils as well as examining some future technological opportunities which may add value to the characterisation of soils. Microwave and electro -magnetic sensing technologies promise to allow remote measurement of soil moisture in real time. Plant-based sensing techniques could aid in the understanding of critical crop stress points and the development of broad scale networking technologies will advance the ability to measure environmental variables in a cost-effective manner.

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Foreword

Water – life depends on it

As dryland grain growers, we have no power to influence the quantity our climate provides. All we can do is make the most of what we receive. My job as manager of a large dryland grain farm in Southern New South Wales in Australia is to sustainably convert as much of the water as I have available into profits based on grain production.

A Nuffield Scholarship has provided me with the resources to investigate different ways of operating a farming business used by other farmers around the globe. Sometimes the lessons were what to do and sometimes what to avoid!

I have met many wonderful people and experienced a vast array of cultures. My travels have taken me through Ireland, the United Kingdom, Singapore, The Philippines, China, Canada, the USA, Israel, Brazil and New Zealand.

To say that the completion of a Nuffield Scholarship is an enriching experience on both a professional and personal scale would be an understatement.

Acknowledgments

Logistically, the awarding of a Nuffield Scholarship presents some big challenges and I have some heartfelt acknowledgements to share.

Firstly, to my wife, Brooke, who bravely encouraged and pushed me out the door with instructions to ‘get out there and do it’. At the time this seemed relatively straightforward but the events of 16th May 2016 added a level of unexpected and unwelcomed pressure – Brooke suffered a TIA (mild stroke). This was two weeks prior to my Nuffield Global Focus China Tour and cancellation for me was the likely and sensible option. Brooke bravely insisted that I had to go and that there was little I could do at home that would change her circumstances. It was a brave decision, a difficult time, and I am truly in debt for her support.

To Ed and Sara our children, I have missed you both dearly in my 16 weeks of absence, but you have both stepped up and been both helpful and supportive to mum and dad – thank you.

To my employer, Warakirri Cropping, thanks you for your support financially, logistically and personally. Squeezing in a 16-week absence in a twelve-month timeslot is a challenge in an industry where holidays are never easily taken but Brad, Keith, Jannie and recently Karl have kept the business functioning normally in my absence.

To my investors the Grains Research and Development Corporation (GRDC), special thanks. Without your decision, to support two Scholars from the Northern GRDC region in 2016, there was a strong possibility that I wouldn’t have been chosen. I hope I can provide a good return on your investment.

Abbreviations

AEGIC – Australian Export Grains Innovation Centre

APSRU – Agricultural Production Systems Research Unit

APSIM – The Agricultural Production Systems Simulator

BOM – Australian Bureau of Meteorology

CLL – crop lower limit

EM – electro magnetic

EPO - external parameter orthogonalisation

GBI - growth based irrigation

GRDC – Grains Research and Development Corporation

Ha – hectare

IRRI – International Rice Research Institute

LoRaWAN – Long Range Wireless Area Network

NIR – near infra-red

PAW – Plant Available Water

PAWC – plant available water capacity

PLSM - partial least mean squares

VRI – variable rate irrigation

WUE – Water Use Efficiency

Objectives

The aim of this research was to investigate novel methods to assess and map PAWC in farming landscapes where variable soils limit productivity, by:

- Promoting the importance of understanding soil characteristics to the Australian grain grower.
- Investigating the challenges grain growers face understanding soils and their ability to act as a soil water reservoir.
- Studying how soils are characterised today and investigating which advances in technology may simplify this process.
- Appreciating what farm managers can do to achieve their yield potential and to maximise profitability.

The goal was to advance profitability, not only in the author's enterprise, but to use the Nuffield platform to promote best practice to the Australian grains industry as a whole.

Chapter 1: Introduction

The Australian grains industry represents an important and often complementary sector of Australia's diverse agricultural economy. In 2015–16 the estimated gross value of production (GVP) for the grains industry was almost $14 billion. (ABARES 2017).

One of the greatest limitations to Australia's broadacre crop productivity is plant available water. In most of the Australian cropping regions evapotranspiration closely matches average rainfall (Figures 1 and 2). The effect of this relationship is that there is very little water lost to stream flow and very little available from local sources for irrigation – the vast majority of the Australian grain crop is therefore produced from available rainfall.

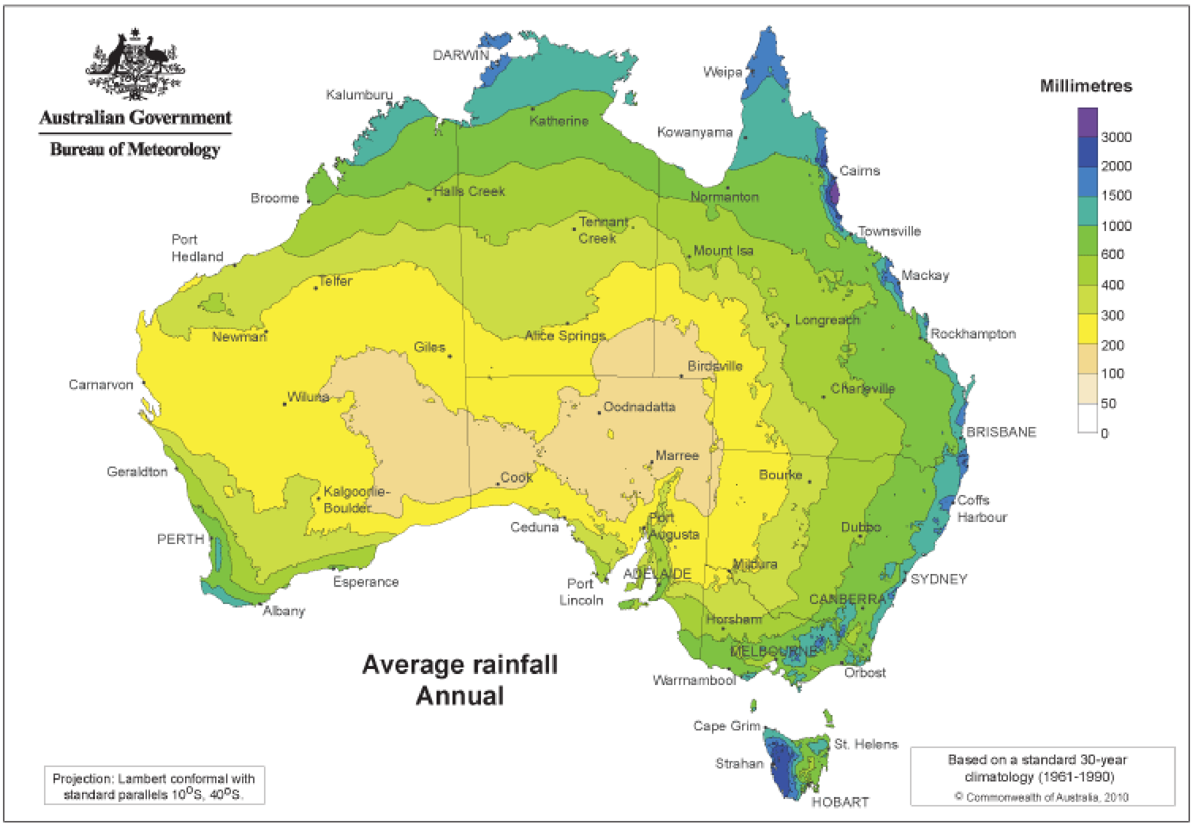

Figure 1: Australian average annual rainfall (Bureau of Meteorology (BOM))

