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The agronomy jigsaw: Finding the pieces that maximise water use efficiency

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The agronomy jigsaw

Finding the pieces that maximise
water use efficiency

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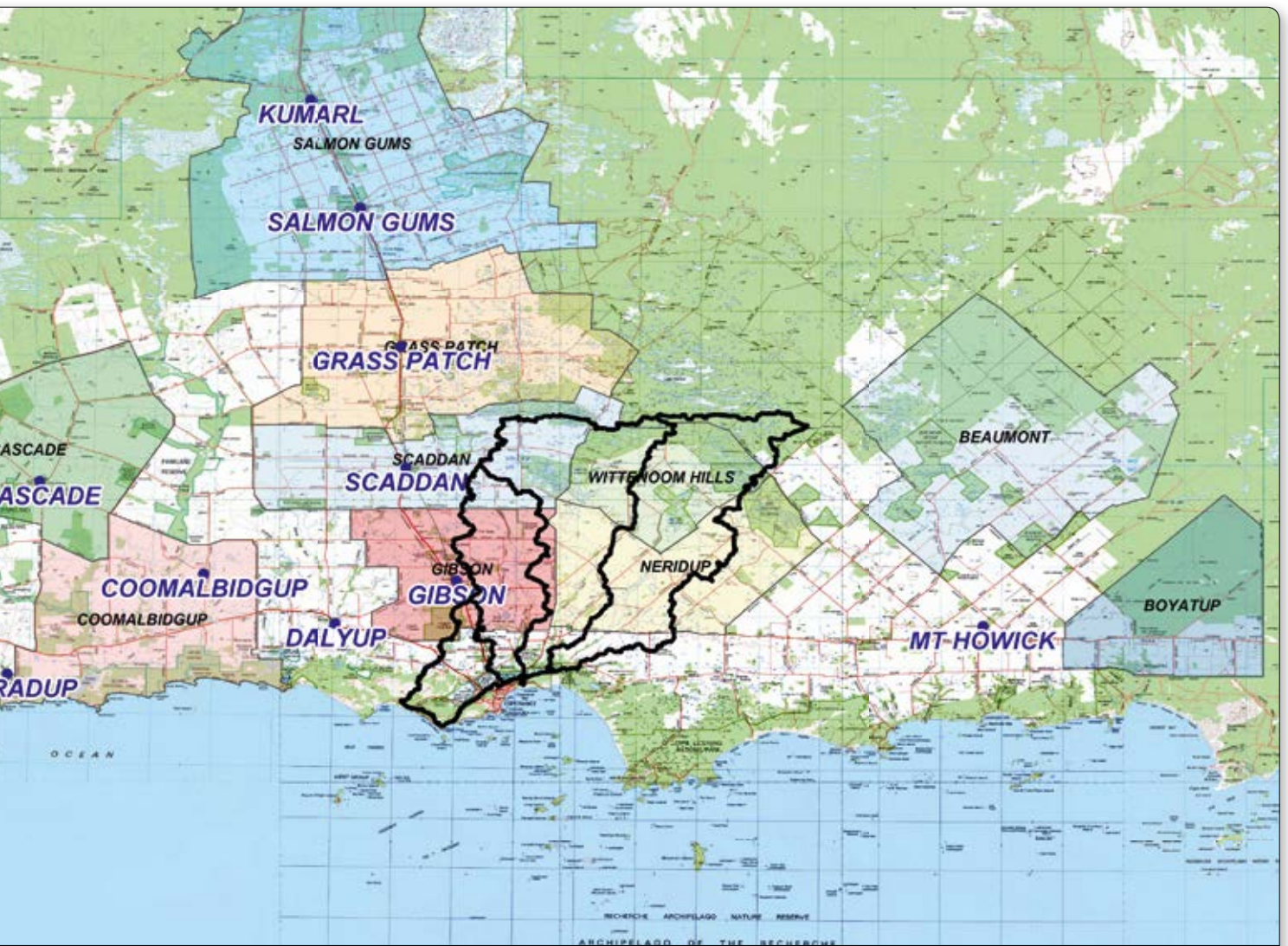
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Legend

	Lake Warden Catchment		CASCAD E
	Labels of Locations		COOMALBIDGUP
	Locations		GIBSON
	Locality Labels		GRASS PATCH
	BEAUMONT		HOPETOUN
	BOYATUP		

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Agronomy Jigsaw locations along the south coast



	JERDACUTTUP		RAVENSTHORPE
	JERRAMUNGUP		SALMON GUMS
	MOUNT MADDEN		SCADDAN
	MUNGLINUP		WEST RIVER
	NERIDUP		WITTENOOM HILLS

Jigsaw agronomy localities

GIS Officer, Kalgoorlie District Office
Department of Agriculture & Food

Date: October 2013
Job ID: 2013380 Projection Universal
Transverse Mercator Zone 51,
Southern Geocentric Datum of
Australia 94

Acronyms

bik-K	Bicarbonate extractable K
CEC	Cation exchange capacity
CLL	Crop lower limit
DAFWA	Department of Agriculture and Food, Western Australia
DDL	Diffuse double layer
DEMs	Digital elevation models
DPPC	Dual pathway parallel conductance equation
ECa	Apparent electrical conductivity
ECEC	Estimated cation exchange capacity
EM	Electromagnetic (induction)
EMh	Electromagnetic induction horizontal mode
EMv	Electromagnetic induction vertical mode
ESP	Exchangeable sodium percentage
FS	French and Schultz WUE method
gamma	Gamma radiometrics
GIS	Geographic information system
GPS	Global positioning system
GSR	Growing season rainfall
K	Potassium
N	Nitrogen
NDVI	Normalised difference vegetation index
NIR	Near-infrared
NVT	National Variety Testing
OC	Organic carbon
OSR	Out-of-season rainfall
P	Phosphorus
PA	Precision agriculture
PAA	Precision Agronomics Australia
PAW	Plant-available water
PAWC	Plant available water capacity
pHBC	pH buffering capacity
ppm	Parts per million
RTK	Real Time Kinematic
S	Sulphur
SAR	Sodium adsorption ratio
SEPWA	South East Premium Wheat Growers Association
TC	Total count
Th	Thorium
TWI	Topographic wetness index
U	Uranium
VR	Variable rate
VRT	Variable rate technology
WA	Western Australia
WUE	Water use efficiency
WUE _{FS}	French and Schultz's method of assessing WUE
WUE _H	Hunt and Kirkegaard's method of assessing WUE
WUE _O	Oliver et al's method of assessing WUE

1 Introduction: the Agronomy Jigsaw project

The Agronomy Jigsaw project is an initiative of the Department of Agriculture and Food, Western Australia (DAFWA) in collaboration with the South East Premium Wheat Growers Association (SEPWA) and Precision Agronomics Australia (PAA). The Grains Research and Development Corporation (GRDC) funded the project under the water use efficiency initiative (DAW193).

Improving water use efficiency (WUE) is the key to increasing crop production in dryland agriculture. In southern Western Australia (WA), water use efficiencies of wheat can vary from 8 to 22kg/mm/ha. The purpose of the Agronomy Jigsaw project is to understand this variation at paddock level: What are the main causes of this variability and how can we manage it to improve profitability?

The project investigates using precision agriculture (PA) techniques to identify and manage soil and crop variability. These techniques use spatial data — yield maps, elevation contours, biomass imagery (NDVI), electromagnetic induction (EM) and gamma radiometrics — to identify and interpret variation in crop yields and soil properties. PAA's method of combining precision agriculture data with in-paddock agronomy is a new approach to identifying and managing factors resulting in poor WUE. Through collaboration with PAA, the Agronomy Jigsaw project has identified seven main topics where the greatest gains in understanding variation in WUE can be made. These are:

- using remotely sensed data such as EM and gamma radiometrics (gamma) to map soil constraints, soil types and WUE
- correlating land-based radiometric and EM survey data compared to airborne survey data
- identifying the correlation between radiometric survey potassium levels and soil test potassium levels
- investigating gypsum application theory and trial demonstrations
- determining lime requirements — predicting where and how much to apply
- defining a protocol for strip trial analysis
- exploring potential uses for elevation models to understand WUE and how they can be used with other remotely sensed data.

Benchmarking water use efficiency for the south coast of WA

David Hall, DAFWA

Rainfall and soils

The south coast area of Western Australia (WA) includes four million hectares of farmed land stretching from Albany to Esperance and extending 80km inland from the coast. Soils, landscapes and farming systems are commonly divided between the lighter textured coastal sandplain and the heavier textured inland mallee. Average annual rainfall varies from 325mm in the northern Esperance mallee areas to more than 650mm along the coastal sandplain fringe.

The soils are classified mainly as Sodosols. Sodosols are predominately duplex (sand over clay), neutral to alkaline pH and have high levels of exchangeable sodium (> 6%) within the clay subsoil.

However, Sodosols vary in plant available water capacity (PAWC) due to root restrictions and changes in texture with depth. Due to the variation in rainfall and soil types along the south coast, there is a corresponding variation in the potential productivity of wheat.

Water is often the major limitation to crop production in dryland (rain-fed) farming systems. Optimising profits entails converting rainfall to grain production efficiently. The term “water use efficiency” or WUE is a measure of a crop’s capacity to convert water into plant biomass or grain. This conversion is expressed as kg(of grain)/mm/ha. There is considerable literature in Australia on the calculation and interpretation of water use for cereals. These calculations can be used to benchmark the productivity of cereal production systems across a range of soil types, rainfall zones and seasons.

This chapter analyses the WUE of wheat crops grown on the south coast of WA between 2000 and 2009 as part of trials by SEPWA (the South East Premium Wheat Growers Association) and NVT (National Variety Testing). This chapter aims to identify:

- the basic relationships between wheat yields and rainfall
- the WUE of crops grown on specific soil types and regions
- the most appropriate method for determining WUE on the south coast of WA.

Data collection

Wheat yield data were collated from the SEPWA and NVT trial sites along the south coast of WA for 2000–09. The location of these sites ranged from the south Stirling Range in the west to Mt Howick in the east (Appendix 2A). This resulted in a dataset with more than 174 crop years of data. Mean, maximum and minimum wheat yields were extracted from the SEPWA dataset. Only average wheat yields were available from the NVT dataset.

Monthly rainfall data was obtained for each trial site from the Bureau of Meteorology [climate data site](#)

Rainfall station and trial coordinates were plotted to determine the nearest weather station to each trial site. Most rainfall stations were less than 20km from the trial site. Where rainfall records were incomplete, the data was patched from the nearest rainfall station.

Wheat yields and rainfall were plotted using the procedure of French and Schultz (1984a). An arbitrary upper boundary line was fitted to the data for both the mallee and sandplain sites.

Three methods of assessing WUE were used:

Oliver et al. (2009)

Oliver et al. (2009) modified the French and Schultz (FS) equation in several important ways. First, they modified the growing season rainfall (GSR) to the sum of rainfall between the start of May to the end of October. Second, they included one third of the out-of-season (January–April) rainfall. Third, they decided that the sum of GSR and OSR (out-of-season rainfall) could not exceed an upper limit of seasonal rainfall according to the plant available water capacity of the soil. If it does, then the maximum PAWC applies.

WUE_O is Oliver et al.'s method of assessing WUE.

$$WUE_O = \text{Crop yield kg.ha}^{-1} / ((\text{GSR} + (\text{OSR} \times 0.33)) - \text{SoilEvap mm})$$

If $\text{GSR} > 180$, $\text{SoilEvap} = 130\text{mm}$

If $\text{GSR} < 180$, $\text{SoilEvap} = 90\text{mm}$

If $\text{GSR} + \text{OSR} > \text{PAWC}$, then $\text{GSR} + \text{OSR} = \text{PAWmax}$

Values of PAWCmax are given in Table 2.1. Hence, if the PAWC of the soil is 130, then the sum of growing season rainfall (May–Oct) and out-of-season rainfall cannot exceed 325mm (Table 2.1). For most soils on the south coast, a PAWC value of 150 was used.

Table 2.1 Values of seasonal PAWmax according to PAWC (Oliver et al. 2009)

PAWC	May–Oct (mm)
80	270
90	280
100	290
110	300
120	315
130	325
140	335
150	345
160	355
170	365
180	375

French and Schultz (1984ab)

WUE is calculated from the mean crop yield divided by the growing season (April–Oct) rainfall (GSR) minus soil evaporation, which is 110mm where GSR is greater than 150mm, and 40% of GSR where the GSR is less than 150mm.

WUE_{FS} is French and Schultz's method of assessing WUE.

$$WUE_{FS} = \text{Crop yield kg.ha}^{-1} / (\text{GSR} - \text{SoilEvap mm})$$

If $\text{GSR} > 150\text{mm}$ $\text{SoilEvap} = 110\text{mm}$

If $\text{GSR} < 150\text{mm}$ $\text{SoilEvap} = \text{GSR} \times 0.4\text{mm}$

Hunt and Kirkegaard (2009)

This method similarly uses aspects of the French and Schultz (FS) model with the main differences being the inclusion of a plant available water (PAW) term that is used to include out-of-season rainfall. In this case:

GSR is April–October rainfall

WUE_H is Hunt and Kirkegaard's method of assessing WUE.

$WUE_H = \text{Crop yield kg/ha} / \text{PAW(mm)}$, where $\text{PAW} = \text{GSR} + (0.36 * (\text{OSR} - 83))$

WUE models: an assessment

Relationship between wheat yields and rainfall

Wheat yields were broadly found to increase with increasing GSR values between 100 and 300mm. Wheat yield tended to plateau beyond 300mm of GSR. The slope of the upper boundary for both sandplain and mallee soils was 20kg/mm/ha, which is consistent with the French and Schultz model. However, the intercept values related to soil evaporation differed markedly between the mallee and sandplain sites. Whereas an intercept of 110mm was found for the sandplain, the corresponding value for the mallee was 40mm. While the intercept for the sandplain sites is consistent with previous findings (Tennant 2000), the intercept value for the mallee sites is lower than the 60mm generally used in lower rainfall regions.

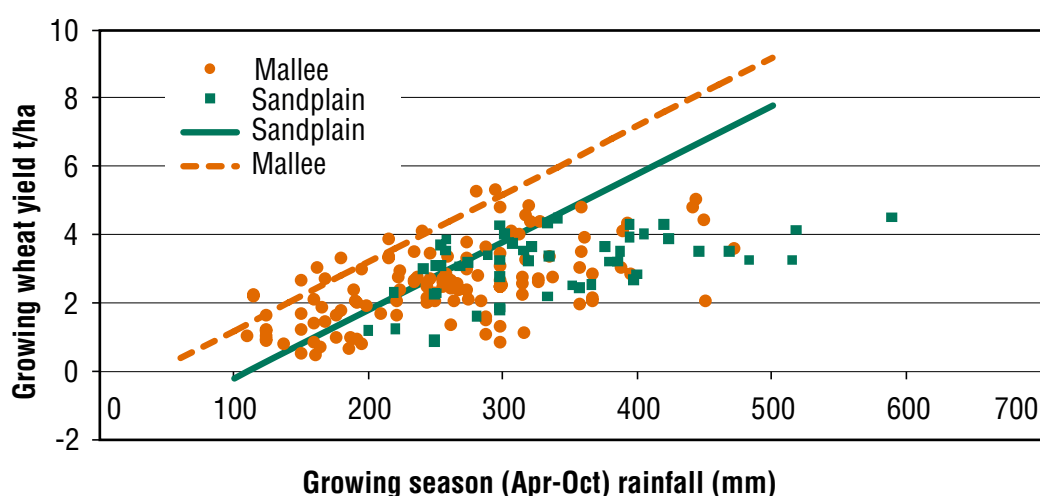


Figure 2.1 Relationship between wheat yields and rainfall for sandplain and mallee environments. Equations for the upper boundary lines are: mallee $(\text{GSR} - 40) * 0.02$ and sandplain $(\text{GSR} - 110) * 0.02$.

Water Use Efficiency

Water use efficiency (WUE_{FS}) varied markedly between the regions and ranged from 11 to 24kg/mm/ha (Table 2.2). French and Schultz (1984a) used the value of 20kg/mm/ha as the upper threshold in their studies. Of the 19 regions that we studied on the south coast, five regions achieved the FS potential when averaged over all sites and years. The high-achieving regions were all in mallee environments. Generally, the mean WUE_{FS} for mallee regions was 20kg/mm/ha compared to 15kg/mm/ha for the higher rainfall sandplain regions (Table 2.2).

The wheat regions that included Jerramungup, Jerdacuttup, Munglinup, Ravensthorpe and Dalyup tended to have WUE_{FS} values lower than 15kg/mm/ha — a value that has been used by researchers in WA for the past 20 years as a benchmark for wheat crops (Tennant 2000). The reason for these regions achieving less than others is unclear, providing the basis for future targeted research and development.

Table 2.2 Water use efficiency data for mallee and sandplain sites along the south coast of WA. WUE is calculated using the methods of French and Schultz (FS), Hunt and Kirkegaard (H), and Oliver et al. (O). The location of each site is given in Appendix 2A.

			Ave WUE_{FS}	Ave WUE_H	Ave WUE_O
Region	Area	Site years	kg/mm/ha	kg/mm/ha	kg/mm/ha
Mallee	Beaumont	9	17	10	15
	Cascade	13	22	9	14
	Grass Patch	8	23	11	17
	Jerramungup	12	14	8	12
	Mt Ridley	4	18	11	16
	Mt Madden	26	19	8	13
	Ravensthorpe	2	12	7	11
	Salmon Gums	18	22	10	15
	Scaddan	12	24	13	20
	West River	1	10	3	6
	Wittenoom Hills	11	22	11	16
Mallee total		116	20	10	15
Sandplain	Coomalbidgup	8	16	10	15
	Dalyup	7	11	7	10
	Gibson	7	15	10	13
	Hopetoun	2	19	11	18
	Mt Howick	8	17	11	16
	Jerdacuttup	11	14	8	12
	Munglinup	11	12	8	11
	South Stirling Range	4	17	11	17
Sandplain total		58	15	9	13

The Oliver adaptations to the FS model resulted in lower WUE values for all regions primarily due to the inclusion of out-of-season rainfall in the calculations. Furthermore, the differences between mallee and sandplain were less pronounced using the Oliver model. The average WUE_O for the mallee and sandplain soils were 15kg/mm/ha and 13kg/mm/ha. The divergence in results between the FS and Oliver models were most pronounced where seasons had high OSR rainfall and low GSR.

In these situations, WUE_{FS} values were as high as 50kg/mm/ha. In comparison, no WUE values were higher than 30kg/mm/ha using the Oliver model. Similarly, the Hunt model resulted in much lower WUE values than either the FS or Oliver models, mainly as a result of the inclusion of a proportion of OSR and the removal of the soil evaporation term. Despite the differences between the models, the ranking of regions was similar between all three (FS, Hunt and Oliver) methods.

One key difference between the methods was the degree of spread between the individual sites. Generally, the FS and Hunt methods tended to over-predict actual yields in higher rainfall years and environments compared to the Oliver method (Figure 2.2). This is undoubtedly due to the restriction of rainfall not being able to exceed the PAWC of the soils in the Oliver method. Consequently, the Oliver method tended to reduce the variation between actual and potential yields on the south coast of WA.

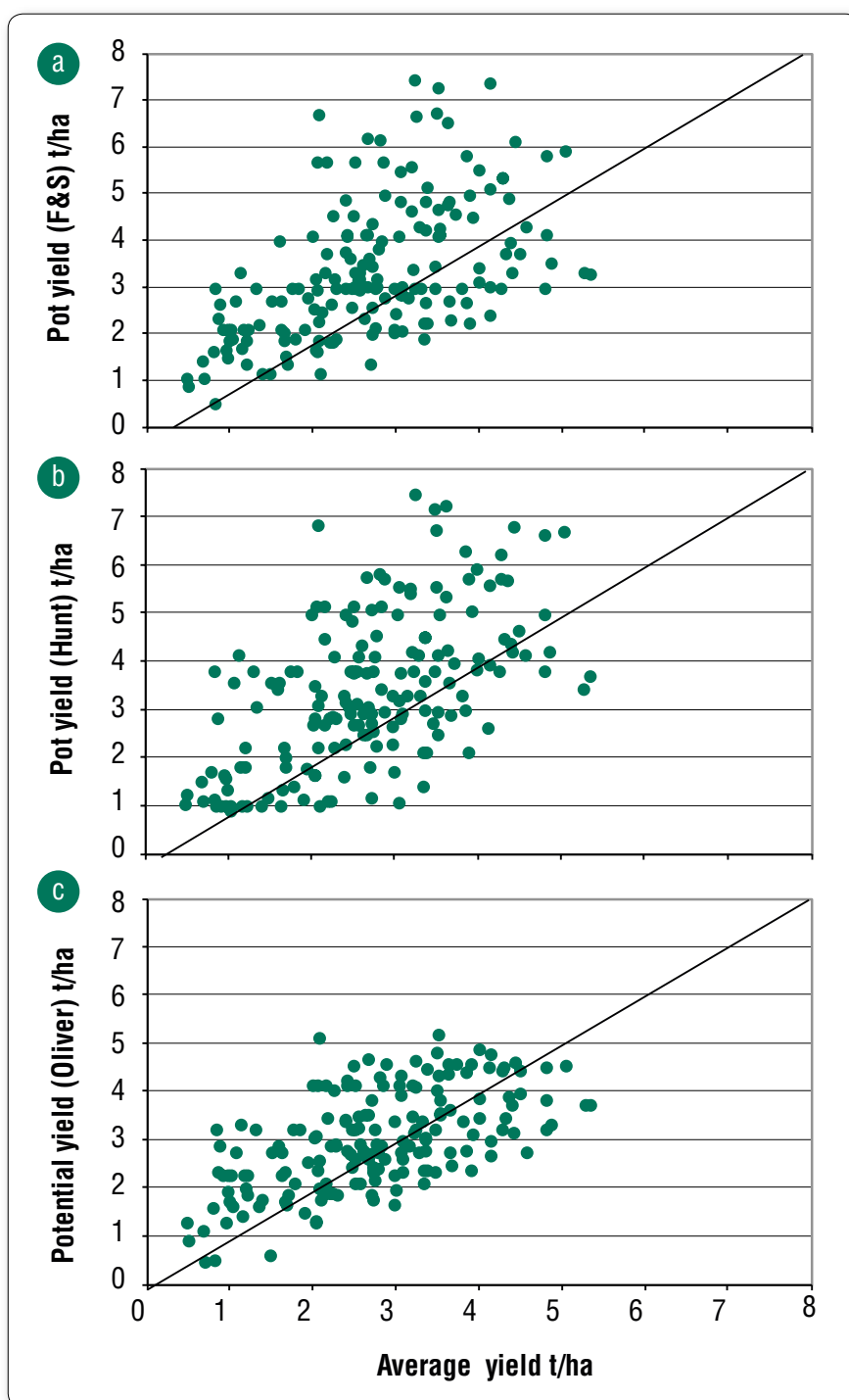


Figure 2.2 Relationship between actual and potential yields calculated using the (a) French and Schultz (FS), (b) Hunt and (c) Oliver methods for all sites and regions. The line has a slope of 1:1.

Variations in WUE results

Relationships based on the French and Schultz model between wheat yields and rainfall were developed for distinct agricultural zones (mallee and sandplain) along the south coast of WA. Based on more than 174 crop years of data, the slope of the line (20kg/mm/ha) and intercept (40 to 110mm) were consistent with previous studies. The intercept for the mallee regions (40mm) was lower than expected but not unrealistic.

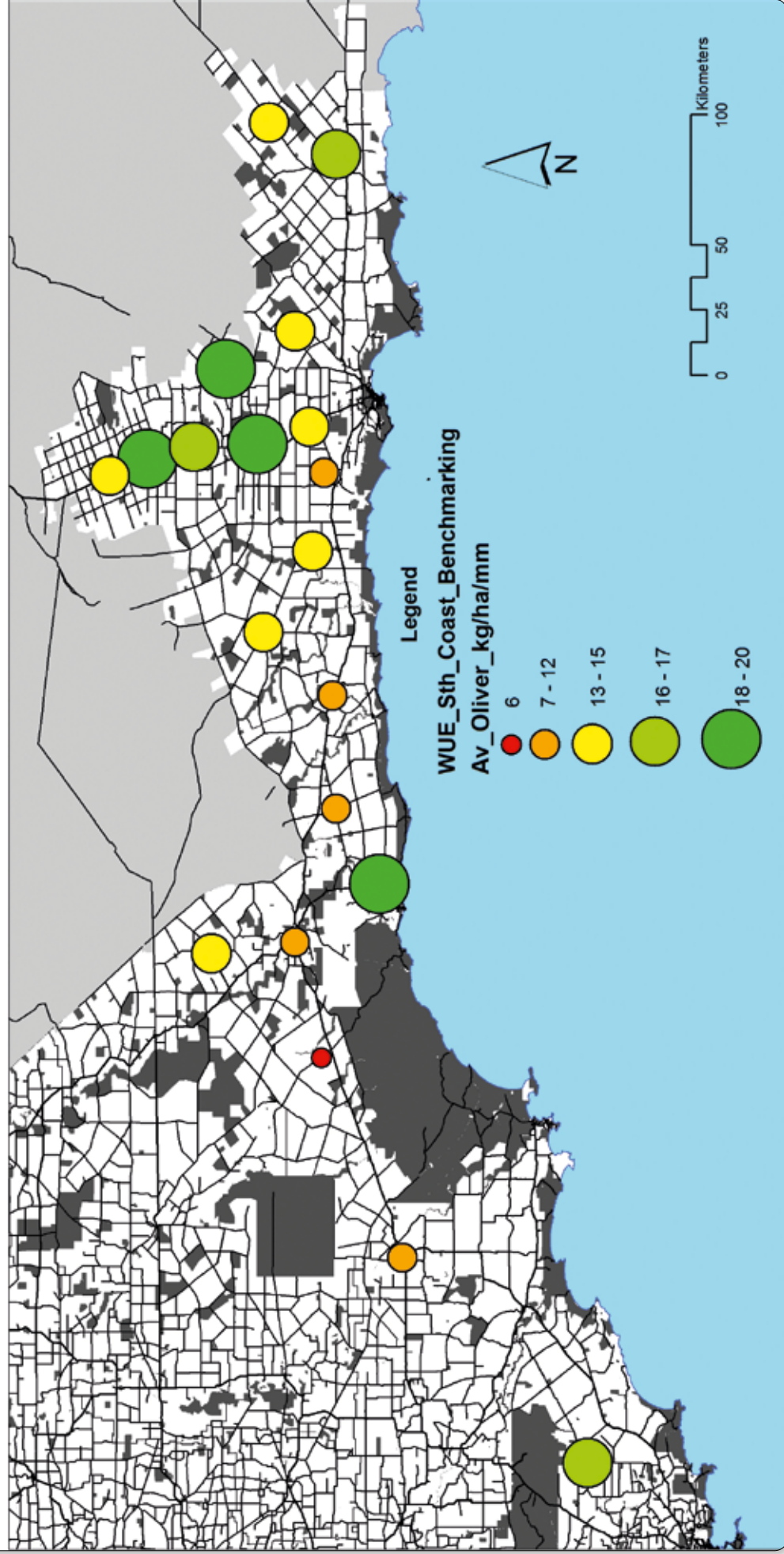
Wheat yields were linearly related to growing season rainfall between 100 and 300mm. Beyond 300mm, there was little yield response to additional rainfall.

The three methods of determining WUE — French and Schultz (1984a), Hunt and Kirkegaard (2009) and Oliver et al. (2009) — although producing different numbers, ranked the sites in a similar order. The mallee sites tended to have WUE values near potential (20kg/ha/mm) whereas the sandplain sites averaged 15kg/mm/ha.

Within the mallee and sandplain, considerable variation in WUE was found between certain districts, with values ranging from 9 to 24kg/mm/ha. This analysis will enable lower performing areas to be targeted for further research and development.

The various methods for determining WUE were assessed. In this preliminary analysis, it was found that the Oliver method resulted in the least variation between actual and potential yields.

South Coast WA - Average WUE Oliver Method



Yield maps – The basics – What is GIS?

Kelly Kong, DAFWA

A geographic information system (GIS) is a computer-based tool for capturing, analysing and displaying landscape features and events in the form of maps, reports and charts. Physical features such as lakes and buildings, and events such as cyclones and disease outbreaks, can all be mapped using a GIS.

To operate a GIS several components are required. First, you need hardware — essentially a computer — on which the GIS software will run and where the data will likely be stored. Additional items, such as GPS (global positioning systems) for capturing data in the field, are also useful. Second, you need specific GIS software, which allows you to display and analyse spatial information. Numerous such software packages are available. Last, and perhaps most important, you need data — coordinate point data, which comes in two formats: vector and raster.

Vector data represents geographic features as points (yield, EM, gamma), lines (paddock boundaries, roads) or polygons (farms, paddocks, dams). Raster data uses grid cells, arranged in columns and rows, to represent features. Raster data is commonly used to produce “smoothed” maps, including paddock yield, EM, gamma, aerial photography and satellite imagery. The smaller the cell size, the greater the resolution of the image.

Point vector data is converted to raster data by mathematical “interpolation”, a process that transforms point data into a grid, resulting in a continuous or “smoothed” map surface. The interpolation processes can vary but the underlying principle is that known data points closest to an unknown grid point will have a higher “weighting” than those located further away. Inverse distance weighting and a technique known as Kriging are common interpolation methods.

GIS is a powerful research tool used in many disciplines, including precision agriculture (PA). In trial analysis, we use GIS to process yield data for analysis. Consider the following example of simple yield data processing.