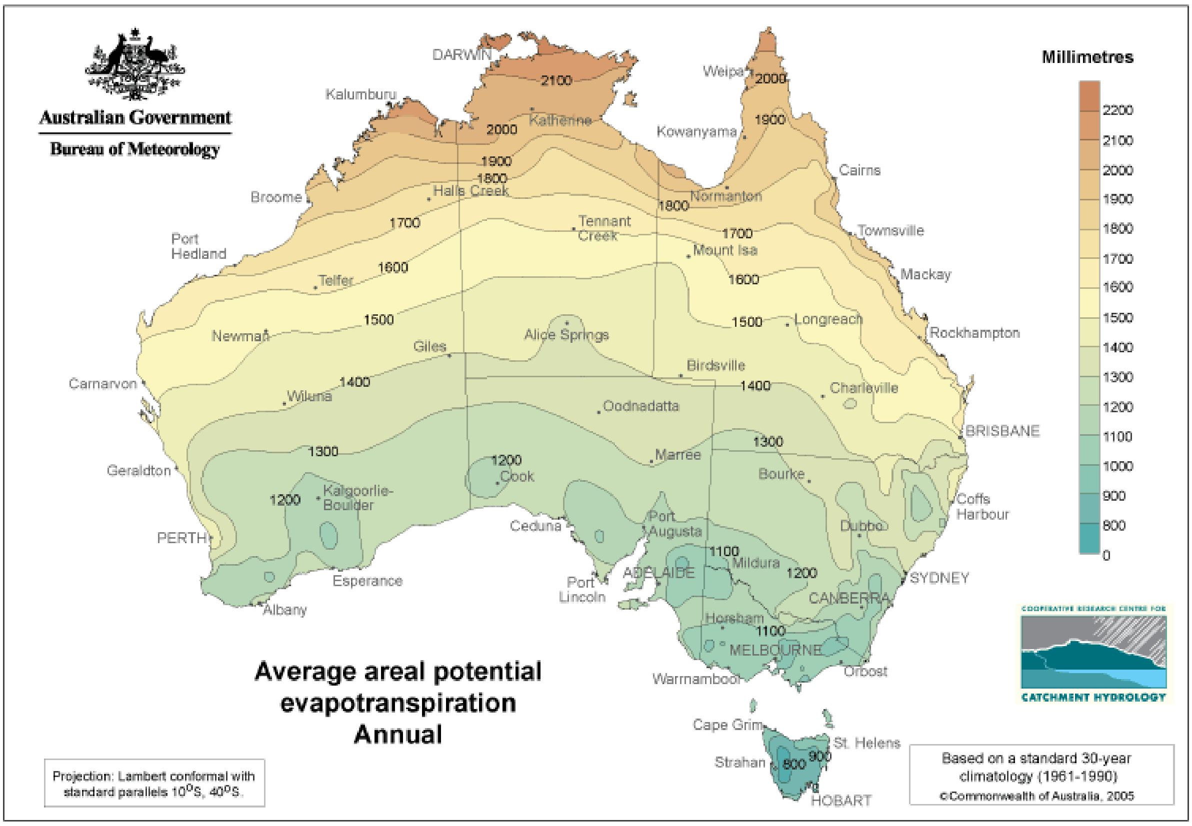

Figure 2: Australian average annual evapotranspiration (BOM)

However, actual rainfall does not always coincide with the needs of crops grown. In southern regions of Australia, it is common for 25–30% of annual rainfall to occur when no crops are growing, through the hot summer period. In northern regions which experience two cropping periods this proportion can grow to be over 50%. The remaining 'in-crop' rainfall often has a distribution which does not match crop needs. For example, during the 2015 season in the traditional winter cropping region of Wagga Wagga, New South Wales, a high proportion of the annual rainfall fell outside the growing season (April to October) and the monthly rainfall was substantially different to the long-term mean (Figure 3).

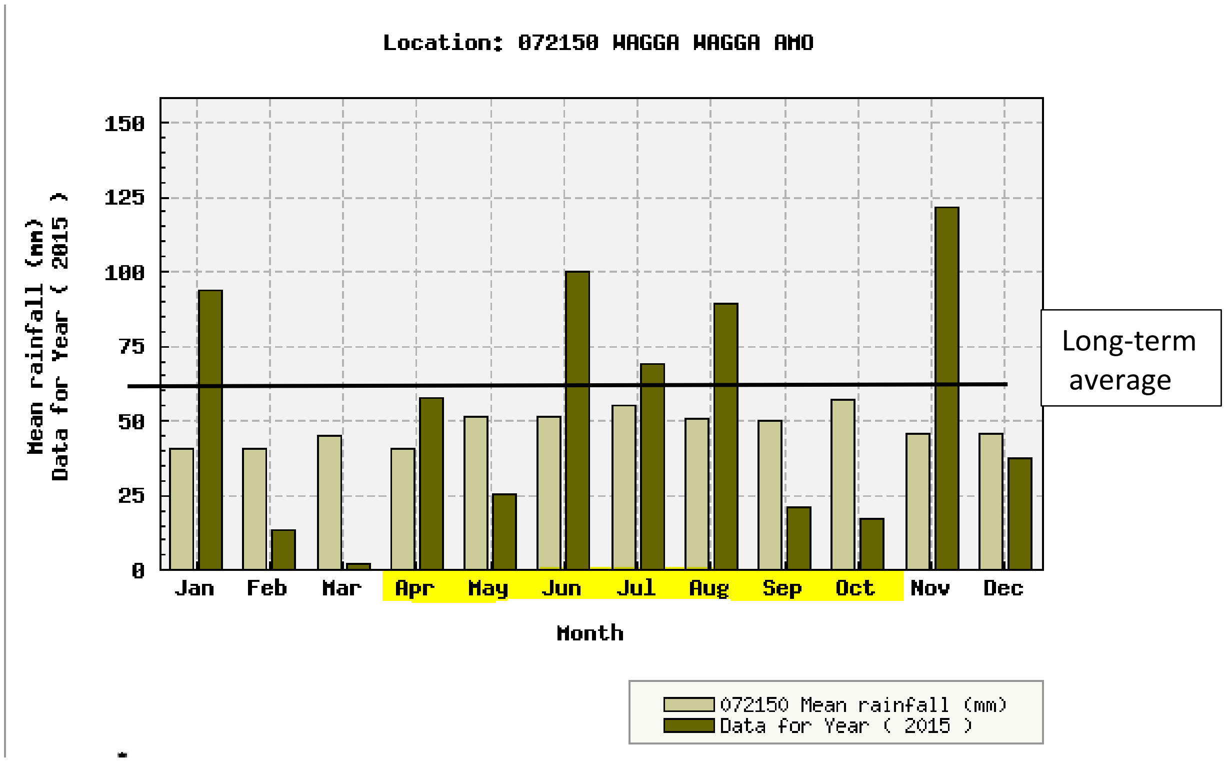

Figure 3: Long term mean and 2015 monthly rainfall at Wagga Wagga NSW (BOM)

To manage this variation between crop needs and rainfall distribution, growers utilise soil as a storage medium to hold moisture for later use.

The concept of the soil being used as a medium to capture and store moisture is well understood and farming techniques have developed over the last four decades which significantly improved the efficiency of soil water storage. Extensive sampling and testing has been completed on over 1,000 GPS-logged sites around Australia to 'characterise' soils to determine their plant available water capacity (PAWC) and this data is freely available via the Agricultural Production Systems SIMulator (APSIM) website: (https://www.apsim.info/Products/APSoil.aspx).

Once PAWC is accurately determined, grain growers have the ability to:

1. Manipulate crop agronomy by optimising nutrient and seed inputs and application timing.
2. Ameliorate soil constraints if present.
3. Optimise production for soil type.

PAWC is a valuable soil measure for a grain producer to understand. There are a number of complexities with its use that determine this value, including:

1. Knowledge of where and how much rain has fallen.
2. Understanding where to sample to measure the variability of subsoil properties.
3. Knowing the ability of different crops to extract stored soil moisture.

PAWC can be measured by growers, although it is a complex and time-consuming affair, typically taking 12 months between the harvest of one crop and the next.

To successfully determine the PAWC the soil must be artificially filled to its drained upper limit (DUL) and then effectively drained to crop lower limit (CLL) with the use of 'rain out' shelters to allow the crop to extract all available soil moisture without additional rain (Figure 4).

Figure 4: Watering to drained upper limit (DUL) (left) and draining to crop lower limit (right) (GRDC 2013)

Even when PAWC is successfully analysed using the conventional techniques, it relates only to the crop type tested and the location of the analysis. The variability at the surface of a paddock, for example Paddock KP01 (Figure 5), is very clear from the air in a satellite image, with distinct regions of red and grey clays visible. The third dimension, below the surface, is harder to analyse as it is hidden from view. Soil depth, soil strength and soil chemistry vary greatly – with gradual change rather than defined boundaries being the norm.

Figure 5: Satellite image clearly showing surface variability in soil colour of paddock KP01, a 620-ha field at Yarrabah, Bidgeemia (Google Earth Pro, 2017)

The aim of this research was to investigate novel methods to assess and map PAWC in farming landscapes where variable soils limit productivity.

Chapter 2: Measuring Landscape Variability

A number of different approaches were observed during the overseas study period; some were extensively used for soil characterisation and some were in the development stage.

Electro-Magnetic induction surveying is widely used and was the base level for farm landscape management on farms visited in Scotland and New Zealand. In the arid production regions in Israel, plant stress monitoring was a well-developed system which had allowed producers to refine irrigation application to match production zones, optimizing the use of the expensive and scarce water resource. In the United States there was a prototype system, now commercialized by Veris technologies, which allowed the use of spectrographic analysis to assess soil below the surface. A Canadian engineer has adapted the use of active microwave remote sensing to allow the mapping at depth of soil moisture in real time, and this is currently being used on centre pivot irrigators.

Electro-magnetic induction survey

Electromagnetic induction (EM) survey measures the electrical conductivity of the soil (ECa). ECa is affected by the soil's salt content and type, clay content, mineralogy, depth to bedrock, soil moisture, organic matter and temperature (State of New South Wales Office of Environment and Heritage 2013).

An EM survey instrument has two coils, one transmits a current, the second is a receiver. The separation of the coils and the frequency of the current determine the depth to which the instrument operates. In agriculture the EM38 is commonly used, allowing measurements down to 1.5m in the vertical mode or 0.7 metres in the horizontal mode. This range is ideal as most productive agricultural crops and pastures in Australia would not have root activity beyond this range

Maps of EM surveys illustrate the changing soil characteristics at depth, as shown for Paddock KP01 (Figure 6). There are similarities between the visual satellite image (Figure 5) and the EM survey (Figure 6), however the magnitude of the changes across the landscape can be quantified using EM survey. In this instance the red areas of the map represent areas of high electrical conductivity and green areas lower conductivity.

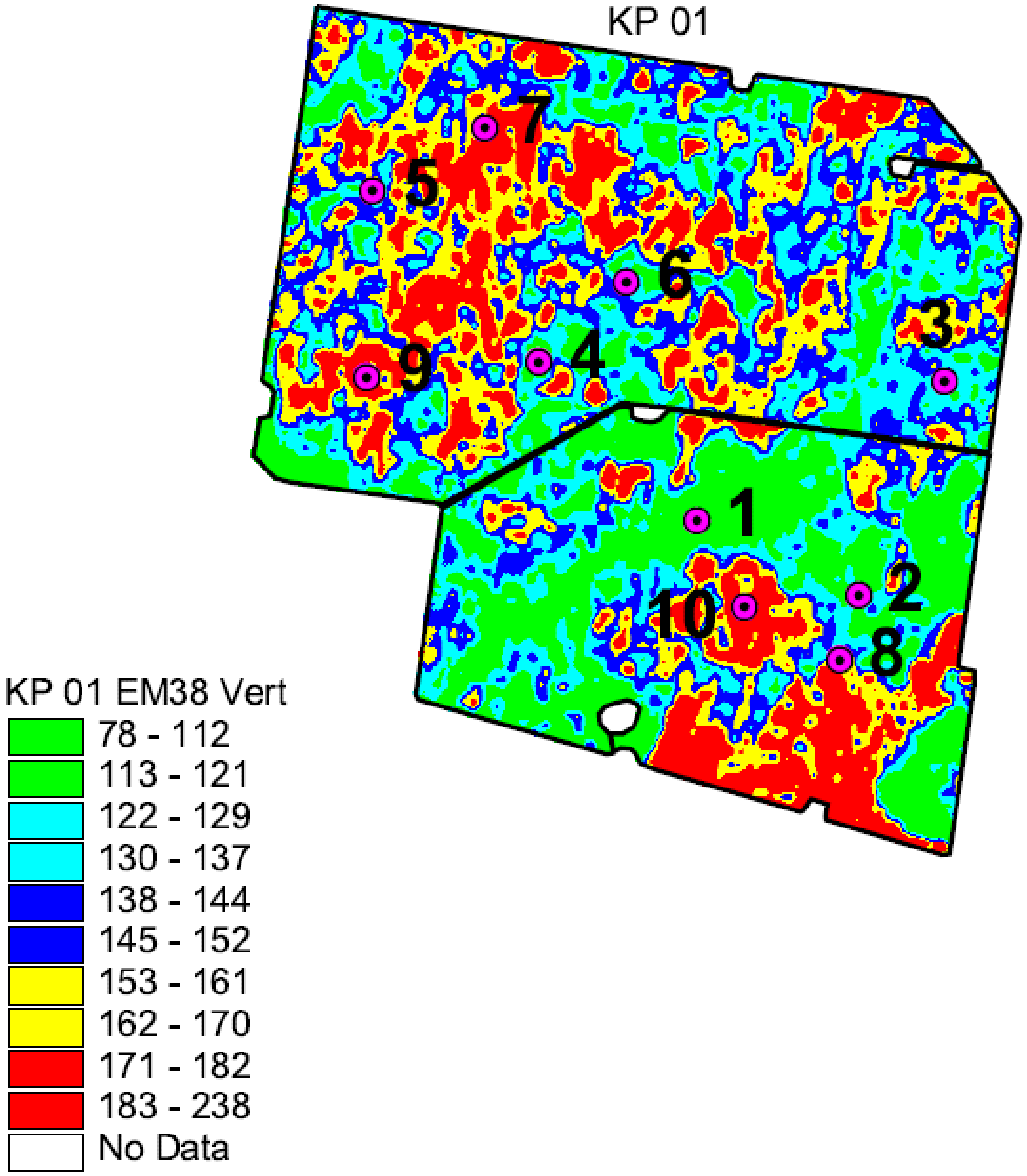

Figure 6: EM38 (vertical) survey map of Paddock KP01, showing the variability in soil characteristics at depth.

Once an EM survey has been completed, the user is able to define areas for sampling which will in turn qualify the cause of the variability. In the case of the field in Figures 5 and 6 these changes were mostly due to differences in clay content and chloride levels. Good, uniform soil moisture at the time of sampling ensures reliable results. Dry soils can produce unreliable results, particularly if there are any cracking clay soils.

How do some of the world's most productive arable farmers utilise EM38 technology? The Nuffield experience allows scholars great opportunity to find out. Whilst many of the world's leading agricultural systems have seemingly unlimited moisture there are other challenges and EM38 technology is being used successfully to address these.

Case Study 1: McGregor Farms

McGregor Farms, Coldstream Mains, Scottish Borders – July 2016

Generous hosts Colin McGregor (owner) and David Fuller (Arable Technical Manager) showcased leading edge UK arable farming with their innovative business model and pristine facilities.

Figure 7: Seeding canola in a vining pea field harvested the previous night (Source: Author)

Colin and David have mapped the properties using EM Survey. Using the survey, they have 'ground-truthed' the soils to develop a comprehensive soil texture map.

The pair operates 3,500 hectares within a 30km radius of Coldstream Mains, 24km inland from the coastal town of Berwick-upon-Tweed. 304 hectares is owned, with the balance being farmed on a contract basis for 14 other landowners. Astonishingly, and in dramatic contrast to Australian grain farms, there were in excess of 500 fields under management. Economies of scale are leveraged to the benefit of the businesses by purchasing bulk inputs, selling bulk outputs and spreading overheads and variable costs over the combined operations.

Figure 8 shows the result of their survey work. Electrical conductivity and topography are closely linked in their environment, with the light calcareous soils at higher elevation and heavier soils at lower elevation.

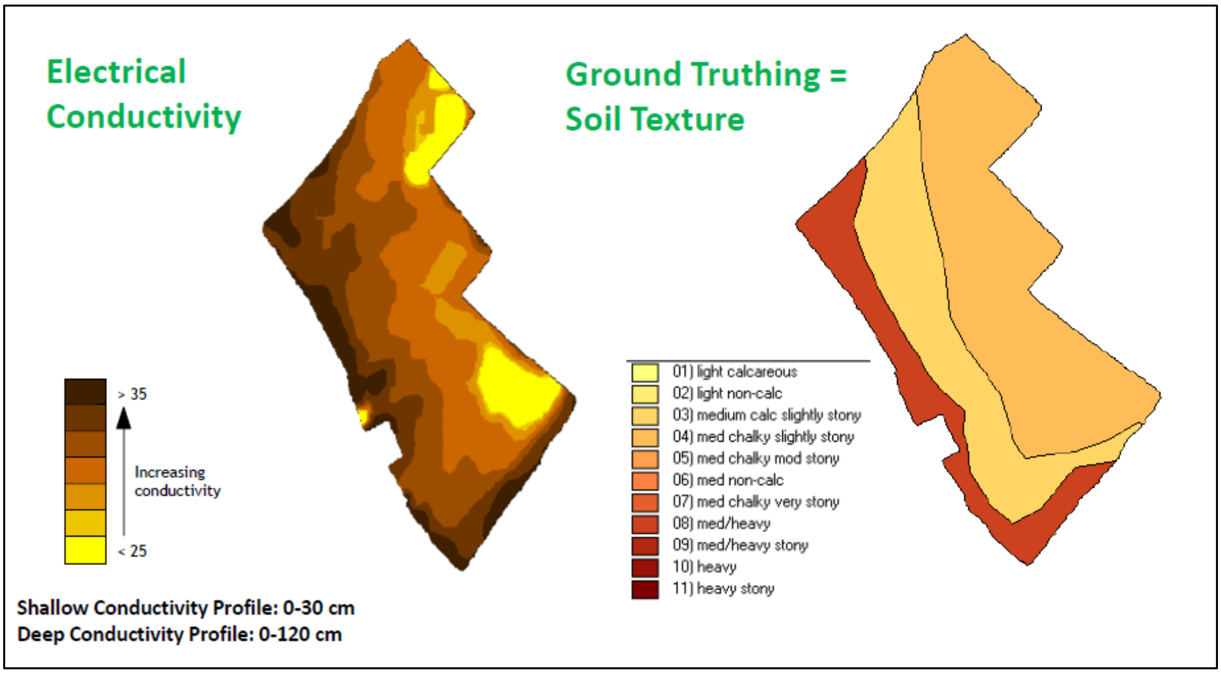

Figure 8: Example of EM based soil texture map (MacGregor Farms Presentation, 2016)

These maps are then used to vary inputs based on the productive capacity of each soil type. Of note was the use of variable seeding rates, where a different seeding rate was used for each soil zone, targeting uniform plant populations. The seed-rate changes were based on the ease of establishment; those soils where crops germinated well were planted at a reduced rate and soils which were problematic for establishment received a higher seed rate (Figure 9).