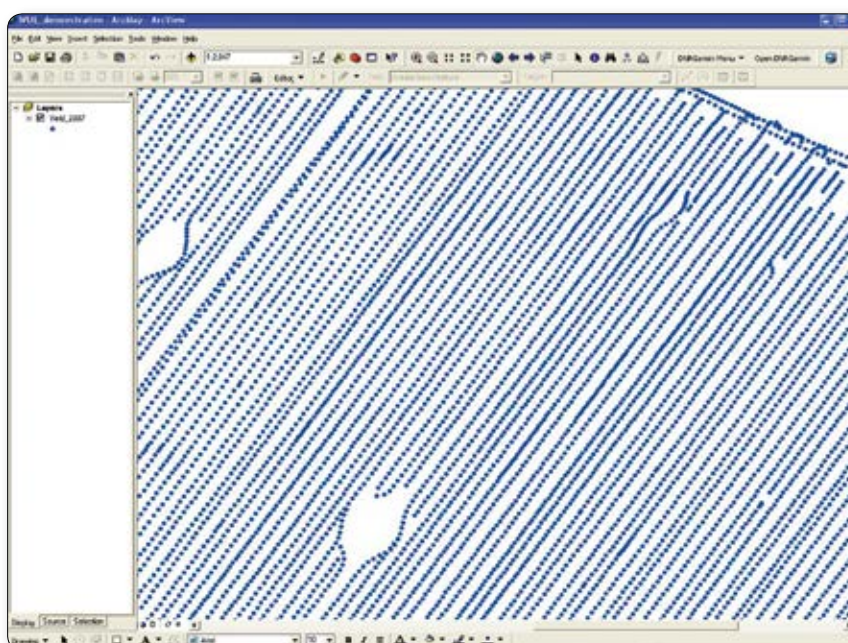


Figure 3.1
Example of spatial
distribution of
data points from
a header yield
monitor.

Figure 3.1 shows the raw yield data captured by a harvester's yield monitor in point format. The string of points represents the header's path across the paddock. It indicates where the monitor has recorded a GPS position and associated attributes that go with that position. In this case, the attribute of interest is the recorded grain yield.

Figure 3.1 shows the raw harvest data in vector point form, which, simply put, is a string of GPS points. This vector point data needs to be converted into a raster before it can be displayed. Conversion turns the points into a single continuous layer of small grid cells. Each cell contains a single yield value, similar to the original point data format. However, where point data is not present (i.e. the grid cell is between two data points), the computer mathematically estimates the cell value from the surrounding values — the process described above as interpolation.

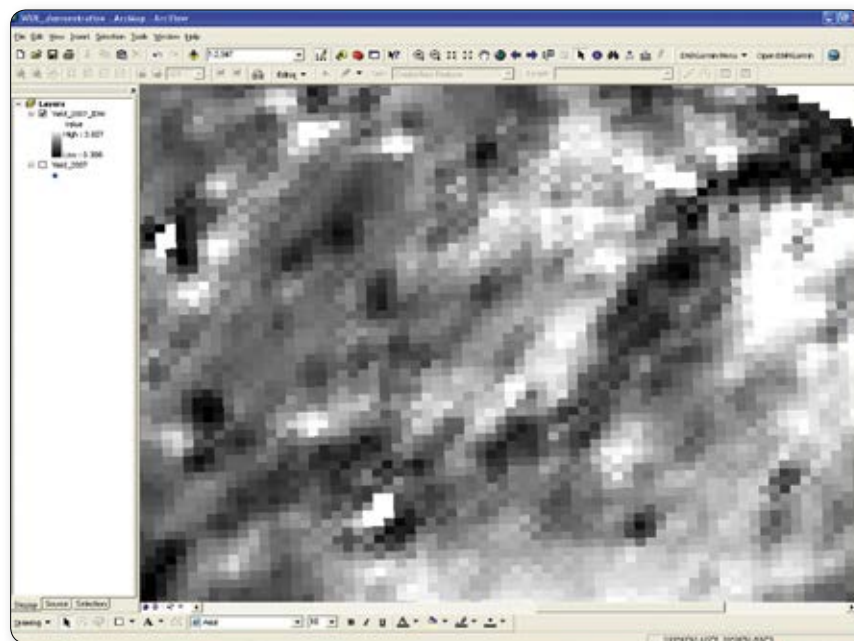


Figure 3.2 Point data converted to raster format.

Once our information is in raster format, the next step is to group the yield values into ranges and give them different colours. This makes it easier to visualise low, medium and high yielding areas of the paddock.

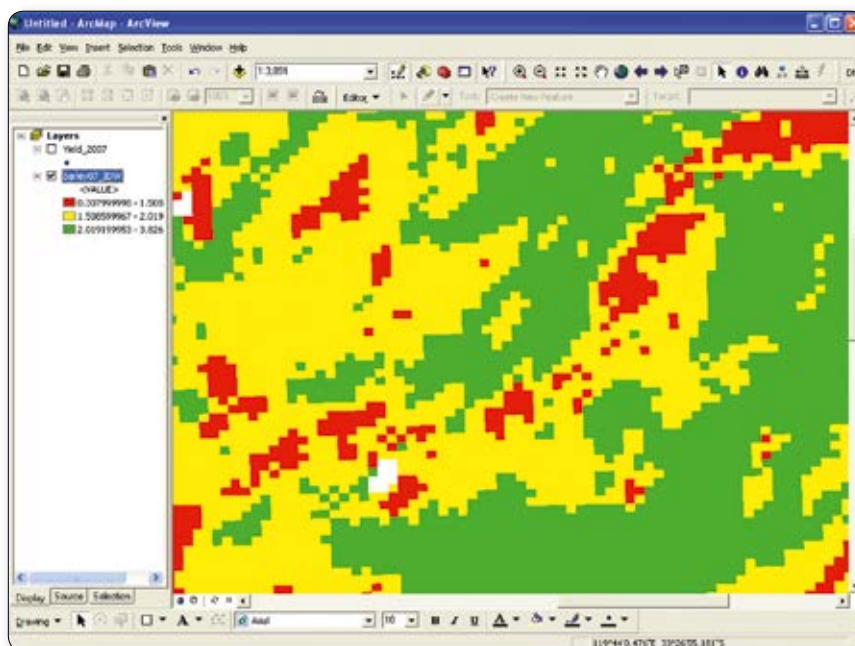


Figure 3.3 Completed yield map format commonly used in precision agriculture.

Yield maps: an important tool for measuring variation of WUE

Nigel Metz, SEPWA

Yield mapping technology has been packaged into harvesting machines since the 1990s and is now standard in new machines. In the past, however, support for technical and software training for yield mapping has been inadequate, and growers have been left on their own to develop these skills. As a result, lapses such as accidental data deletion, overwriting of the previous year's data cards, and failure to back-up (copy) cards were common. This has resulted in lost years and incomplete datasets.

In some cases, growers using variable rate technology (VRT) have not viewed their yield data and hence have no evaluation of VRT management.

A heavy workload (and a degree of apathy among some growers) means data collection is always going to be a lower priority during harvest. Previously, reliable technology may have been the weakest link in yield data management; however, this area has improved significantly with larger data cards that reduce the need for frequent downloading. Where growers have developed an understanding of their yield data, they begin to appreciate its value and make time during harvest to download and back-up data cards from their harvesters as necessary.

The gap in grower skills for archiving and interpreting yield data holds back assessment of the spatial variation of yield and WUE in paddocks significantly. Several years of data are required to consider factors such as yield consistency and to identify causal factors such as subsoil constraints, waterlogging and sand blow-outs. If growers are equipped with the skills to archive and display their yield data properly, they will further develop an appreciation for paddock variation and may develop ways to economically manage the difference. Bearing in mind that the purpose of a yield map is not to precisely record yield but to contrast yield variation across a paddock, they quickly become useful performance indicators.

For the purposes of the Agronomy Jigsaw project, a yield map is an indicator of water use efficiency (WUE). If we assume that a paddock has relatively uniform rainfall, then the variation in yield represents significant variation in WUE. Hence, the yield map history becomes a key spatial dataset in determining factors that are affecting paddock WUE. How can we better manage WUE? What is economically feasible?

Cleaning and processing yield data

Practices for cleaning and processing yield data have simplified over the years. Early development of valuable yield mapping practices by the University of Sydney's Australian Centre for Precision Agriculture involved complicated stages of data cleaning and interpolation to make the common contoured or raster yield map.

Ping and Dobermann (2005) articulated a working example of this technical approach. Their methodology, based on a Nebraskan maize field, involved some six stages of data filtering to produce a clean yield map. Despite the technical nature and depth of their work, more than 70% of the data they removed were points where the header front was up or where yields had not stabilised at the beginning and end of a run. Similar data-cleaning results may also be achieved by simply "topping and tailing" the yield range.

Topping and tailing means excluding data from the yield map that is outside the reasonable biological limits of a crop type. A WA example may be only retaining canola yield values between 100 and 4000kg/ha while wheat may be 200 to 8000kg/ha. This data exclusion can be done during the data card reading process from the harvesters or at numerous other stages during data manipulation. The minimum yield value is set to remove data points where the harvester is not processing crop and the maximum yield value is set to remove data points where irregular speed and crop flow overstates actual yield.

When considering yield map data, growers and researchers need to remember that data from a yield map will never be an absolute value due to the nature of grain sensors in a harvester. Yield map data does, however, provide a means to index yield between different parts of the paddock and so highlight yield variation. In this context, it is difficult to justify the complex data cleaning processes advocated in the past. Simple topping and tailing produces similar results.

In addition, PA yield-mapping software has significantly improved in recent years with more GIS query capabilities, the creation of prescription maps, and guidance lines and paddock setup information exported to tractors ready for VRT application. Growers can now combine various spatial datasets and their yield data within the one software package and make decisions based on the integration of these datasets.

Getting into GIS: selecting a system and tools

PA farming systems employ many computer software brands to manage, interpret and display information. Here, we outline the software tools and programs used for the Agronomy Jigsaw project but note that many other software products also are available.

Microsoft Excel. Although not mapping software, Excel is an extremely useful PA tool, particularly for analysing yield data. Raw yield data can be sorted and cleaned in Excel while in text file format (.txt or .csv). These text file formats in turn can then be easily displayed in most GIS and PA programs as a map. The high compatibility and prevalence of Excel text files among growers and agronomists facilitates data sharing. Other useful features of Excel are tables, graphing functions and X–Y scatter plots that show header runs and machine speed. Excel also can perform simple statistical analyses and calculations.

ExpertGPS. This relatively basic software is useful for interfacing with a handheld GPS. It can import a wide range of file types and, best of all, it can instantly convert to .kml or .kmz file formats for display in Google Earth. The display functionality is basic; the program tends to be a staging point for loading data from text format or shape files to or from your GPS ready for fieldwork. ExpertGPS can be bought online for around A\$160.

SMS/AFS/PFS. These three software brands are virtually identical. SMS was originally written by Ag Leader Technology and then re-licensed to Case IH and New Holland under the AFS or PFS/PLM brands. This software is aimed at reading farm machinery data cards into computers, storing and displaying this data and then creating prescription maps to go back into machinery monitors. To its credit, the software is almost a one-stop shop for PA. It will read just about any data card from a harvester or tractor. And, provided you pay maintenance fees, ongoing updates ensure the latest monitors also can be read. The ability to import generic data (e.g. soil tests and EM data) in different file formats is also handy for compiling information into the management tree, which can be filtered quickly to sort data by farm, paddocks, years or operation. This software costs around A\$750 initially, with subsequent maintenance costs of around A\$300 every two years. However, maintenance is only required when you are upgrading machinery monitors.

Apex. John Deere's flagship software has some good functions in its set-up. Unfortunately, the "John Deere only" approach limits the software's usefulness as an overall farm-based PA option. Apex would be useful for growers who only own John Deere equipment; however, it is unsuitable for a research project dealing with multiple farmers and hence multiple machinery brands. In this project, Apex was used only to extract yield data.

VESPER. This program, developed by the Australian Centre for Precision Agriculture (ACPA), is designed to interpolate point data on a grid system to form a continuous map surface. It is unlikely to have much use for growers now that most PA mapping programs incorporate the interpolation function in the background.

Google Earth. Critics once scoffed at Google Earth, poking gentle at the GIS "toy". Admittedly, Google Earth does not have the accuracy found in products like ESRI Arc software, nor does it allow you to manipulate data. However, it is a universal viewing platform that is very simple to use — and this is its strength. Google Earth is free to download on PCs or tablets. This means many people have at one stage or another used Google Earth to look around the globe. The basic navigation is easy

to learn and, with Google Earth, growers, agronomists and researchers can start to share maps quickly for greater on-ground adoption of PA tools. Having said that, data layers need to be created in other GIS software and published to Google Earth, which means it is not a standalone tool for either GIS or PA.

ArcGIS. ESRI, which produces ArcGIS, make several software versions and is considered the GIS pioneer. Their shapefile format has become the industry standard as a GIS file. ArcGIS is used by the CSIRO for their PA research and is one of the most versatile GIS software programs available. However, its PA application is overly complex for the purposes of individual growers and agronomists. Combined with this complexity, the cost of A\$5000 plus extensions (possibly another A\$3000) makes it an expensive program that needs trained operators.

GeoMedia®. GeoMedia is in similar league to ArcGIS in terms of cost and functionality. DAFWA uses GeoMedia for its GIS platform, which ranges from single paddock yield maps to the whole of WA's cadastral, roads and land tenure details. Although the project has uses for PA applications, it is unlikely to be widely encountered as PA software.

ER Mapper. This high-end software specialises in raster or grid file formats. DAFWA uses this software to create NDVI images (normalised difference vegetation index) from multispectral satellite scans. Again, cost and the requirement for specialist skills means this software is unlikely to be used outside large organisations.

Software	Cost	Functionality	Ease of use	PA suitability
MS Excel	Low	Limited	Excellent	High
ExpertGPS	Low	Intermediate	Good	High
SMS/AFS/PFS	Moderate	Excellent	Good	High
Apex	Moderate	Limited	Moderate	High
VESPER	Free	Limited	Moderate	Moderate
Google Earth	Free	Limited	Excellent	High
ArcGIS	High	Extreme	Low	Moderate
GeoMedia	High	Extreme	Low	Moderate
ER Mapper	High	Extreme	Low	Moderate

Mapping soil properties with remotely sensed data (EM and gamma)

Paul Galloway, DAFWA

Collecting remotely sensed data

The use of remotely sensed data, particularly EM and gamma radiometrics, is becoming more widespread across the south coast of Western Australia (WA). Remotely sensed data is any data that is collected without direct disturbance of the entity being measured. Data can be collected using sensors mounted on ground vehicles, aeroplanes, helicopters and satellites. The data usually results from a form of electromagnetic radiation: aerial photographs are an example of remotely sensed data that uses EM radiation in the visible light range. Gamma radiometrics (gamma) measures very high-energy radiation emanating from radioactive decay of elements found in soil and rock (similar to X-rays). EM (short for electromagnetic induction) data is collected by machines that generate a primary electromagnetic field that induces small electrical currents in any conductive materials within the fields' range. These small currents create secondary electromagnetic fields, which are then measured by the same machine.

EM and gamma each have their strengths and weaknesses, which may provide good data for particular soil properties, and little or no useful information for others. Together they provide a suite of information that has in the past been used to create thematic maps of numerous soil properties, including surface texture, salt storage, sodicity, “sandiness”, boron content, and other themes. The challenge remaining is to combine the many algorithms that generate these focused “themes” into a paddock soil map that identifies latent WUE or potential yield that remains valid over varying seasonal conditions.

It should be noted that other datasets (in addition to radiometrics and EM) and local knowledge — combined with a thorough understanding of soil formation, geomorphology, agronomy and soil constraints limiting yield — should all be used to inform management decisions and prioritise implementation. A recent example of this integrated approach using EM data combined with other data to solve a particular soil management issue is a paper by Triantafilis et al. (2009a).