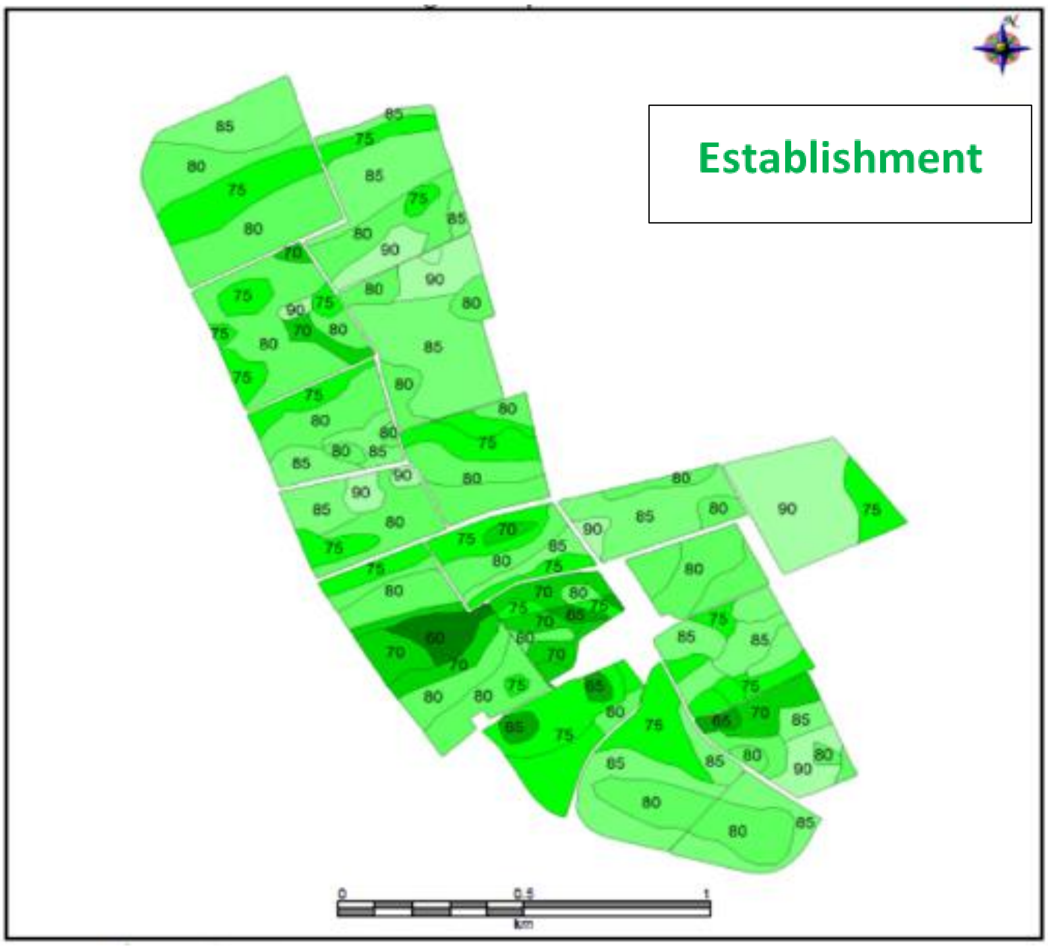

Figure 9: Variable seeding rate map showing the target rates (kg/ha) depending on soil type. (McGregor Farms Presentation 2016)

Of interest was whether plant available water was a factor in McGregor farms decision process. With annual rainfall of 700mm and cereal yields up to 12 t/ha it seemed logical that at times moisture would be a limiting factor. However, the most limiting environmental factor in the region is solar radiation (sunlight): evaporation is not even officially measured. Rainfall distribution is relatively consistent from month to month and soils are rarely dry. Of greater concern to the farm team was excessive moisture and while drainage was an important remediating measure for waterlogging, the main goal of the farm was to have plants growing in the soil for as much of the year as possible. The outcome of this constant living crop presence is that the water-use efficiency for the soils is optimised as is farm profitability.

Case Study 2: Greenvale Pastures, Agri Optics, Three Springs Dairies

Greenvale Pastures, Methven, South Island, New Zealand, March 2017

The Canterbury Plain in New Zealand is the home of the current world record wheat crop yielding 16.79t/Ha. Land values are in the vicinity of $AU50,000/ha, which has driven the adoption of intensive dairy and specialty crop production. With this land-use change there has been an increased environmental impact from the localised concentration of nutrients. EM38 technology has been adopted to assist farmers to optimise inputs which in turn has reduced the environmental impact of agriculture and increased profitability.

2008 Nuffield Scholar, and 2016 New Zealand Precision Farmer of the Year, Craige Mackenzie, farms with wife Roz on the Canterbury Plains around Methven. Their Greenvale Pastures property is a 200-hectare intensive irrigated arable property producing a range of specialist seed and cereal crops. The area is home to some of the most fertile soils in New Zealand with land values to match; recent land sales in the area have seen prices ranging from $NZ58,000-62,000 per hectare. Understanding the productive capacity of these soils is essential to allow local producers to optimize water and nutrient inputs.

Figure 10: Craige in a crop of Chicory for seed with a lateral irrigator and the scenic foothills of the Alps in the background (Source: Author)

Craige is also CEO and Director of Agri Optics New Zealand Ltd. Agri Optics specialises in the collection, use and analysis of precision agricultural data to aid New Zealand producers with their management decisions.

A key dataset for many of Craige's clients is EM data. Agri Optics collects the data with a trailed sensor, whilst at the same time logging elevation to 2cm accuracy. Five readings are collected per second, usually on a 12-metre swath, creating not only a soil texture map but also a 3D topography map.

Figure 11 Agri Optics EM Survey collection equipment (Source: Author)

Water is abundant on the Canterbury Plains, either as rainfall through winter or irrigation through summer. In Australian terms, water is very cheap and often pressurised through gravity alone, as water drains from the Alps to the Pacific Ocean. Local farmers have adapted soil texture maps for the variable application of nutrients and water. This is achieved with the use of Variable Rate Irrigation (VRI).

VRI allows irrigators to maintain optimal levels of Plant Available Water in the soil profile. Under regular irrigation (without the ability to use VRI) watering schedules are generally based on the needs of the areas of the field with the lowest PAWC (Figure 12). The effect of this is that other soil types have too much water applied, which wastes water and can lead to loss of nutrients through deep drainage and even yield decline due to waterlogging. A study by Professor Ian Yule, at Massey University Centre for Precision Agriculture, found water savings of 20-25% on a 22ha trial site over three years of VRI compared to regular scheduling.

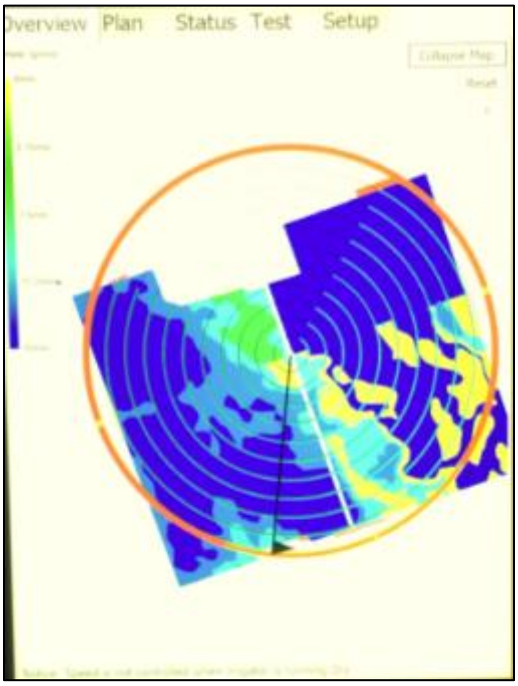

Figure 12: Variable Rate Irrigation control panel at Greenvale Farms

Craige and Roz use VRI to great effect on their arable farm with pivot and lateral irrigators addressing issues associated with undulating terrain and variable soil types. They also use VRI on the Three Springs Dairy farm they own in partnership to water pastures for grazing. In a research study with Massey University the overall benefit of the VRI system was found to be $89NZ/ha per year from the accumulated benefits of reduced water consumption, drainage costs, nitrogen loss and energy consumption.

The Mackenzie farms are a model for successful integration of technology into agricultural practice, with wireless connectivity to sensors and controllers allowing remote monitoring and control of many critical systems.

The Mackenzie's confirm the effectiveness of EM survey as a technique to assess PAWC across variable soils; however, their operation also highlighted the need to be able to measure the incoming water, as is possible through overhead irrigation. This technology has allowed growers to smooth out the variation in productivity across their farms. In the dryland environment of Australia's major grain production regions, the ability to measure rainfall and water infiltration is still some way from reality.

Chapter 3: Plant-Derived Soil Variability Mapping

As discussed in the previous examples, EM surveys allow samplers to deduce the variability of a soil by measuring its electrical conductivity and making assumptions based on these measurements. This enables growers and consultants to make assumptions on soil quality by monitoring and measuring plant performance in soils, either historically by measuring productive output (yield mapping), or actively during plant growth (plant monitoring).

Yield mapping

Yield mapping is not new to agriculture but provides an important historical data set, which allows producers to assess the productive capacity of their arable land at the time of harvest. Yield maps are created by measuring crop output and linking the yield output to geo-referenced spatial data at a pre-determined frequency. Once the data has been processed and erroneous data points removed the user is able to graphically layer the information over a base map layer (Figure 13). Over a number of seasons and crop types, trends can be identified across the landscape. As the number of datasets increases, the reliability and accuracy of the trends observed improves and correlations between soil characteristics and yield across the landscape can be strengthened.

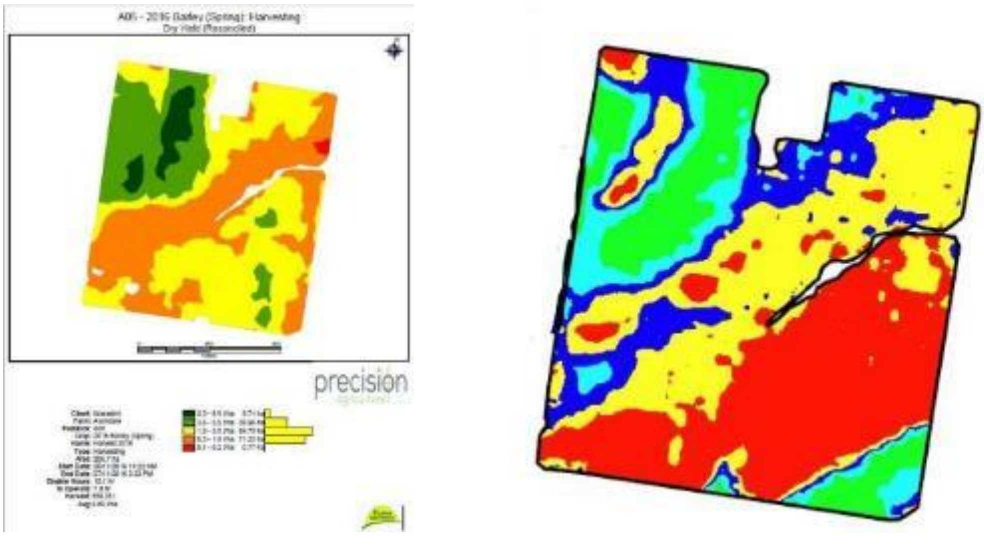

Figure 13: Example yield map (left) from 2016 harvest compared to the EM38 survey map (right)

As can be seen in Figure 13, there are correlations between yield maps and EM surveys. The yield map shown relates to 2016 with an extremely high (decile 10) growing season rainfall. In this case soil saturation has significantly reduced crop yield on low lying areas. An extreme season like this provides a useful dataset for calibration.

While it is a relatively common practice amongst Australian grain growers, yield mapping by growers visited overseas was the exception rather than the rule. A major limitation to the adoption of yield mapping in many areas was the use of older harvesting equipment without the ability to yield map. A shortage of service providers to process data was also highlighted, particularly in Brazil.

Plant monitoring

Aside from yield monitoring there are various methods of monitoring plant growth throughout the growing season. Irrigated agriculture has been a strong driver of this technology, as the supply of irrigation water has decreased and water prices increased. If a dryland field is monitored for a number of growing seasons, the influence of moisture and nutrient deficits can be reduced and plant growth patterns can be correlated with soil variability. A visit to Israel demonstrated the value of this technique.

Research visits – Israel

Israel is a fascinating destination for a Nuffield Scholar on several fronts. Israeli agriculture is simultaneously historic, productive and innovative. Israel is chronically short of fresh water, and necessity has driven innovation for agricultural water use efficiency. From 1975 to 2013 the average requirement for water by irrigated agriculture has fallen from 8.7 megalitres/hectare to 5.5 megalitres/hectare through the widespread adoption of drip or micro sprinkler irrigation, departing from the previous flood irrigation practices (Israel Ministry of Foreign Affairs, 2013). Over the same period the output of Israel's agricultural sector has increased an incredible twelve-fold from the same volume of water.

At the leading edge of irrigated water-use efficiency are two Israeli Agricultural technology companies Phytec and SupPlant. Phytec headquarters are located in the Afek Industrial Park on the outskirts of Tel Aviv. I was introduced to the Phytec team by company agronomist Omer Sagee. Phytec has developed direct plant sensing technology to identify periods of stress in real time, which can be used to objectively control irrigation scheduling. The Phytec hardware measures the daily cycle of expansion and contraction exhibited by a plant stem as it accumulates and expels moisture through the heat of the day, as transpiration takes place and plants lose water to the atmosphere. Overnight the plant moisture is replenished. The Phytec team have developed highly sensitive electronic potentiometers which measure plant stem diameter in microns (1/1000th of a millimetre).

As plants grow, the size of the stem increases from day to day, although there are still shrink/swell periods within each day. Researchers have identified normal growth patterns without water stress and have been able to identify points in the shrink/swell cycle which indicate a period of moisture stress is imminent. Using computer algorithms and machine learning, irrigators are able to water crops prior to a period of moisture stress. The result is that, on average, an irrigator can reduce water consumption by 20% compared to traditional intuitive irrigation scheduling. Yields of 15% above average are common using the system because the plants do not endure any yield-reducing moisture stress.

The author met with the team in Tel Aviv and showed in real time cotton and corn crops in northern Texas. Using simple traffic-light graphics, (red, yellow and green) it was possible to see the stress levels of each part of several centre pivot irrigators.

Supplant is a brand of the Agro Web Lab (AWL) Group. AWL was formed in 2012 as an R&D project to engage in agricultural monitoring, data analysis and crop management, using a Software as a Service (SaaS) model. The group develops software for farmers and agricultural companies to enhance their decision making and improve productivity. AWL headquarters is located in the Northern region of Israel in the town of Afula in the fertile Jezreel Valley and was visited on 6th February 2017. AWL Vice President of Business development, Oded Rahav and Chief Marketing Officer Ori Ben Ner were gracious hosts. Supplant is primarily designed to aid irrigation and the software package is described as Growth Based Irrigation (GBI). In a similar fashion the Phytec the Supplant monitoring measures stem diameter; however, many other plant metrics are measured and analysed by the system:

- Water movement through the root zone is tracked using soil moisture capacitance probes.
- Environmental variables are measured using weather stations.
- Leaf temperature is measured and compared to ambient temperature. When leaf temperature exceeds ambient by more than 2°C, the plant is becoming moisture stressed.
- Fruit size and growth can be measured in a similar fashion to stem diameter.

The various plant and soil metrics are then analysed using proprietary algorithms to schedule irrigation.

Both Phytec and Supplant were great examples of the power of data and the internet in modern agriculture. Both businesses were investing heavily in streamlined, wireless data flow to cloud-based storage, where decision-making algorithms could be applied to control water supply. The continuous feedback loops provided by the system allowed a level of machine-learning, based on whether the correct watering amount or interval was used on previous applications. Both companies commented that the watering interval using automated systems was much more frequent and of lesser volume than if it were controlled by humans, who were likely to allow crops to become visually stressed prior to irrigation. The systems were readily adaptable to all irrigated crops in Australia and are currently installed on some cotton and nut producing enterprises. Their usefulness in a dryland situation is limited, as growers have no control over water supply. There is certainly a use for the technology to assist with PAWC assessments as the sensors could be deployed across previously identified soil boundaries to aid growers in assessing crop lower PAWC limits.

Chapter 4: Future Concepts for Measuring Soil Variability

While technologies such as EM38 and yield mapping enable the identification of field zones where there are contrasting soils, the search continues for technologies which can automate the characterisation process. A heavy clay soil field with a redundant sandy stream bed running through it will have hugely contrasting PAWC measurements. The ability to quantify these extremes in situ should lower analysis costs could improve profitability of soils at both ends of the productive spectrum.

Vis-NIR spectrometry

The science of spectrometry is not new and dates back to 1886, when Eugene Goldstein observed Canal Rays (later named cathode rays). In layman's terms, spectrometry measures the comparative reflection or absorption of light spectra from a material depending on its composition. Spectrometry uses nanometres (nm) as its unit of measure; there are one billion nanometres in a metre. Visible light is in the 400-800nm range. For example, absorption of light near the 2200nm wavelength in a soil sample is related to clay particles (Rossel et al 2016).