EM surveys

EM is a method of measuring the apparent electrical conductivity (EC_a) of the near-surface soil and regolith material. It works by generating a primary magnetic field that penetrates the soil material to a depth regulated by the machine or its height above the ground surface. This field generates small electric currents in conductive materials within the soil, which in turn generate a secondary electromagnetic field, which is measured by the machine at the soil surface (see Bennett et al. 1995 for details). The strength and orientation of the primary electromagnetic field can be varied, and this varies the ultimate depth to which the EC_a is measured. This feature of EM gives rise to the range of different EM machines. These include the EM38 (measures 0.5–0.7m in horizontal mode and ~1.5m in vertical mode), EM31 (measures ~3–6m), and dual EM (measures ~0.5 and 1.5m simultaneously).

Many factors affect soil conductivity. The primary parameter is soil salinity (electrical conductivity of the soil water) and the main additional ones are soil moisture content, base cation saturation percentage, soil temperature and texture or clay content. Rhoades et al. (1989) introduced a unified, deterministic model to describe the relationship between these parameters in order to accurately measure soil salinity from EM measurements. This model is commonly referred to as the Dual Pathway Parallel Conductance (DPPC) equation. Other soil factors affecting conductance include, but are not limited to, soil organic carbon content, cation exchange capacity, sodicity (or exchangeable sodium percentage ESP), boron content and bulk density.

Importantly, EC_a measurements integrate all factors, making it difficult to reliably and consistently extract information specific to one or more factors of interest. For example, a mildly saline and relatively dry sandy soil may have a similar EC_a measurement as a non-saline, wet clayey soil.

Thus, EC_a values collected from EM instruments provide an estimate of EC through all depths of soil materials. They provide extensive spatial data horizontally but very little vertical data. This is important in WA because of the variable spatial distribution of differing soil horizons, especially the depth of both the topsoil and subsoil horizons and their variable soil parameters (mentioned above). The conductance of upper (near-surface) layers contributes more to EM response than that of deeper soil layers (Corwin and Lesch 2003, Callegary et al. 2007), and Taylor (2005) notes that shallower sensing EM meters are more affected by surface roughness, which is pertinent for mobile ground-based platforms. Further, when soil conductivity is less than about 100mS/m, a linear model adequately relates the EC_a measurements to the soil conductivity profile. However, when soil becomes more saline, as it may at depth with some WA soils, more complex models are required to resolve the depth at which soil conductivity increases (Borchers et al. 1997, McBratney et al. 2000).

Recent attempts to use such complex models to map the depth of the B horizon surface with EM data have had some success (Triantafyllis and Monteiro Santos 2010), but appear to be in early stages of development, in that they tested the method along a transect to generate depth results in two dimensions. Triantafyllis et al. (2009b) also created a map of cation exchange capacity (CEC) variation with depth, using related technology and methods.

EM surveys of the top ~1m of soil and regolith materials are most often ground-based. Airborne EM surveys are usually commissioned for regional scale salinity, groundwater and regolith studies; they map regolith conductance from several metres to tens of metres deep. They are also expensive in comparison to airborne radiometric surveys. Spies and Woodgate (2004) provide a comprehensive summary of mapping methods for salinity in the Australian context.

EM surveys have traditionally been conducted to determine soil salinity, by measuring EC_a at many sites across an area, sampling and analysing soils and soil solution at selected sites, and then correlating the actual electrical conductivity of the saturation extract to the apparent electrical conductivity values. This method reduces the number of samples required and thus reduces the cost of salinity survey.

Utility of EM surveys has been extended to mapping other soil parameters that affect conductivity in addition to salinity. Lesch et al. (2000) provide a statistical software package to analyse EM data, produce salinity maps, provide recommendations for soil sampling density and location, and map secondary soil variables related to

conductance (such as the additional parameters mentioned above). More recently, Corwin and Lesch (2005) used this program to define site observation density and location when conducting a soil quality assessment of arid-zone soil in the US.

Strong correlation was obtained between EC_a and the soil properties of the saturation extract (EC_e, Cl⁻, HCO₃⁻, SO₄²⁻, Na⁺, K⁺, and Mg²⁺), exchangeable Na, and sodium adsorption ratio (SAR). Other properties were poorly correlated, including: volumetric water content, bulk density, percent clay, base cation saturation percentage, exchangeable sodium percentage, Mo, CaCO₃, gypsum, total N, Ca²⁺ in the saturation extract, and exchangeable cations (K⁺, Ca²⁺, and Mg²⁺).

Zhu et al. (2010) conducted repeated EM surveys over fields in the US, under different soil moisture regimes, to improve soil-mapping products. Despite conducting six surveys in different seasons to average seasonal variability, the best correlations they obtained relating to soil texture was silt content at $r^2 = 0.45\text{--}0.47$. They concluded that wet spells were the optimal time to conduct EM surveys in order to map soil distribution in the landscape they studied (Zhu et al. 2010).

A different application that required drier conditions was reported by Llewellyn et al. (2007), who successfully used EM mapping in the mallee of Victoria, Australia, to map soil moisture remaining after harvest to estimate plant unavailable water, which may indicate areas where soil constraints are limiting productivity. However, they advise caution and careful interpretation to reduce errors associated with late-season rain and other confounding factors (Llewellyn et al. 2007). Strength of correlation of secondary soil qualities with respect to EC_a is poorly studied in WA.

In general, using EM to map soil distribution at the paddock level has had variable success, with variations in methodology often working at one site but not being readily transferable. Methods to map particular soil properties have also been successful where the purpose is well defined, but again is often site-specific. For example, an approach that used EM and other data to successfully map different management units within a paddock with strongly sodic soils was that of Triantafyllis et al. (2009a). They also recommend using additional datasets, such as radiometrics, to improve the quality of mapping.

Radiometric surveys

Radiometric surveys have been both ground-based and airborne. Airborne surveys have been used routinely for conducting mineral exploration studies for many years (IAEA 2003), and have been used more recently in WA for soil-landform mapping and studies by several researchers (e.g. see Cook et al. (1996), Taylor et al. (2002) Pracilio (2007), Verboom and Pate (2003), Wong and Harper (1999)). Ground-based surveys are 1 to 2 orders of magnitude more expensive than airborne radiometrics on a per-hectare basis (Spies and Woodgate 2004), but do have higher resolution if conducted according to published guidelines (IAEA 2003).

Standard guidelines exist for conducting both ground-based and airborne radiometric surveys (see IAEA 2003), and practitioners conducting radiometric surveys should adhere to the guidelines for survey specifications detailed in this document.

Gamma radiometrics is a method of measuring naturally occurring radioactive elements found in soil and rock, by “catching” the gamma rays emitted during the radioactive decay of those elements. The elements in question are potassium

(K), uranium (U) and thorium (Th). Below is a graph of the gamma ray emissions from regolith material, with three peaks corresponding to K, Th, and U gamma ray emissions, and the sum of ranges included as total count (now referred to as the “dose rate”). The important point is that the peaks for each element do not overlap, so the signal for each is distinct and separately measurable.

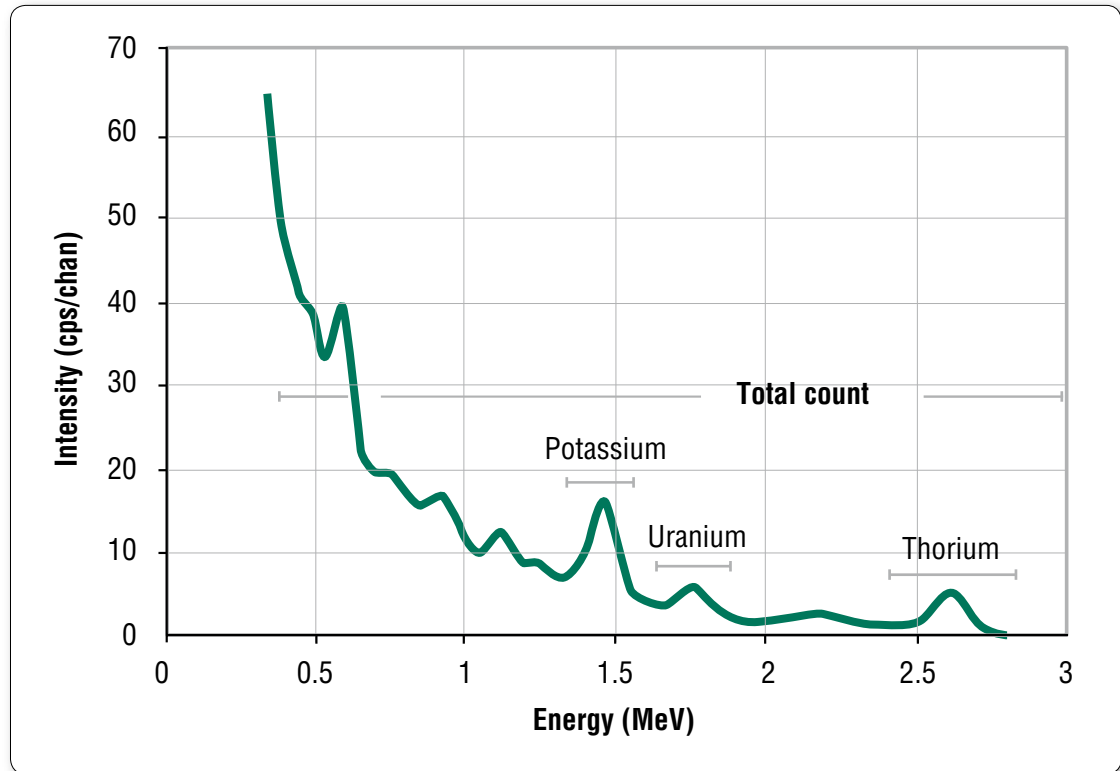


Figure 4.1 Typical gamma ray spectrum showing the positions of the conventional energy windows (from IAEA 2003, reproduced with permission).

Measures of potassium from radiometric data are presented as per cent values and are direct correlations from the machine to the ground concentrations. Measures of both Th and U are presented as ppm values, because they are present in much lower concentrations in the lithosphere. They are also presented as “equivalence units” because the measurements do not provide a direct correlation from the machine to the ground concentrations. This indirect correlation occurs because the decay series of both Th and U are complex. The gamma rays of several intermediate radioactive elements (daughter isotopes) are used in determining ground concentrations. This is not much of a problem for Th, because the entire series is invariably in equilibrium, and so Th equivalent ppm values can be used with confidence. It is problematic for U, because of several factors, the most critical of which is the daughter isotope at one step of both of the convoluted decay series is radon, a mobile gas. The importance of this is explained in the next section.

Attenuation of gamma rays

Because gamma radiation is high-energy electromagnetic radiation (similar to X-rays but slightly higher energy band), it can penetrate objects to varying degrees (in the same way X-rays can penetrate through flesh but are stopped by bone). However, it does not pass through everything indefinitely. Attenuation is the process that “absorbs” gamma rays before most reach the atmosphere. As a rule of thumb for dry soil, 50% of gamma radiation comes from the top 10cm, and 90% comes from the top 30cm.

The situation is more complicated in reality. The probability of gamma rays reaching the sensor depends on both the mass density and electron density of the medium they travel through. Attenuation increases as bulk (mass) density increases, as soil depth increases, and as soil becomes wetter. In other words, gamma rays can emanate from deeper within a loose, dry soil profile than from a wet or dense soil profile or from rock.

A further confounding factor relates to the gamma emission signal for Uranium (U). Because U has a complicated decay series (i.e. there are multiple possible paths from unstable to stable, and stability takes 1.5 million years to establish), the proportion of U in the ground to the gamma rays that betray its presence is often in disequilibrium. Thus, U measurement and the use of U alone or in ratios is the least reliable. This is most exaggerated by radon, a radioactive gas produced as part of the decay series of U. Radon can diffuse away from the original source material and thus “dilute” the gamma response. It can also accumulate in valleys and landscape hollows during still weather and artificially increase readings. Further, it is forced out of soil during rain, as water fills soil pores previously air-filled, so U readings collected during and up to several hours after rain may be artificially inflated. These last two factors will generally affect ground-based measurements more than airborne measurements.

Sources of radioactivity

Rocks and soil contain small amounts of naturally occurring radioactive isotopes that spontaneously decay, emitting gamma rays of characteristic energy. Three isotopes, namely potassium (^{40}K), thorium (^{232}Th) and uranium (^{238}U), are capable of emitting gamma rays from soil with enough intensity to be measured by recording devices mounted on vehicles or in planes (IAEA 1991). Because the energy of a gamma ray is generally characteristic of the isotope producing it, and because the isotope can be related either directly or indirectly to the total concentration of the element in near-surface materials, an airborne gamma-ray spectrometer can be used to map the variation in levels of K, Th and U in the rocks and weathered materials. It is also usual to map the total count of gamma rays received from all radioactive elements.

Sources and concentration of K in near -surface material is dealt with in the following chapter. Differentiation of U and Th is summarised below.

Proto-earth (early Earth) initially had uniform trace distributions of U and Th (about >10ppb and ~30ppb, respectively), which are in similar proportions to those found in proto-solar system dust clouds of supernovae (Th is about three times as abundant as U).

Early in Earth's tectonic history, from ~4.5 to 3.5 billion years ago, U and Th became concentrated in magmatic-related silica-rich fluids and aqueous solutions. This resulted in these elements becoming more abundant in felsic rock, such as granite; than basic and ultrabasic rocks such as basalt, dolerite and greenstones (Cook et al. 1996, Hazen et al, 2009). Granite typically contains about 10ppm U and 30ppm Th.

Weathering, erosion and deposition further concentrated some radioactive elements, but it was not until the great oxidation event, when life on earth formed free oxygen, that Uranium (U^{4+}) was able to be oxidised (in large amounts) to U^{6+} , forming the Uranyl ion (UO_2^{2+}), which is soluble and therefore mobile. The reduced form of U (U^{4+}) forms and precipitates in anoxic (oxygen-poor) environments.

U is removed from highly permeable sediments in oxic (oxygenated) and leaching environments, and so the U concentration of granitic sands forming from granite is less than that of its parent rock. The leached, siliceous sands of the Esperance sandplain are almost devoid of U, and the U concentration in clay soils depends on the original parent material and the cation exchange capacity, since U is adsorbed onto clay in proportion to CEC. Thus, illite clay will show higher U concentration than kaolinite.

The rise of land plants about 400 million years ago led to a further phase of U deposition. Oxygenated near-surface waters mobilise the Uranyl ion, which precipitates when it meets anoxic, organic-rich sediments. A pertinent example for the south coast is concentration of U-enriched sediments in the closed depressions of salt-lake systems, as encountered in the mallee. Such concentration occurs when oxic groundwater solutions containing the soluble U^{6+} uranyl ion contact anoxic (low oxygen) sediments containing reduced organic materials and sulphate-reducing bacteria, causing reduction of U^{6+} to U^{4+} , and precipitating uranium minerals (Hazen et al, 2009).

Uranyl cations combine with the carbonate anions to form the insoluble uranium carbonate, which co-precipitates with marine sources of calcium carbonate, so becomes elevated in coral, limestone and limesand deposits. This contrasts with the exclusion of Th from limestone carbonate lattices, which, combined with the moderate accumulation of K-bearing sediments in shallow marine deposits, explains the unique gamma signature of the coastal calcareous dunes and limestone sediments of the south coast.

Uranium's several redox states contrast with Thorium, which has only one valence state (Th^{4+}), and is not mobile in either oxidising or reducing environments. However, both U and Th are elevated in ironstone gravels, which is surprising given the general immobility of Th, and the mobility of U in oxygenated, leaching environments. This anomaly is resolved by understanding that both U and Th are chelated and mobilised by the same organic acids exuded in large proportion by proteaceous plants that mobilise iron in oxic environments. The chelated organic-metal complex is then consumed by soil microbes which precipitate the metal component as a rind on the surface of gravel (be it Fe, Al, U, Th or other metal) (Verboom and Pate 2003).

Taylor et al. (2002) stress that thoroughly understanding the mineralogy and geochemistry of parent material and the weathering history of an area is a prerequisite to interpreting soil properties, as they have a strong influence on the radionuclide content of soil. Verboom and Pate (2003) highlight this in their study on laterite development as a consequence of particular native vegetation, and the effects this has had on the concentration of Th and U in ironstone gravels.

Soil water effects on gamma and EM

Presence of soil water affects the results of gamma and EM surveys in contrary ways. Soil water reduces the quality of radiometric maps because it attenuates gamma emissions, thus reducing the depth from which gamma sources are detected. The example that Cook et al. (1996) give is illuminating: “It may be difficult to distinguish between highly weathered sands of low radioactivity and waterlogged soil of high radioactivity.” To maximise resolution, gamma surveys should be conducted when soil is dry: a 10% increase in soil moisture will decrease gamma counts by 10% (IAEA 2003).

A confounding factor affecting radiometric maps is that, although moisture will in general reduce gamma counts, percolating soil moisture can artificially increase the U count by forcing gaseous radon (a daughter element in the U decay series) from soil pores into the atmosphere, thus increasing near-surface radon density. Radiometric surveys should not be conducted within three hours of rain (IAEA 2003).

Conversely, some soil moisture is required for EM surveys to establish conductance routes and generate measurable apparent electrical conductivity (EC_a) of soil. Timing EM surveys to optimise the soil moisture content for the intended purpose of the survey will affect the end product.

Ground-based versus airborne survey

Previous natural resource management (NRM) project activities have conducted landscape-scale airborne gamma surveys across part of the WA wheatbelt. This survey data has been used to broadly describe variation in soil types at a landscape level in several situations. These datasets may have application in PA applications, particularly in alerting farmers to regional soil conditions affecting WUE.

Taylor et al. (2002) found variable relationships between ground-based and airborne measurements, with airborne data more accurately reflecting texture changes. Conversely, ground-based correlations were more accurate for relationships between Th and ironstone gravel content of soil, and between K and feldspar content of soil.

The accuracy of different survey methods depends mostly on the scale of variability of soil and regolith materials matching the scale of the survey. For example, a ground-based survey may not identify a linear feature (such as a narrow gravel ridge on a dolerite dyke) if traverses run perpendicular and straddle the feature. On the other hand, the stronger relationship Taylor found between ground-based Th and gravel may be due to the additional precision of ground-based measurements — the longer time of gamma collection due to slower ground speeds and sensor proximity to source, combined with the higher energy Th emissions, is likely to identify localised gravel sources from greater depth than airborne data.

Ground-based gamma surveys have great utility when combined with field observations directly under the sensor path, because relationships between soil attributes and gamma signal can be identified. This strength can be magnified by using airborne regional gamma data to extrapolate to areas where no observations have been sited, or to areas where point observations exist but no ground-based gamma survey data exist.

Summary of work to date

- A “one size” or “one method” fits-all for EM does not exist.
- Some site-specific EM surveys successfully mapped soil variability; others did not.
- Specific soil parameter mapping has had some success in the past, if used cautiously. A pertinent example is mapping areas where crops have left significant soil moisture in the profile, indicating soil limitations to growth.
- Additional datasets can improve accuracy and resolution.
- Timing and soil moisture content of paddocks will alter EM survey values; so the purpose of a survey must be defined and timing matched appropriately.
- Existing software can assist sampling programs.
- EM should be considered as one tool, not a complete solution.
- Past studies have identified rules of thumb for interpreting radiometric data, particularly for the granitic terrain of WA.
- Studies using radiometric data to map soils on mixed sedimentary and granitic geology on the south coast are limited.
- Radiometric data is unlikely to inform about soil materials below 30–40cm deep.
- Radiometric data should be considered as one tool, not a complete solution.
- Combining various scales of data may generate insights that individual methods fail to identify.
- Both EM and radiometrics can be used to minimise costs of soil sampling for soil mapping purposes; however, soil (and plant) sampling for agronomic performance, combined with local knowledge, will still be required.

Correlation between radiometric and soil test potassium levels

Paul Galloway, DAFWA

The requirement for fertiliser applications of potassium (K) on the south coast of Western Australia is strongly driven by soil type. The ability to map soil K and its variability would be a very useful tool in variable rate crop nutrition and hence improving overall paddock water use efficiency (WUE). Unfortunately, the correlation between soil test K (Colwell bicarbonate) values and gamma radiometric K (gamma-K) is not always straightforward, as previous research shows. The Agronomy Jigsaw project attempted to clarify situations where gamma K can predict soil K for reliable application of variable rate management. At least, the project expected to identify broad areas where gamma K is insufficient to identify marginal and deficient K zones, allowing farmers and agronomists to better target zones for soil or tissue testing to identify K deficiency.

Potassium sources in south coast soil

Potassium is the seventh most abundant element in soil, with an average crustal abundance of about 2–2.5%. In Australia, K ranges from less than 0.01% to more than 3% in soil (Williams and Raupach 1983). Natural K in soil is derived mostly from primary minerals of micas (muscovite and biotite) and feldspars (orthoclase and microcline). On the south coast of WA, these minerals are found in igneous (principally granite) and intensely metamorphosed (principally gneisses) parent rocks. Natural sources of K also derive from sedimentary rock, the amount of K varying with the amount and type of clay minerals (particularly illite) deposited in the sedimentary environment. Sandstone has very little K, but shales can range from 2–4%.

Little information exists about the K content and variability of marine tertiary sediments of the south coast, and only regional overview maps of the surface distribution of these sediments are available in the public domain. However, given the sediment types, the K content of these materials is likely to be generally low. Research indicates that the marine sedimentary clay sequences have higher K content than non-marine clayey sediments, which are dominated by kaolinitic clay of low K status (Lonnie 1982). Since south coast sedimentary clay sequences expressing at the surface are generally limited to upper units of the Werillup Formation, in a non-marine deposition environment (Cockbain 1967), the K content is likely to be low. Pallinup siltstone K content is also likely to be low due to low clay content.

Weak weathering of primary rocks can remove some K, but leaves significant amounts of primary minerals in the sand and silt fractions of the soil, particularly the K-feldspars microcline and orthoclase, since these are most resistant to weathering. The primary minerals of muscovite and biotite also contain significant K, but are more easily weathered, degrading to form clay minerals, notably illite. Thus, soil formed on fresh rock (granite and gneiss) has similar or slightly less K than the primary rock, depending on the geomorphological environment influencing leaching, erosion, deposition and lateral translocation of clay through winnowing and vertical translocation through illuviation. However, this K fraction is mostly present within the crystal lattice of primary feldspathic minerals (called “structural K”), and so is only slowly released to the plant-available pool.

More intensive weathering of primary minerals results in conversion of the more resistant minerals to secondary clay minerals. Illite has the most K of all secondary clay minerals because K dominates the inter-layer substitution space. This K is relatively tightly held between tetrahedral and octahedral aluminosilicate layers, but is not “fixed” within the crystal lattice, and so is slowly released over the growing season, its rate of release dictated by the concentration gradient of K in the soil solution. In other clay minerals, K content is mostly limited to exchange sites associated with negative charges at the margins of clay. Thus, the cation exchange capacity (CEC) of the soil determines K availability/concentration in all soils not dominated by illite. (K concentration reduces from vermiculite > smectite > kaolinite, in the same manner as CEC does).

Intense weathering of parent materials has depleted K in many surface soils, by almost complete removal of both primary minerals and secondary clay minerals from surface soil through weathering and reworking of soils and sediments, leaving quartz sand and clay-sized oxides of iron and aluminium in near-surface horizons, often overlying kaolin-rich subsoils. In these deeply weathered soils, a major contributor of plant-available K is K on exchange sites of soil organic matter in near-surface horizons.

In summary, on the south coast the majority of sandplain soils are depleted in K and so plant-available K content of agricultural soils is dependent on agricultural land use and fertilisation history.

However, some distinctive low-lying areas (swamps, depressions) and crabhole clays have significant amounts of 2:1 clay minerals, including illite and smectite, which will have good natural K levels. Also, areas surrounding granite and gneissic outcrops may still have significant proportions of primary minerals containing structural K.

A “typical sequence” of K concentration in soil on the south coast is (from lowest to highest):

- quartz-dominated sand (pale sand, such as the deep sands in the Esperance sandplain)
- low CEC soil (sands and loamy sands with soil organic matter, such as the deep sandy duplex and gravelly sands of the Esperance sandplain)
- moderate CEC soil (sandy and loamy duplex soil with clays dominated by kaolin, such as the “mallee duplex” or “Scaddan” soils and “Circle Valley loams”)
- high CEC soils and soils with significant “structural K” (clay soil with significant vermiculite and smectite, and clay soil with illite. Examples include the Kumarl and Dowak clay loams and clays, the red clay of Ravensthorpe and crabhole clays on ridges between the Lort, Oldfield, and Young rivers).

Soils freshly formed from granite and gneiss will range in available K, between moderately high and high, because although they can have significant K, much of it is not readily available to plants. Soils formed from recent sedimentary origin (e.g. calcareous sand dunes along coastal margins), have significantly higher K content than weathered quartz sand, but less than clayey soils and fresh granite soils. The alkaline nature of these soils effectively restricts the release of K, so most of the K present is unavailable to plants.

Plant uptake of potassium

K uptake by plants is almost entirely from K in soil solution. Since plant roots only occupy a very small proportion of the total soil volume, K must move to the plant by a diffusion gradient from the bulk soil to the rhizosphere, which is dependent on the rate of replacement of soil solution K by the structural, fixed and exchangeable K (Gourley 1999).

Some research suggests large differences in K uptake among different plant species (Ozanne et al. 1965). They found that although all species obtained most K from surface layers, some deep-rooted species were able to use subsoil K more so than shallow-rooted species. Research in WA on duplex soil found that almost all K taken up by wheat was taken from the topsoil, and that topsoil sampling is adequate to identify plant-available K status for the whole soil profile (Wong et al. 2000). Two driving factors of this are perhaps the higher K buffering capacity of the organic matter-enriched topsoil and the much higher rooting density of most plants within topsoil.

This is important in the context of the south coast, which has large areas of duplex (sand over clay) soil. The clay subsoil usually has significant K on exchange sites and, in some soils, within the matrix of illitic clays. Much of this K may be considered inaccessible due to the limited rooting density of crop plants at depth.

Potassium radioactivity and gamma signal

Radiometric survey can directly infer total potassium in topsoil, because K in the Earth's crust contains about 0.012% of the radioactive isotope ^{40}K , which emits gamma rays with a diagnostic peak at 1.46meV during its direct decay to ^{40}Ar .

K can be measured along with emission from uranium (U), thorium (Th), and their radioactive decay products (Ward 1981; IAEA 1991). The method has been used to determine the total K content of soils (Smith and Talibudeen 1981) and its regional distribution (Duval 1990).

It is estimated that about 90% of the gamma emissions from K emanate from the top 10cm of the soil, and less than 2% come from deeper than 30cm. Soil moisture can increase this attenuation significantly. Gamma technologies cannot detect sources of K located deeper in the profile, such as in subsoil clayey B horizons commonly found in duplex soils of the south coast.

Mapping plant-available K from gamma K surveys

Both airborne and ground-based radiometric mapping have been used in Australia to estimate plant-available K (bicarbonate extractable-K or bic-K) with variable success (Wong and Harper 1999, Pracilio et al. 2006).

The ground-based method of Wong and Harper (1999) on sandplain soils of the south coast in a sedimentary and aeolian geomorphic environment produced strong correlations between gamma-K and bic-K ($r^2 = 0.9$). However, they attribute these strong relationships to the equally strong relationship between bic-K and total-K at the site, which they attributed to the particular geomorphic and pedologic site morphology. Further, they note that the relationship was poor ($r^2 = 0.05$) when bic-K was less than 100mg/kg, a value considered the upper threshold for soils requiring K fertilisation. For example, many duplex soils used for cropping in WA have bic-K

levels between 22 and 89mg/kg, but K responses are not common on them (Gourley 1999). Wong and Harper concluded that ground-based radiometric mapping of soil K to estimate bic-K is limited to identifying areas where soil sampling and analysis should proceed, rather than in providing site-specific K fertiliser recommendations. In this role, it will allow cost savings relative to sampling and analysing the whole area.

Pracilio et al. (2006) used high-resolution airborne gamma radiometric survey (100m line spacing with a sensor height of 20m, one-second sampling using a 32L detector crystal pack) to identify relationships between total-K and bic-K at three contrasting sites in the northern wheatbelt of WA:

- Site 1: Granitic terrain with coarse sandy and feldspathic soils
- Site 2: Sedimentary rock terrain with sandy earths and red hardpan loamy soils
- Site 3: Sedimentary rock terrain with sandy (“sandplain”) soils.

The authors concluded that on site 1, there was no significant relationship between bic-K and gamma-K. However, this is meaningless in an agronomic sense because the large gamma-K measurements represent abundant total-K concentrations in soil, with attendant bic-K measurements indicating adequate exchangeable K not limiting plant growth.

Pracilio found that the gamma-K signal accounted for 50% of the variation in bic-K across both sites 2 and 3. However, at site 2 the bic-K was generally above threshold levels described previously, and so was not useful for fertiliser recommendations beyond recommending no K fertilisation. Conversely, at site 3 where bic-K values were less than 70mg/kg, Pracilio noted a large degree of scatter, concluding that current airborne gamma survey configurations are limited in detecting areas deficient in K to make reliable K fertiliser decisions. The reality is that when low gamma-K mean values are converted back to actual count-rates, the counts are so low as to question the reliability of the technique at low total-K concentrations, an observation raised by Wong and Harper.

Pracilio identified limited instrument sensitivity and processing errors inherent in current airborne technology as significant limitations to the utility of the method for K-fertilisation decisions. Further, Pracilio attributed a component of the scatter to the fact that airborne surveys average counts over footprint areas larger than the actual on-ground variability. A distinct but similar issue arises with ground-based methods. Given ideal environmental conditions, slow ground speed and adequate sensor sensitivity, they can theoretically gather more reliable data than airborne methods over the swath of land they actually traverse. However, the area between swaths remains “unsampled” and is allocated a gamma-K “value” only by mathematical interpolation between real data points.