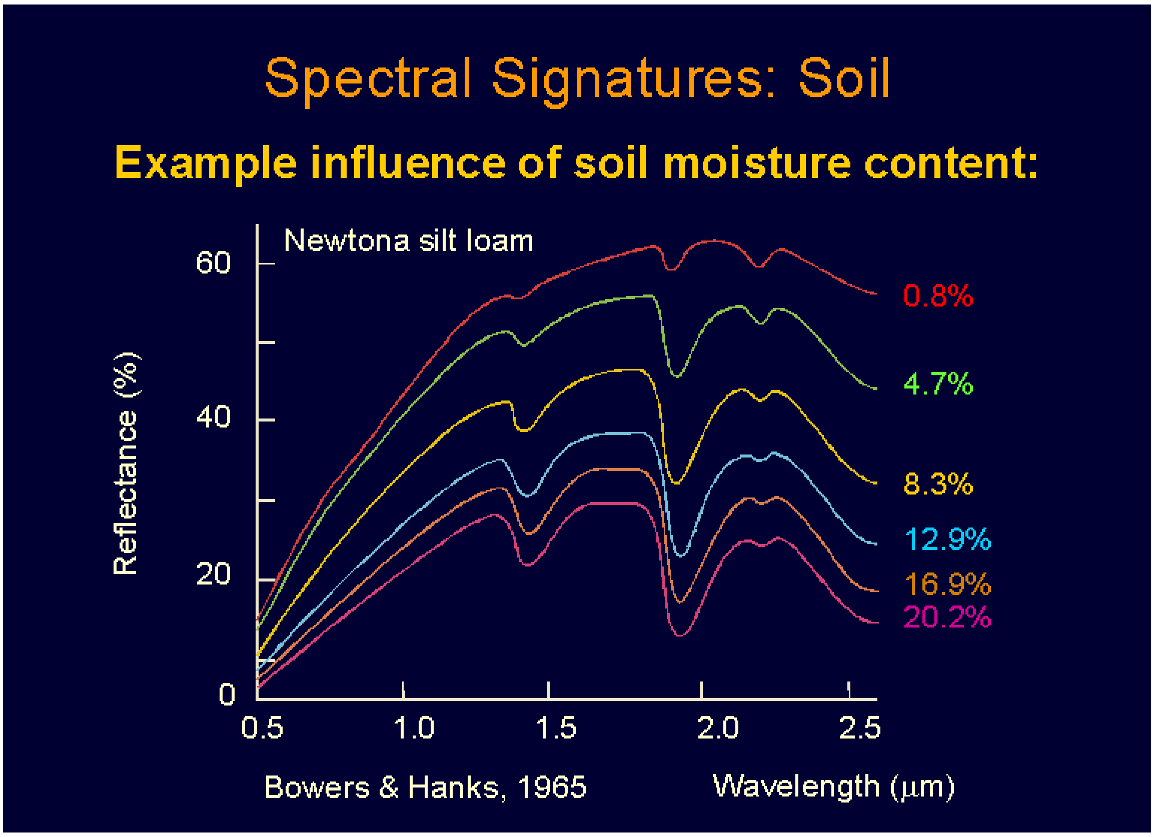

Figure 14: An example of soil spectral signatures showing the influence of variable moisture; note the scale is in microns where 1 micron = 1000 nanometres (Bowers and Hanks, 1965)

Materials give unique signatures when subject to spectrometry; soils, in particular, can be compared and characterised qualitatively and quantitatively based on these results.

Soil spectral signatures are influenced by:

- Mineral composition
- Iron oxides
- Organic matter
- Water
- Carbonates
- Soluble salts
- Particle size distribution

> *"These are the key determinants of soil functional properties: nutrient supply and retention; carbon sequestration; hydraulic properties; erodibility; tillage and engineering properties."* (FAO, 2012)

Measuring materials using spectrometry is relatively straightforward, although the apparatus can be very expensive. It is possible to use spectrometry from satellites, by air, in laboratory or using static or mobile capabilities in-field (Viscarra Rossel et al., 2016). Since February 2009 there has been a concerted international effort to catalogue Vis-NIR data from air-dried soil samples from around the world in the GlobalSoilMap.net project. As of April 2016, there were approximately 24,000 soil spectra catalogued in the database contributed by 45 soil scientists and 35 research institutions around the world (Viscarra Rossel et al., 2016).

Research visit – Department of Soil and Crop Sciences – Texas A&M University

The Department of Soil and Crop Sciences at Texas A&M University is one of the largest such departments in the US and is pre-eminant throughout the world. The author was fortunate to meet with Cristine L. S. Morgan, Professor of Soil Science and Hydropedology at the Universities' College Station Herman F Heep building.

Figure 15: Professor Morgan discussing her work characterising soils throughout Texas (Source: Author)

Prof. Morgan has 48 published scientific papers and is involved in an overwhelming number of soil research projects around the globe. Her work and enthusiasm to promote the importance of soils is astonishing and inspiring.

Professor Morgan has worked in collaboration with the University of Sydney and the University of Nebraska-Lincoln on a research project to calibrate in situ Near VIS NIR soil testing with spectra from air dried and ground soil samples. This is exciting work as it could essentially allow growers to 'see' the soil in three dimensions. A complication with this technique is the influence soil moisture has on the measured soil spectra.

Professor Morgan and her team hypothesised that a complex numerical analysis known as External Parameter Orthogonalisation (EPO) could be used to develop a Partial Least Mean Squares (PLSM) regression model which would align the clay and organic carbon content of moist intact soil with laboratory prepared dry, ground soil Visible-Near-Infra-Red (Vis-NIR) samples. (Ge et al, 2014)

Figure 16: Penetrometer with integrated Vis-NIR Sensor (Source: Author)

The team developed a hydraulic penetrometer (Figure 16) with a hardened clear silicon glass 'window' in the tip to allow transmission and reception of Vis-NIR beams as the unit moves through the soil profile. Data was collected every 20mm through the soil root zone.

The team removed the influence of soil water from the results through numerical and statistical manipulation. They did however find that the reliability of the results decreased as the soil moisture reduced (Ge et al, 2014). Clay was the most reliable element to measure in situ (R2 = 0.77), for predicting plant growth, compared to a ground-dried lab sample under field moist conditions (Ge et al, 2014). The clay content of a soil is highly correlated to soil texture as well as the ability to store moisture. The probe also has the ability to measure electrical conductivity which also correlates strongly with clay content.

The question then arises how useful this technology could be to the Australian grains industry. If the penetrometer mounted probe and the numerical and statistical analysis of the data can be developed to the point where results are commercially acceptable it will enable soils to be characterised and profiled with a level of ease currently unavailable.

As science develops, and the cost of technology decreases, growers may in time be able to utilise spectral imaging to measure a host of additional soil metrics. Soil nutrition, moisture, salinity and pH are all important soil constraints.

Passive Microwave Radiometry

Passive Microwave Radiometers can be used to measure soil moisture. NASA has satellites in orbit with sensors to assess soil moisture that are based on this principle. Essentially all matter has a microwave signature, with water having a much stronger signature than dry soil. The radiometer can measure the microwaves reflected from soil to distinguish differences in the moisture content.

Skaha Sensing is an agricultural technology start up based in Naramata, British Columbia, Canada. The company specialises in mapping soil moisture of crop fields and vineyards and are actively developing unique sensing solutions for agriculture, civil engineering and oil-and-gas industry.

Founder and principle, Maik Wolleben, was contacted to determine the applicability of passive microwave radiometry to the goals of this report topic. Maik reported that the technology has been deployed to actively monitor and manage irrigation on centre pivot systems. The company has also equipped aerial drones with small sensing units, however they are limited in their power output due to weight constraints.

As an early adopter a grower can fit five sensors to a centre pivot irrigator for $5,000CAD with a $2,000CAD buyout after two years. On a 125-hectare centre pivot the system would need to save $28 per hectare per year to break even on the investment in a two-year period. There would also need to be investment to enable variable rate application.

Limitations of this technology include interference from heavy vegetation and the variability of depth penetration depending on soil moisture content. For example, the centre pivot mounted sensor can penetrate dry soil to a depth of one meter but only half a meter when the soil is moist. Vegetation can interfere with the microwave signature due to the high moisture content of vigorously growing plants.

While these new remote measurement technologies show promise, there are other physical environmental measurements which are presently able to provide greater accuracy and hence more certainty to growers when making management decisions.

Chapter 5: What else do we need to know?

In a rain-fed grains cropping environment knowledge of PAWC is a powerful metric, but only in combination with other parts of the production 'puzzle'. The variability of rainfall distribution and intensity, position of moisture within the soil horizon and evaporative loss rates are important pieces of information which can assist growers with management decisions that will optimise yield potential.

How best to use PAWC knowledge?

Plant Available Water (PAW) is the most common yield limiting variable in the Australian dryland agricultural landscape. Production modelling based on PAW to determine crop Water Use Efficiency (WUE) has evolved from those proposed by French and Schulz (1984), where rainfall, fallow efficiency and evaporation assumptions could all be combined to give a theoretical yield target. The French & Schulz model was rudimentary, although highly effective in the way it focussed the grains industry on the profitability of stored soil water conservation. French and Schulz modelling is not able to account for the variability in the size of rainfall events, nor the variability in loss from the system due to deep drainage, evaporation or runoff.

In 1990, the Agricultural Production Systems Research Unit (APSRU) was formed as a collaboration between The University of Queensland, Queensland State Government and CSIRO. APSRU developed the Agricultural Production Systems Simulator (APSIM). APSIM is now used in over 110 countries and allows agriculturalists to model the effect of soils, climate and plant biology on plant growth with the benefit of powerful computer processing. Unlike the French and Schulz model, APSIM has the ability to receive live data on climate, nutrition and available water. The model utilises available data to date and simulates the whole range of likely seasonal outcomes until the end of the crop production cycle.

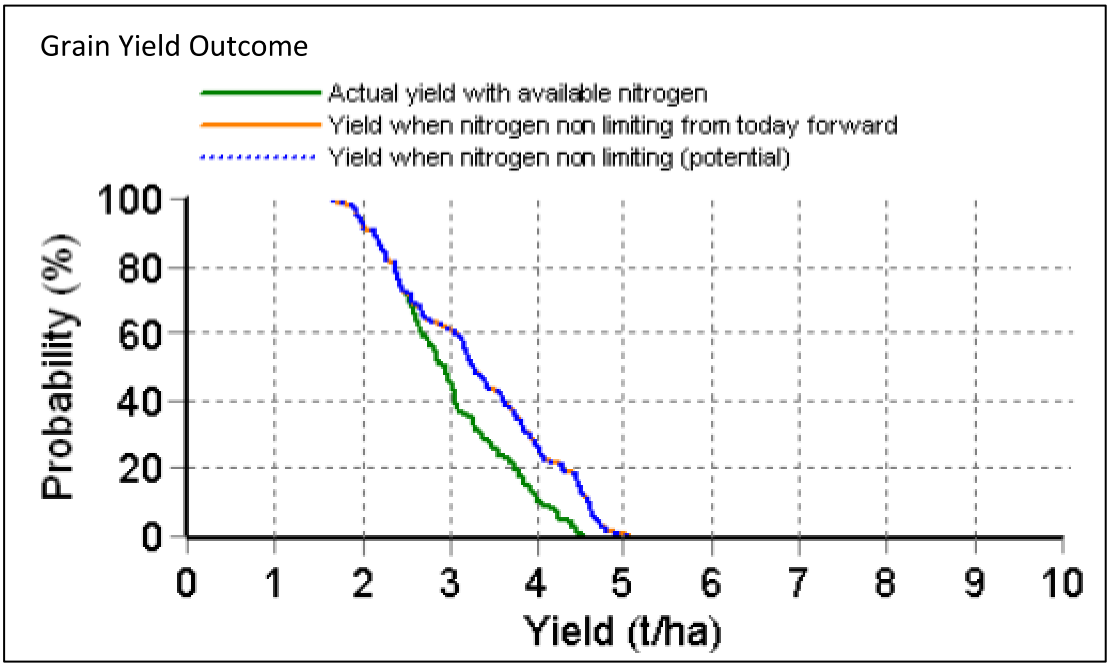

Figure 17: September 2015 APSIM model prediction of wheat yield via the Yield Prophet Platform.