Both studies using contrasting gamma survey methods suggest that:

- Using gamma-K to estimate bic-K must be tempered by prior knowledge of the geomorphic environment being surveyed.
- Gamma-K can identify areas where one would expect bic-K levels to be adequate and thus not limit plant growth.
- The relationships between gamma-K and bic-K break down where bic-K becomes limiting, so gamma-K cannot be used for site-specific K fertilisation recommendations.
- Areas of low gamma-K can be defined to identify areas where more intensive soil sampling and analysis should be conducted for K fertilisation.

Precision agriculture, zone mapping and K response

Different methods have been applied to paddocks for subdividing in preparation for variable rate (VR) K fertilisation. Reliably identifying different K zones in a paddock has proven elusive. In various situations, K response has been linked to soil type, and topography, but past management practices (including K fertilisation, lime application, tillage) have also created new and large variability patterns (Sawchik and Mallarino 2007). Zone management maps for K fertilisation have been created with varying success by using yield maps, EM data, soil-landscape and soil surveys, topographic maps and topography derivative maps in a GIS environment, satellite imagery encompassing mid-season NDVI (normalised difference vegetation index), interpolated grid sampling, and radiometric data, both airborne and ground-based.

Table 5.1 Summary of methods used to identify potassium management zones

Zone delineation method for K fertilisation	Direct/inferred/composite	Simple/complex AND process-based/statistical/composite	Comments	Reference
Grid soil sampling	Direct (estimates direct K requirements)	Simple – Statistical – (direct measure but interpolation required to extrapolate measures)	Sampling density is important, and generally requires <0.8 ha cell size	See Sawchik and Mallarino for actual studies Wong, Corner and Cook (2001) infer that 1ha grid size is insufficient to determine K variability in a WA example
Single year and multi-year yield maps	Inferred (many factors influence yield)	Complex – Process-based (many factors influence yield which integrates all processes acting on crops)		
Soil survey	Inferred (pedotransfer functions may generate indicative K requirement map based on particular soil properties)	Process-based		
Radiometrics	Composite (directly measures total K in topsoil and can infer other topsoil properties)	Simple – Process-based (K tot. can be directly correlated to K exch in some situations May not be sensitive enough to establish plant response levels) Measures integrated pedo-geo-chemical processes	Data collection method determines scale of reliability	Wong and Harper
EM	Inferred –(pedotransfer functions may generate indicative K requirement map based on particular soil properties)	Complex – Process-based		
mid-season NDVI	Inferred	Process		Wong, Corner and Cook (2001)

Potential application of gamma K survey in plant nutrition

There may be merit in using regional-scale radiometric data to provide a first pass at mapping different geomorphic environments. These maps could provide focus for then using airborne regional gamma-K data, calibrated by local ground-based gamma-K data, to map areas where bic-K is likely to be adequate. Generating an inverse of these mapped areas will produce a map of areas identifying potentially low bic-K, where ground-based gamma-K surveys could then identify the limited areas where more intensive soil sampling for K fertilisation will be required. Such a process will maximise grower value for their soil sampling regime by preferentially sampling areas with low K, and possibly low Phosphorus (P) and pH.

It should be recognised, however, that even with ultimate precision in defining soil K concentrations, the relationships between soil K supply and plant fertiliser response are imprecise (Colwell and Grove 1976). The benefit of mapping precise K status by any means is diluted by imprecision of soil analysis–plant response relationships.

Defining production zones from yield maps, NDVI and geophysical measurements

David Hall, DAFWA

VRT management

Traditionally, growers have applied fertiliser and amendments to their paddocks uniformly, regardless of variations in soil type or production history. However, with rising input costs, more interest is being shown in placing inputs where they can be used most profitably. Variable rate technology (VRT) seeks to optimise inputs and production and has been credited with increases in profitability through efficiency gains and reduced risk (Cook and Bramley 1998, D’Emden et al. 2010).

Implementing VRT management zones requires a means of identifying production zones that have sufficient scale to warrant differing input rates and also likely yield responses to a given input level. This chapter concentrates on tools that can be used to identify production zones. Growers now have access to a range of spatial tools including yield maps, normalised difference vegetation index (NDVI) and geophysical (EM, radiometrics) measurements that can be used to “zone” paddocks as the basis for prescription maps. The usefulness of these datasets depends on the accessibility, quality of the information (i.e. degree of correlation with grain yield or soil properties), ease of implementation and stability over time. Datasets that have all of the above qualities can be used as “base” maps from which VRT prescription maps are derived. In essence, VRT prescription maps are base maps that have been condensed to a number of meaningful management zones, each with a differing input rate.

This section reviews the uses of yield maps, NDVI and geophysical surveys as base maps for the purposes of developing VRT prescription maps.

Yield maps

About 50% of growers in Western Australia (WA) currently have yield mapping capability. Yield maps are derived from harvesters that have been fitted with a flow-rate sensor and global positioning system (GPS). Flow rate is monitored every second and converted into grain yield (t/ha). Data is then stored onto a memory card that can be viewed and manipulated through industry specific software (e.g. Ag Leader – SMS, Case IH – AFS, John Deere – Apex, SST Toolbox). The key advantages of using yield maps are their accessibility, high data quality and direct relationship to crop yields. The disadvantage is that growers or their consultants will require data processing skills and versions of the software that allow yield maps to be converted into prescription maps. Advanced software versions can convert individual yield maps into a normalised multi-year map for a given paddock. The normalising process allows yields from differing crops to be directly comparable on the same yield scale. The method for normalising crop yields is presented elsewhere (Bramley 2005).

A prescription map can be generated directly from an individual yield map or the normalised multi-year yield map. The prescription map often has no more than three to four zones, each representing a different application rate. Rate controllers vary application rates according to the seeder or spreader’s location within the prescription map.

Often the biggest limitation of using yield maps is their lack of “stability” between seasons. This is illustrated for a paddock at Esperance where high and low yielding areas “flip-flop” between crops and seasons (Figure 6.1a–d). In this case, the multi-year averaged yield map (Figure 6.1e) and the derived prescription map (Figure 6.1f) do not adequately represent the fertiliser needs of crops in each zone in all years.

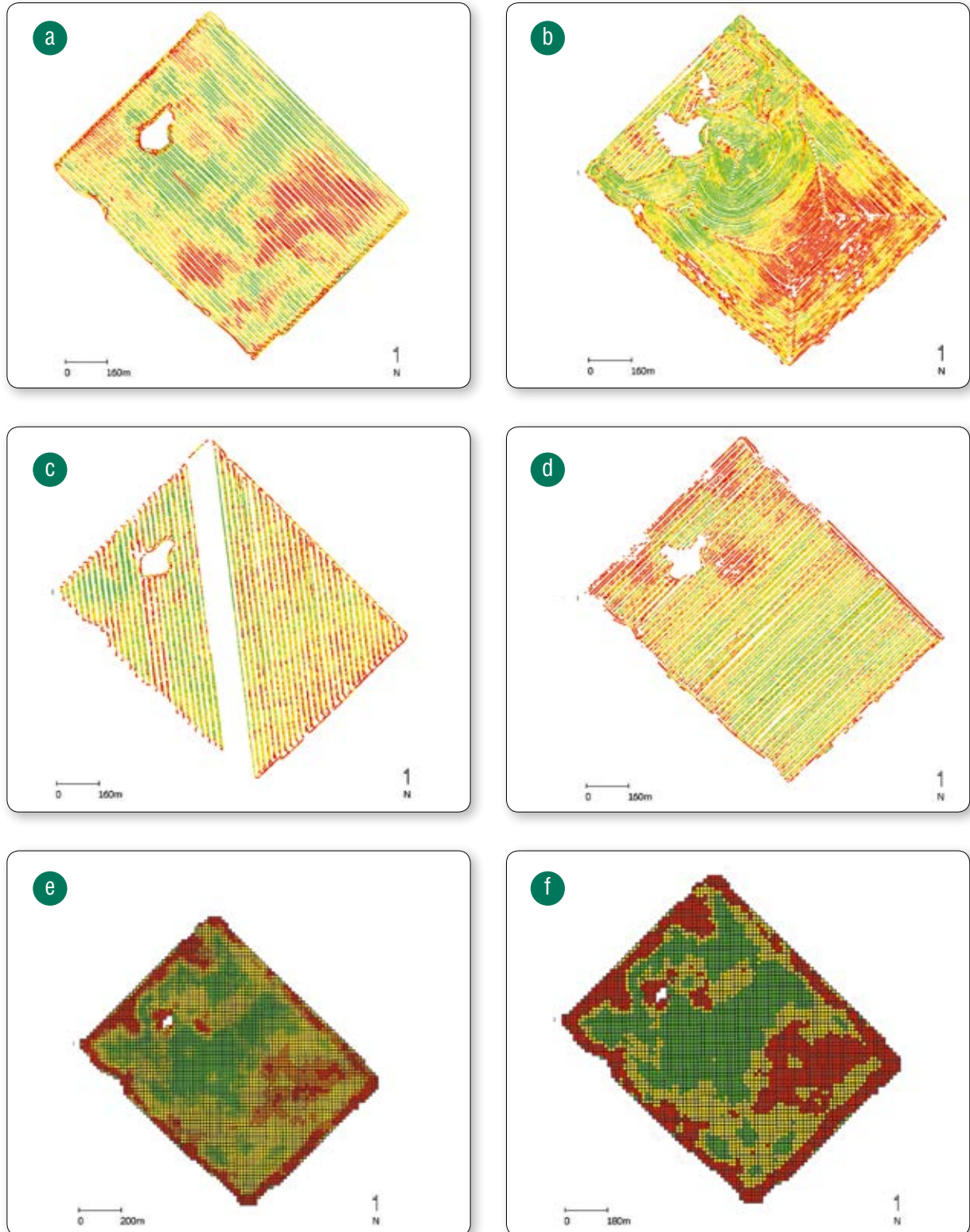


Figure 6.1 Yield maps for (a) wheat 2005, (b) lupin 2006, (c) canola 2007, (d) wheat 2008, (e) normalised yield map, and (f) prescription P map based on normalised yield map (Esperance sandplain).

An alternative strategy is to accept the year-to-year variability and use the previous year's yield map as a base map for nutrient replacement for the following year. This has many merits, as it does not try to constrain the seasonal variability. Replacement theory assumes that a tonne of grain exported from a paddock will contain a known quantity of nutrients (Table 6.1). Hence, using yield maps for fertiliser replacement produces a flexible (instead of a fixed) VRT prescription map. Reprocessing yield maps can, however, be time consuming. Furthermore, replacement strategies will only work where there is adequate fertility to cover nutrient requirements in areas that have flip-flopped from low- to high-producing areas in consecutive seasons. Nutrient replacement VRT strategies are mainly used for fertilisers applied at seeding i.e. Phosphorus (P), Potassium (K) and Sulphur (S).

Table 6.1 Nutrients (kg) required to replace those removed in each tonne of grain (Hyland 1995).

	N	P	K	S
Wheat/Barley	23	3	5	1.5
Canola	41	7	9	10.0
Lupin	53	3	8	2.3

Nutrient replacement tends not to be an appropriate strategy for nitrogen. The N removed in grain comes from three main sources: (1) the mineralisation of organic matter, (2) nitrogen fixation, and (3) applied fertiliser. Replacing N removed in grain through fertiliser alone would result in the over-application of N.

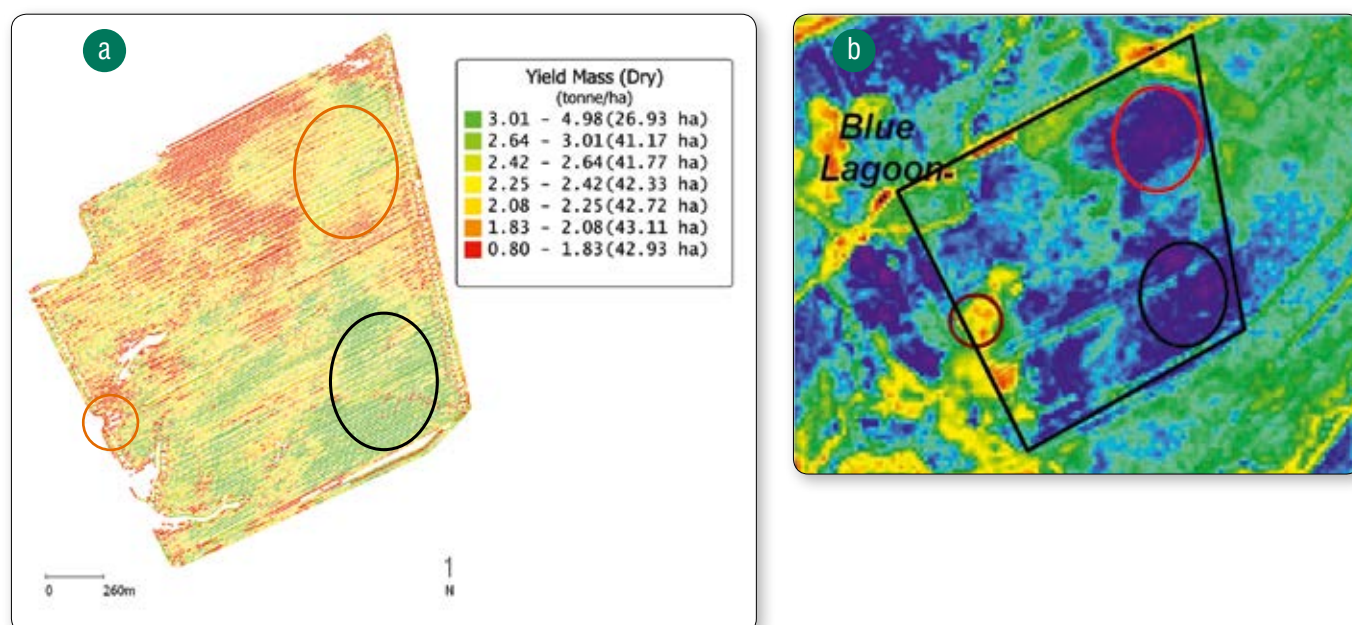
NDVI and greenness indices

Normalised difference vegetation index (NDVI) is calculated using reflected near-infrared (NIR) and red light to assess the chlorophyll density or greenness of plants. Plants that are healthy absorb red light and reflect NIR. Data is mainly collected by satellites (Landsat™, Spot), and ground-based units mounted on machinery. Satellite data is collected every 16 days and has a resolution of 15–30sqm per pixel. NDVI gives a snapshot of crop performance at any point in time. Specialised knowledge, access to data and computing skills are required to convert a satellite NDVI map into a prescription map. Consequently, satellite NDVI data and base maps are almost solely supplied by consultants whereas the tractor-mounted systems allow growers to collect, interpret and vary application rates simultaneously.

NDVI is mainly used as an “in season” tactical tool, particularly for determining application rates for nitrogen mid-season. The advent of GreenSeeker™ and CropSpec™ technology allows the continuous assessment of NDVI and can be linked to rate controllers in spreaders (urea) and sprayers (liquid N products) for “real time” assessment and application. While the science behind this technology is well understood, there has been little testing of the cost effectiveness of these systems.

In many instances, yield and greenness just before flowering are highly correlated. However, NDVI can be unstable over time, may require consultants to use the data and is limited by crop type. For instance, paddocks that have crops that are not green (i.e. canola in flower) cannot be readily interpreted.

The combination of NDVI and yield has been used as a diagnostic for subsoil constraints (Robertson et al. 2007). Areas that show high NDVI at anthesis (flowering) and low yield suggest that the crop has run out of water during grain filling. This may be a result of restricted root growth or low plant available water storage capacity of the soil. An example of how yield maps and NDVI can be used to diagnose soil limitations is given in Figure 6.2. At present, very few farmers (11%) use or have used NDVI as a base map or diagnostic tool (Robertson et al. 2011).



Yield	NDVI	Diagnosis
Low	Low	Major constraint, salinity, waterlogging
Low	High	Root zone limitations, acidity, compaction, boron, PAWC
High	Low	Surface issues, establishment, repellence
High	High	No constraint

Figure 6.2 Using a yield map (a) and NDVI (Z40–50) (b) to identify soil and agronomic constraints. The circles represent areas where there are major constraints (small red circle), root zone limitation (large red circle), no constraint (black circle). The paddock is on mallee soils in Cascade, Esperance.

Geophysics

The theory of electromagnetic induction (EM) and gamma radiation surveys are reviewed in Chapter 3 and other sections of this Bulletin. Based on these reviews, soil properties that affect EM and gamma radiometrics are summarised in Table 6.2. Consultants who collect, process and interpret the data provide geophysical surveys. Surveys are generally conducted during the summer or autumn period where moisture variation is least. Surveys produce datasets with a relatively high number of points. Line spacing widths of 30m will produce about 50–70 data points per hectare. The key advantage of geophysical surveys is that they are stable over time (Llewellyn 2008).

Table 6.2 Geophysical technique, inferred soil property and reference

Geophysical technique	Inferred soil property	Reference
Electromagnetic induction (EM)	Salinity/Sodicity Depth to clay Soil texture Soil water Production zones Soil pH	Rhoades et al. 1989 Knight (pers. comm.) Pracilio et al. 2006 Corwin and Lesch 2003 D'Emden et al. 2010
Gamma radiometrics	Soil mineralogy Soil K from gamma K Gravel from gamma Th and K Bedrock from Total Count Production Zones	Taylor et al. 2002 Wong and Harper 1999 Taylor et al. 2002
EM and gamma	Soil survey	Wong and Pilmer 2008

Electromagnetic Induction or EM

EM measures the conductivity of the soil, which is influenced by salt, water and clay content to a depth ranging from 0.5 to 1.5m, depending on whether the EM machine is in a horizontal or vertical orientation. The usefulness of the EM survey will depend on its relationship with soil properties that can be managed to increase crop yield. In southern WA, EM has been used as a surrogate for sodicity, salinity, depth to clay, plant available water content (PAWC) and acidity when adequately correlated with measured soil properties for each survey. Each of these factors impacts upon crop yield.

Correlating EM with soil properties that affect crop production is essential in determining soil constraints and appropriate amelioration. Statistical methods that optimise soil-sampling designs and locate EM calibration sites within a paddock are available on the internet (e.g. ESAP-RSSD software program). Using this software, high correlations have been found between EM and mallee soil parameters that affect crop yields, including sodicity, salinity and boron in southern WA (Knight, pers. comm.). Based on these relationships, EM maps have been converted into VR gypsum application maps with the underlying premise that the higher the EM then the higher the required gypsum rate. The prescribed rates and zones are based on trade-offs between affordability, soil chemical properties and prior knowledge of how soils are likely to respond to gypsum. For mallee soils on the south coast, gypsum rates will vary from 0 to 5t/ha. Low rates will be applied to deep sands (>50cm) while the highest rates will be applied to soils where sodic clays are nearer to the surface. The similarity between EM and yield maps for a mallee soil is shown in Figure 6.3.

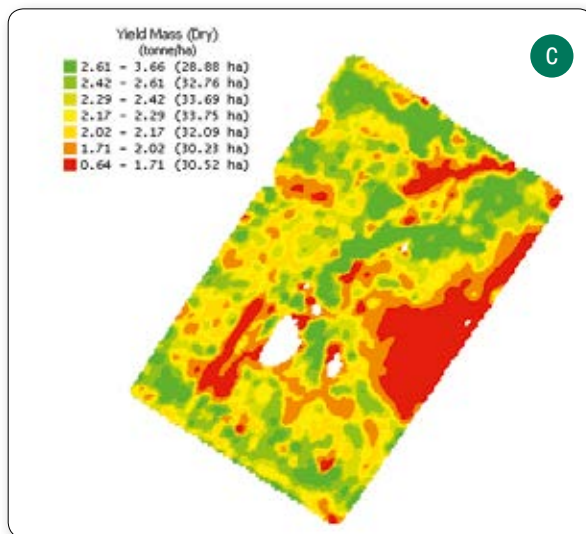
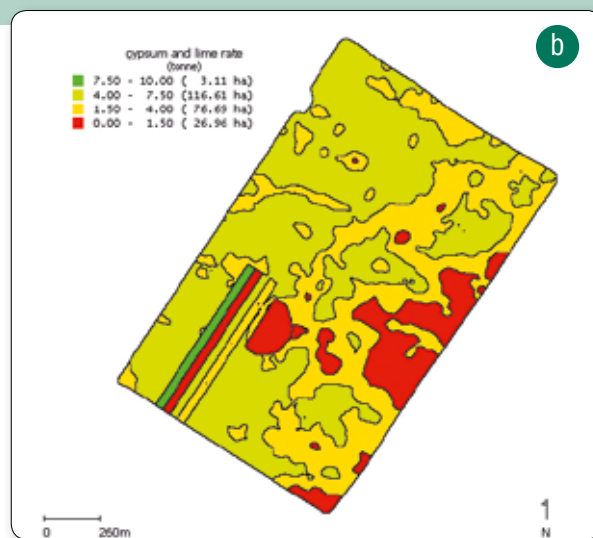
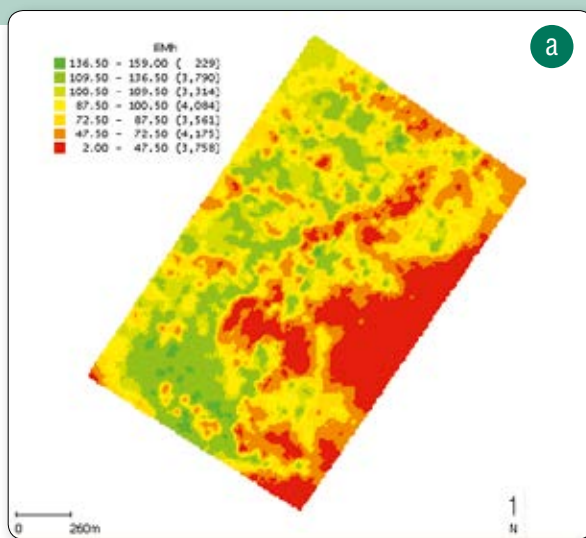


Figure 6.3 Interpolated EM map (3a), VRT gypsum map (3b) with embedded gypsum strip trial and yield map (3c). Data from PAA and Lloyd Burrell, North Ravensthorpe mallee.

Poorer correlations between EM and soil factors that affect yield have been found on sandplain soils, particularly those with deep (>80cm) sand and gravel layers. Both sand and gravel are relatively non-conductive and therefore give very low EM readings. In sandplain soils, EM will be mainly influenced by depth to clay, the presence of perched water tables and salinity. This is illustrated in Figure 6.4, which shows an EM and yield map for a deep sand and gravel paddock. The only feature that is apparent in the EM map is the perched aquifer.

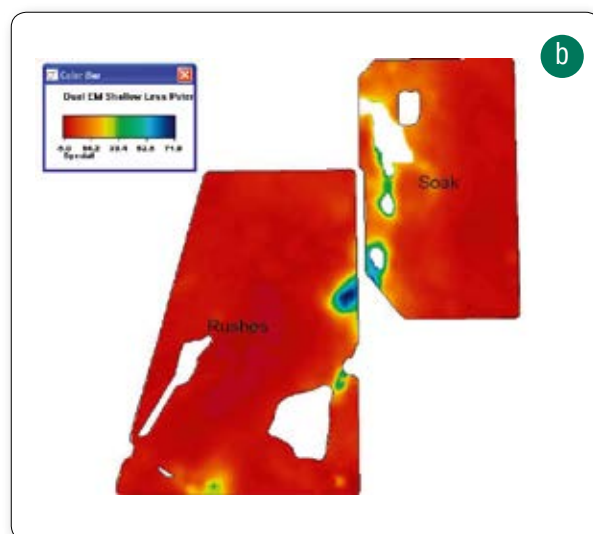
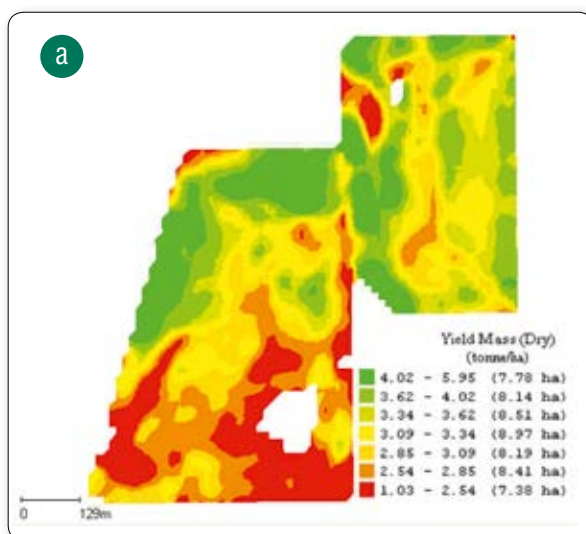


Figure 6.4 Interpolated yield (4a) and EM map (4b) for a paddock with deep sands and gravels at Gibson. The high EM readings are associated with a perched aquifer.

One application of EM that has been used on sandplain soils has been mapping depth to clay. This has been used to identify soils suitable or unsuitable for delving. Delving tines bring subsoil clay to the surface which, when incorporated, reduces water repellence and wind erosion. Where clay is deeper than 50cm, clay is dug from a pit and spread across the paddock using a carry grader at almost double the cost of delving. Hence, knowing the depth to clay can result in considerable savings in a claying operation where the grower has the option to delve.

While in statistical terms the relationship between EMh and depth to clay is highly correlated, in practical terms EMh ranges from 2–25 at the critical depth of 50cm. A useful approach to interpreting and using the relationship (Figure 6.5a) is to define “rules of thumb” based on probability. In the above case, there is a 77% chance that EMh values greater than 10 will have clay within 50cm of the surface.

Because EM is correlated with depth to clay, it is not surprising that relationships exist between EM and PAWC. Clay holds two to three times more available water than sands and is therefore a key determinant of PAWC. The relationship presented (Figure 6.5b) accounts for only 42% of the variation in PAWC and hence such relationships are at best a guide as opposed to a tool for discriminating between production zones.

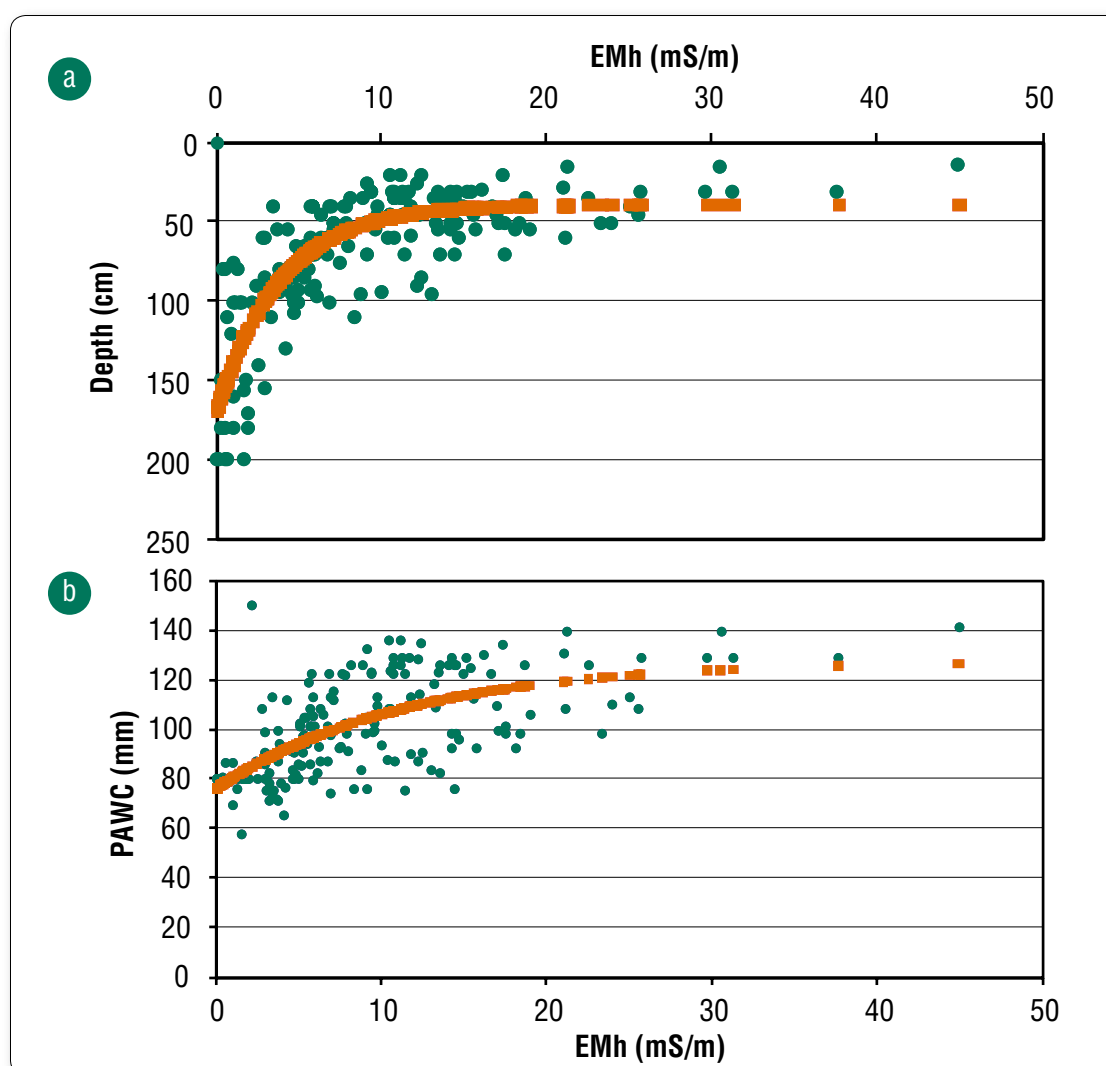


Figure 6.5 (a) Relationship between EM (mS/m) and depth to clay for sandplain soils. Depth to clay = $39.52 + 131.46(0.7701) \text{ EMh}$ - $r^2 = 0.86$, and (b) Relationship between EMh (mS/m) and plant available water content. $\text{PAWC} = 127.54 - 51.53 (0.917) \text{ EMh}$ - $r^2 = 0.42$. Dataset is based on 193 data points from five paddocks located from Gibson to Condingup.