Figure 17 shows the probability of exceeding a range of yield outcomes at a point within the growing season. It takes into account the pre-season soil moisture; the weather conditions so far; soil N and agronomic inputs. The long-term record from the nominated weather station is then used to simulate what would have happened from this date on in each year of the climate record, the yield results are used to produce this graph.

This yield probability curve shows a range of outcomes (particularly related to nitrogen nutrition). This allows growers to adapt nitrogen management to yield, based on current soil water and nitrogen reserves.

The model is also able to estimate the position and quantity of PAW in the soil

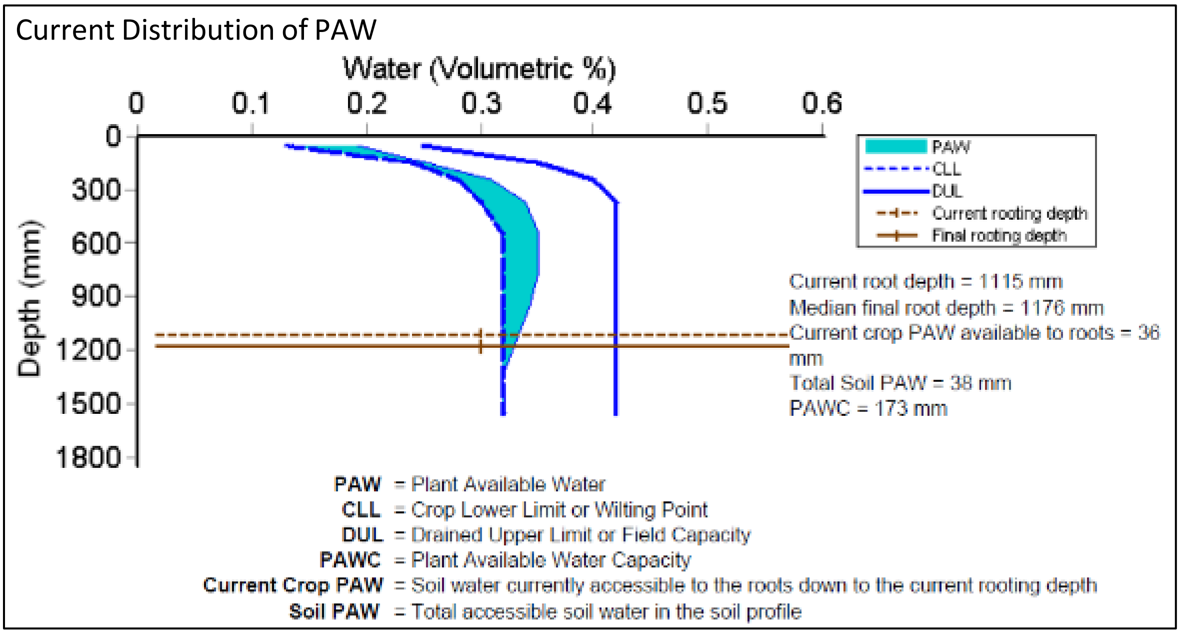

Figure 18: PAW distribution graph produced by APSIM, September 2015.

Whilst the APSIM data is a wonderful management tool for the Australian grain grower, it is limited by the accuracy of the data provided to the platform. In a situation where soils are as variable as Figure 18 there would potentially be five zones, all requiring a different set of parameters to be entered into the model for it to provide useful information to the farm management. APSIM also accumulates inaccuracies over time as it relies on probabilities of future climatic events based on the occurrence of these events in the past. The user can correct these inaccuracies as the crop progresses by adding the actual climate data to the model.

Rainfall data

The movement of precipitation events across the landscape is highly variable. Wind direction and strength, barometric influences and atmospheric moisture load can determine whether rain is widespread or isolated. Generally speaking, Australian growers will base rainfall assumptions on the measurements recorded in a single manual rain gauge on each farm. On large Australian grain farms with the ability to manage variability down to the nearest metre, measurement of rainfall needs to be increased to a higher resolution. Collecting data from manual rain gauges is time and labour intensive and technology has a place in easing this load and simplifying the process of rainfall data collection. Low Power Wide Area Networks (LPWAN) systems are rapidly developing to network devices inexpensively over long distances. With battery endurance of up to ten years, LPWAN-enabled rain gauges have the potential to link multiple devices to a central server automatically at a relatively low cost. Fully commercialised ‘tipping bucket’ rain gauges on a LPWAN network will cost about $300 per unit, with no data transmission charges.

Soil moisture probes

Once a grower is aware of the water collected through rainfall it becomes important to understand the relative accessibility of this moisture to the growing crop. Soil moisture probes can alert a grower to the change over time and depth of moisture in the soil profile. They can also aid with the identification of crop rooting depth, which in turn can help identify potentially growth-inhibiting chemical and physical soil constraints.

Soil moisture is drawn down into the soil profile under the influence of gravity and will essentially 'fill' the soil water bucket from the bottom up. Under the influence of high summer temperatures, water will be drawn back up by capillary action and will evaporate from the surface. This can result in a dry layer of soil between deep soil moisture and surface moisture derived from autumn rain. Plant roots are unable to pass through this dry area and the effect is a reduction in PAWC.

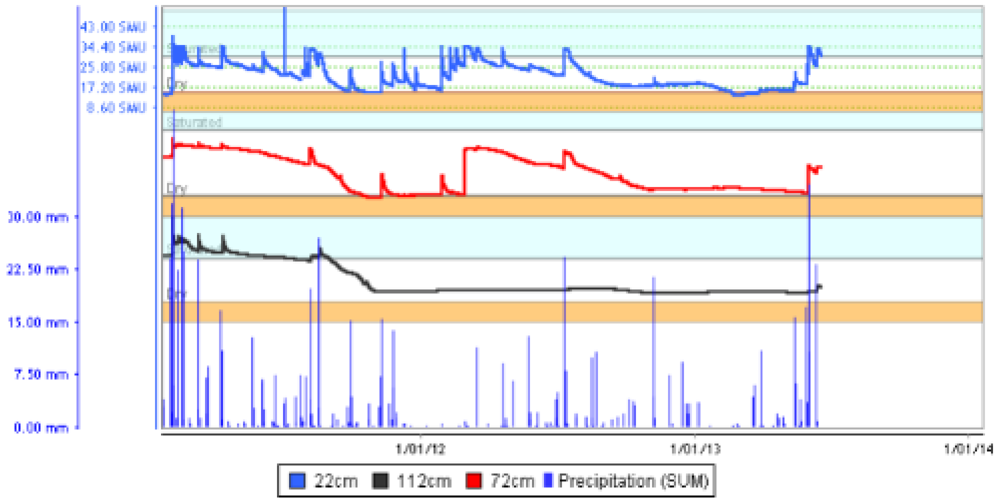

Figure 19: Example data of soil moisture capacitance probe data output (Farmlink Research 2013)

Chapter 3: Case Study – Brazil

Identifying soil variability and its interaction with crop production potential was found to be important in the highly developed systems visited in the United Kingdom, New Zealand and Israel. In further investigations, the author visited the pioneering cropping regions of Brazil to understand the importance of soil characterisation in a region only recently cleared for arable agriculture. As the second generation of farmers emerge and the demand for good land increases, PAWC will be an important link to land value and the ability of farmers to achieve adequate returns on investment.

Two weeks were spent in Brazil, one in Matto Grosso State around the city of Sorriso and the second in Paraná State around the city of Campo Mourão.

Brazil is truly an agricultural producer of global significance. It has an arable area almost double that of Australia (World Bank, 2017) with rainfall in these regions ranging from 1,300 to 2,200mm per annum (Alvares et. Al.,2013). 85% of Brazil's grain production consists of soybean and corn. In recent years Brazilian farmers have learned to crop their land twice in the growing season, growing soybeans from September until February, followed immediately by corn which is harvested in the dry heat of June. Much of this enhanced productivity is attributable to the adoption of no-till technology and genetically modified varieties.

Figure 20: The author with Alexandre Bonfim and Alexandre Franco (Nufarm Brazil) in a corn field planted one week after soybean harvest, near Sorriso in Brazil

In spite of this productivity, Brazil has struggled to develop infrastructure at the same pace as agriculture. In the 15 years from 2001 to 2016, Brazilian grain production has expanded 254% with arable land area only increasing 54% (Suzuki, 2017). Poor roads and high rainfall make transport of the exportable commodities, with distances up to 2500km to port locations, treacherous and inefficient.

In addition to the poor state of Brazilian infrastructure there is uncertainty with the value of the local currency. As a result of this a strong barter system has developed in Brazil where physical crop is comitted as payment for major farming inputs. Joint ventures between commodity traders and input manufacturers have provided certainty for growers and large cooperatives act as an important interface between growers and agribusiness.

Figure 21: Typical situation observed following rain at soybean harvest in Mato Grosso State. Grain destined for port was delayed due to poor roads (Source: Author)

Figure 22: Open drainage near the Pantanal Conservation area in Brazil beside a dryland rice crop (Source: Author)

Given the substantial annual rainfall it would be expected that water is rarely a limit to production. In fact, the opposite is true; the PAWC of many soils in Brazil is actually quite poor. There was consensus within each farm visited that should a rain event not occur within a 14-day window during crop growth, yield would be penalised. From the perspective of an Australian grower operating with one quarter of the growing season rainfall, this fact was difficult to comprehend. Across the landscape there were deep and substantial drainage networks moving excess soil water to local rivers.

The reason for the poor PAWC of soils is the hostile subsoil environment. In much of Brazil the soil is naturally acidic. Since being developed for agriculture there has been a strong focus on acid soil amelioration using ground limestone. Lime application neutralises the acid soil and in turn reduces the effect of hostile elements such as aluminium and increases the availability of many useful nutrients such as phosphorus. Unfortunately, lime is relatively immobile in the soil profile, so it is unable to move to depth without mechanical incorporation. High rainfall, often intense in nature, can cause substantial erosion and loss of topsoil in Brazil. Unfortunately, the erosion risk excludes the safe use of deep cultivation.

As land values climb and pressure mounts for commercial returns on capital, growers are likely to gain a clearer understanding of the need for subsoil improvement to keep productivity on a rising plane. Hopefully in time they will devise techniques to ameliorate soils without the risk of soil loss. The current practices allowing deep drainage of water and nutrients through the soil to river systems will be environmentally unsustainable given similar experiences around the globe.

Technology to identify PAWC and limitations will be of great value to the Brazilian producer and will add value to an already impressive production system.

Conclusion

It is important for the Australian dryland grains industry to understand that many production limitations occur in only a few other parts of the agricultural globe. Crops are grown through winter following a hot dry summer, harvest in spring, have infertile ancient soils and highly variable rainfall distribution. Plant Available Soil Water is a crucial metric to understand, and soil variability makes this a challenge to many. The Australian grain industry is at the leading edge of understanding PAWC, and in particular the modelling of the resulting crop performance.

Around the globe farmers are faced with the same challenge; converting moisture and sunlight to food and fibre as efficiently as possible. In areas where annual rainfall is high, work is needed to ensure roots are not restricted physically or chemically, allowing them to exploit more of the available soil water and nutrition. Not only can this understanding enhance yields but it also protects the environment from accumulated chemicals and fertilisers lost through deep drainage. In low rainfall areas understanding and ameliorating subsoil constraints can enhance the size of the PAWC 'bucket'.

A good understanding of PAWC will allow growers to optimise crop inputs and yield, keeping profit margins strong and enhancing financial sustainability. The grains industry needs to maintain and improve the focus of grain growers on PAWC. Technology such as the in situ Near-Vis-NIR penetrometer has great potential in the Australian broadacre environment mainly due to its ability to physically contact and analyse the sub soil. This three-dimensional perspective of the soil has only been possible with disruptive excavation until now. If used in combination with EM38 surveying, it provides the farmer with the opportunity to quantitatively analyse soil variability across the landscape. For example, the field in Figures 5 and 6 could use the penetrometer to check the red and green zones. This adds credibility to the EM38 readings which can be heavily influenced by different soil physical and chemical properties. If numerical analysis can be used to remove the effect of moisture on the Near-Vis-NIR data of soils, it seems reasonable that algorithms may one day be developed to allow the change in soil moisture to be quantified. Professor Morgan agreed that this could one day be a reality – an exciting possibility as it could also indicate depth of plant root activity and help to improve our soils. As this technology is only at a developmental stage it is not possible to analyse economically although as with any farm costs there will need to be a clear and positive benefit cost ratio for grower adoption.

Once soils have credible zones identified and characterised subsequent surveys with EM38 sensors are likely to indicate soil moisture change. The rationale behind this thinking is that most of the chemical properties of soils which influence EM38 data are unlikely to significantly change over time, with the notable exception of water. This methodology is being adopted in the production regions of Southern Queensland (Darling Downs) and North-West NSW where stored moisture in heavy clay soils is often a prerequisite to crop planting. Costs for a 36m grid-based EM38 survey are $6/Ha and the pricing changes relative to the desired resolution (a 72m grid survey costs $3/Ha). Capacitance probes, neutron probes or soil moisture cores can then be used to ground truth the collected results and the relative change in EM38 readings will indicate drier or wetter areas of the farm. This can be important information in a region where storm activity can be both isolated and intense and allows growers to match seed rates and nutrition to the apparent soil water status.

The plant stress monitoring technology seen in Israel is a commercial reality in many intensive agricultural and horticultural crops globally as a technique to manage irrigation and crop development. These systems could find a place in broadacre cropping as a method to monitor adjacent soil-type zones, to indicate the timing of serious crop stress (crop lower limit). However, they will rely on the development of capable wireless communication systems to be effective. A Long Range Wireless Area Network (LoRaWAN) system will allow real time monitoring of up to 10,000 individual sensors in real time with very low power requirements. A sensor with a daily data update and a lithium-ion power source will have a battery life close to ten years, with no need for an external power supply. The author has deployed this system to monitor rainfall remotely with 20 remote rain gauges being installed over 8,000 hectares. Accuracy of rainfall measurement has been one of the data deficiencies observed during these investigations, especially in Australia, with the rationalisation of weather bureau data sites and the expansion of both farm and field sizes. In a field 6km from north to south the difference in rainfall over a year may be quite significant. The rain gauges installed cost about $400 each and will provide timely, accurate data. Soil capacitance probes using LoRaWAN are also being trialled.

Technology using microwave spectrometry is now in Australia and is being trialled on centre pivot and lateral move irrigation systems. The sensors are likely to cost $2,000 each, once the technology is commercialised, with an average pivot requiring five sensors. The developer hopes to one day fit sensors to machinery to take measurements as it passes through fields, allowing the grower to collect a moisture map in real time. While the technology is exciting, it is at an early stage of development and its ability to operate at the required soil depths in a dryland situation is yet to be proven.

Once PAWC is well understood growers can apply inputs such as seed, macro and micro nutrients in a much more targeted and efficient way. Soils with low productive capacity can have inputs matched to yield potential, while better soils can be nourished to meet their productive potential.

Knowledge is power in agriculture and in a world with a rising population and a declining resource base, growers need to continue the quest to produce more with less. Decision support tools and advances in machine learning have a capacity well beyond the grower’s intuition. However, they will only provide a useful output for growers with the use of reliable and accurate data inputs.

Recommendations

Australian farmers need to:

- Promote the adoption of improved rainfall recording infrastructure using inexpensive Long Range Wide Area Networking technology.
- Promote and adopt low cost soil moisture probes, which could also be connected to low power Wide Area Networking technology.
- Engage with service providers of expensive high-resolution EM soil mapping technologies to optimise their cost-effective implementation in a broadacre environment.
- Collaborate with researchers to develop technologies, such as passive microwave radio-spectrometry and penetrometer based Near-Vis NIR Spectrometry.
- Further engage with industry to provide data on the economic benefits of greater understanding and use of PAWC to grain growers.

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Plain English Compendium Summary

Project Title:	**Closing the Yield Gap. Measuring plant available water in Australian soils**
Nuffield Australia Project No.:	1612
Scholar:	John Stevenson
Organisation:	Orange Park, Lockhart, NSW 2656
Phone:	0429 206 238
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Objectives	• What challenges do grain growers face understanding soils? • How are soils characterised today? • How might soils be characterised tomorrow? • Once we understand our soils, what can we change?
Background	Australian Grain producers operate in an environment of fragile, relatively infertile soil types, with variable and often erratic rainfall patterns. Understanding Plant Available Water Capacity (PAWC) of soils in this environment enables growers to make sound management decisions which subsequently add value to their business.
Research	Grain production and crop research enterprises were visited through the Middle East, Europe and the Americas to evaluate current and emerging technologies associated with soil characterisation and the farm management decision processes influenced by PAWC.
Outcomes	Australia is at the leading edge of relating PAWC to management decisions. An expanded use of electromagnetic surveys was observed, as well as the use of real-time plant stress monitoring in situ, using near-vis NIR spectrometry and microwave radiometry.
Implications	There is the potential, with declining technology costs, to bring techniques from intensive agriculture and horticulture to the broadacre grains market. Real time monitoring of rainfall and soil moisture distribution will provide better data for advanced crop modelling tools, such as APSIM, to allow them to produce meaningful output.
Publications	Presentation at the Nuffield Australia National Conference in Darwin, NT, September 2017