One of the key benefits of EM is that it is stable over time (Llewellyn 2008). This is illustrated in Figure 6.6 where EM values were collected in the same paddock at different dates and by two different providers. Although the absolute values vary, which may be due to differences in soil water content at the time of surveying, the key features of the maps are essentially identical.

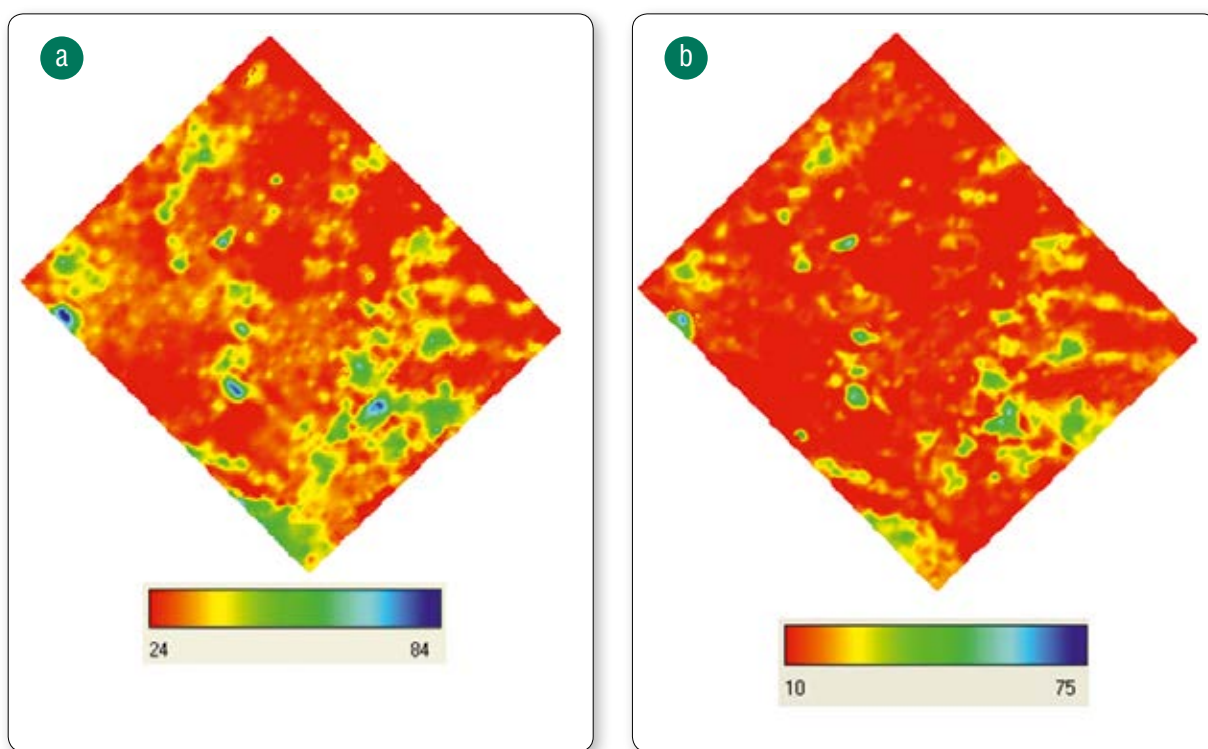


Figure 6.6 EM38 (mS/m) values for the same paddock taken at different times (a in 2007, b in 2010) by two different consulting companies illustrating the stability of the measurement. The paddock is a sandplain soil located north-east of Condingup in WA.

Gamma radiometrics and sandplain soils

Gamma radiometrics measures the natural emission of radioactive isotopes and daughter radionuclides of uranium (^{238}U), potassium (^{40}K), and thorium (^{232}Th) to depths ranging from 10–30cm (see Chapter 6 “Defining production zones from yield maps, NDVI and geophysical measurements” for details). The combined count of detected gamma rays is measured as the total count (TC counts/sec). Because differing soil minerals contain varying levels of these isotopes, emissions have been used to discriminate between soils with differing mineralogical properties (i.e. rock, gravel, clay), and profile development processes (i.e. drainage line). Generally, high radiometric counts are found where there is clay, rock or gravel close to the surface. Low counts occur on deep sands that have been highly leached over time.

Airborne radiometrics have been flown over the Lake Warden catchment in Esperance. The ternary image (Figure 6.7) for the catchment shows coloured combinations of the isotopes of K (red), U (green) and Th (blue). The image highlights the differences in soil properties between the Torradup (coastal – red), sandplain (central hinterland – black) and the mallee (northern hinterland – red) land systems. The black for the sandplain indicates very little gamma radiation while the pink in the mallee is linked to shallow duplex soils where clay is close to the surface. Conversely, the pink/red on the coastal fringe is related to gamma K sources associated with marine-derived feldspar clays preserved in alkaline environments

(Galloway, pers. comm.). Gravel soils are shown in the sandplain as light blue, whereas bedrock highs are white, indicating high levels of the three radioisotopes. Hence, at a broad scale, airborne radiometrics is influenced by mineralogy, which is a function of the parent material and soil development processes.

The utility of airborne gamma radiometrics is still being developed. Its main use has been to define land systems, bedrock highs, gravels and drainage lines. However, the large footprint (40m x 80m) and limited delineation of soil properties below a depth of 10cm limits its application at a paddock level.

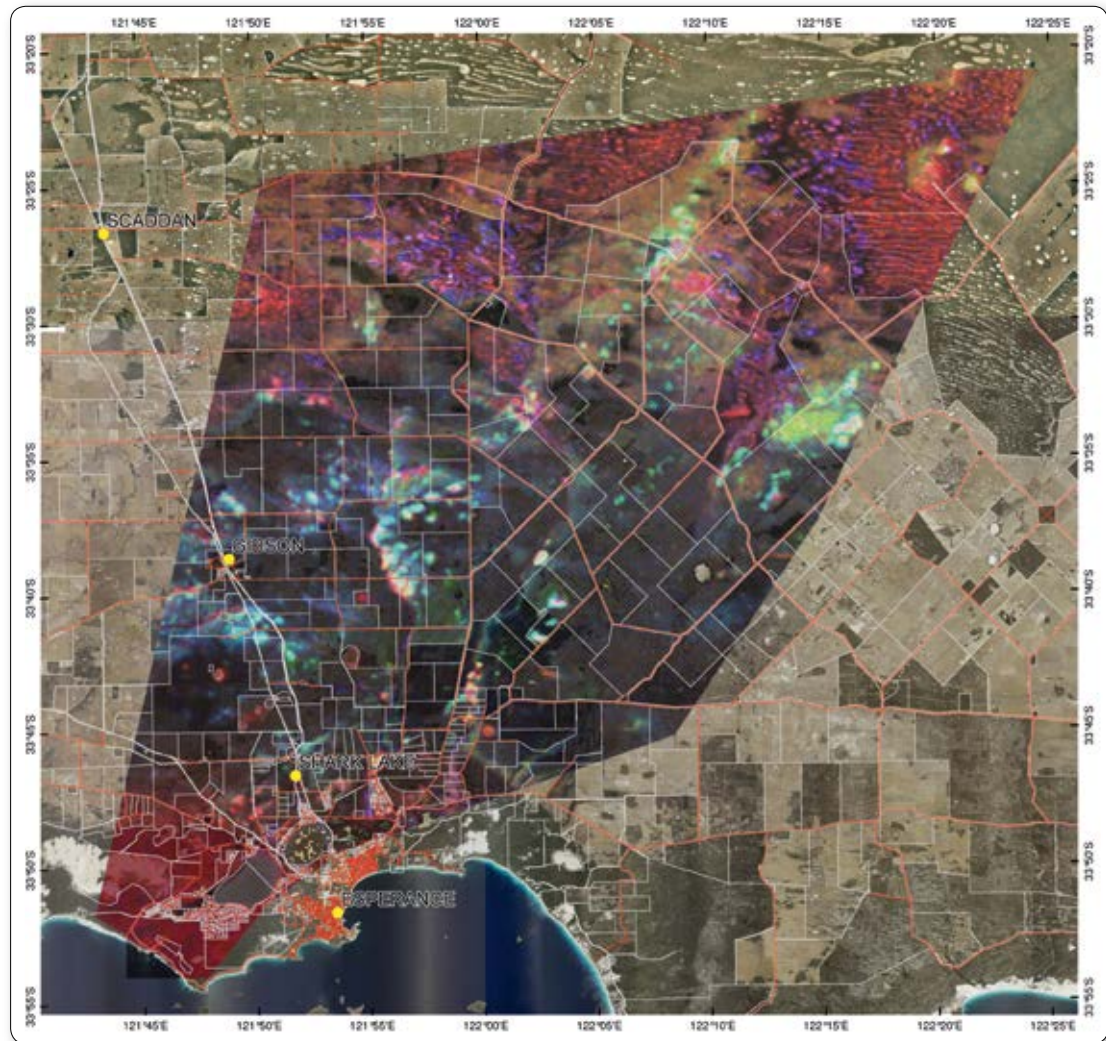


Figure 6.7 Ternary map of the Lake Warden catchment, Esperance. K (red), U (green) and Th (blue).

As opposed to airborne surveys, ground-based gamma radiometrics have a small footprint of 1m² and measure soil properties to 40cm depth within the soil profile. Surface soil properties dominate ground-based radiometrics with the gamma emission halved with every 10–11cm depth increment from the surface (Cook et al. 1996, Wong et al. 2009). Consequently, higher correlations between gamma Th and gravel and gamma K and feldspar clays have been found between ground-based as opposed to airborne surveys (Taylor et al. 2002). So far, the main application of ground-based gamma radiometrics has been to relate gamma K to Colwell K, gamma Th to gravels, and to use thresholds of EM and gamma total count (TC) to define soil production parameters.

Several authors have found gamma K and Colwell K to be highly correlated when measured at sites with a wide range of soils of differing textures, mineralogy and parent materials (Wong and Harper 1999, Taylor et al. 2002, Pracilio et al. 2006). However, over the range of values that K is likely to be deficient (i.e. <100 ppm K) the relationship between gamma K and Colwell K has been found to be poor. Gamma K accounted for only 5% of the variation in Colwell K in a survey conducted at Jerramungup (Wong and Harper 1999). The reason for the poor relationships is that gamma K does not discriminate between available and unavailable forms of K (Cook et al. 1996). On the Esperance sandplain, gamma K explained 23% of the variation in Colwell K (Figure 6.8). Part of the variation is due to the commercial use of potassium fertilisers, which increase Colwell K levels without emitting gamma K. The results do show, however, that almost 70% of the values less than 0.2% gamma K have a Colwell K less than 50ppm.

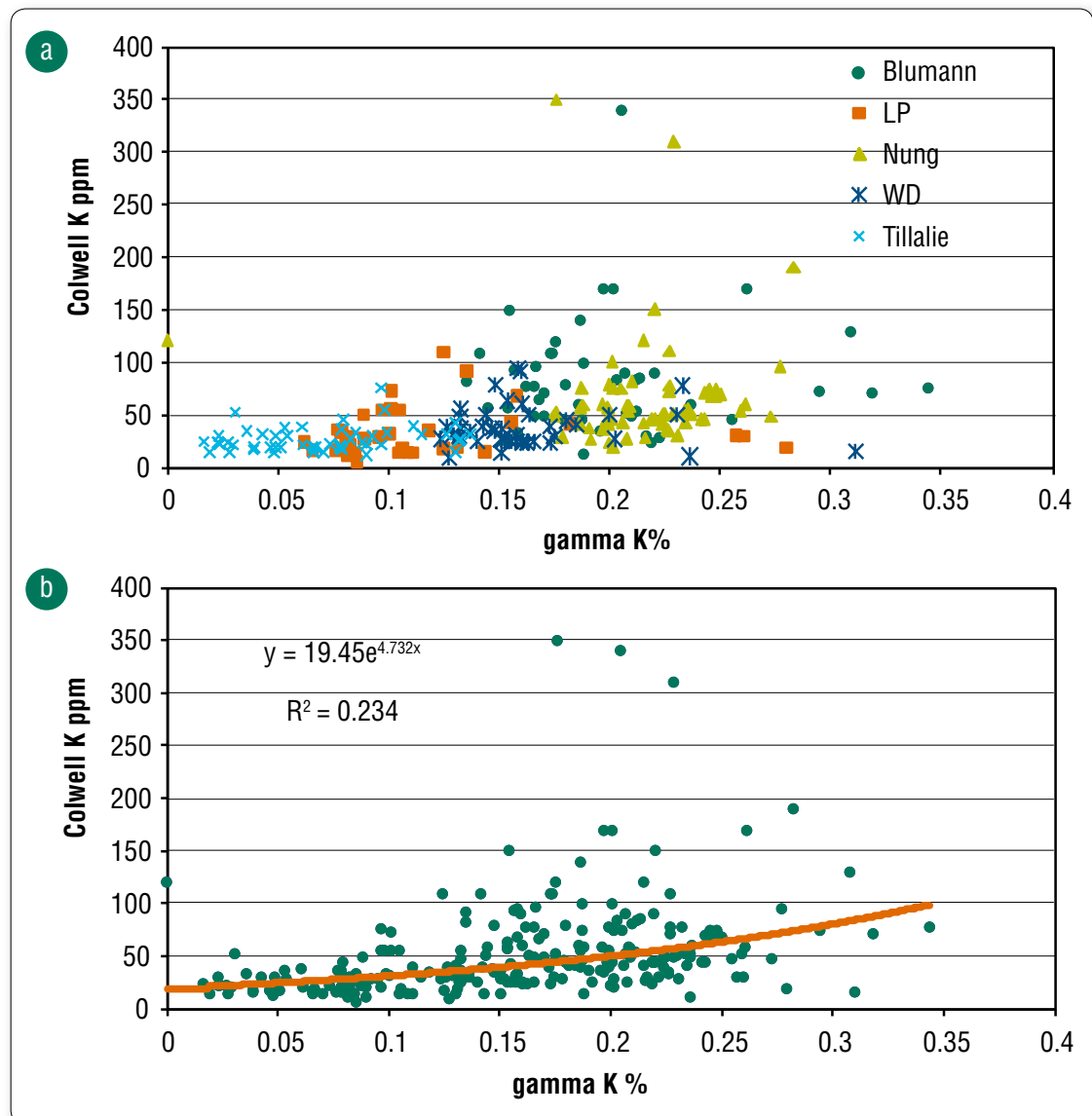


Figure 6.8 Relationship between gamma K percentage and Colwell K ppm (0–10cm) for sandplain soils showing (a) individual paddocks and (b) combined data. Soils were collected from five paddocks located at Gibson, Neridup (2) and Condingup (2).

As shown in the ternary image (Figure 6.7), Th is often an indicator of ironstone gravels. Associations between gravels and increasing U, Th and decreasing K have been found near Wyalkatchem, resulting in the Th/K ratio explaining 56% of the variation in gravel in the 0–10cm layer (Taylor et al. 2002). This compares to only 15% of the variation accounted for using gamma Th alone in both air and ground surveys. Associations between gravel index (depth weighted average 0–30cm) and thorium for the Esperance sandplain are given in Figure 6.9. While for each individual site there is a positive correlation between gamma Th and the ratio of Th/K, when data from all sites is used, the relationships are poor. This suggests that in the case of thorium and gravel, the relationship will need to be defined on a paddock-by-paddock basis.

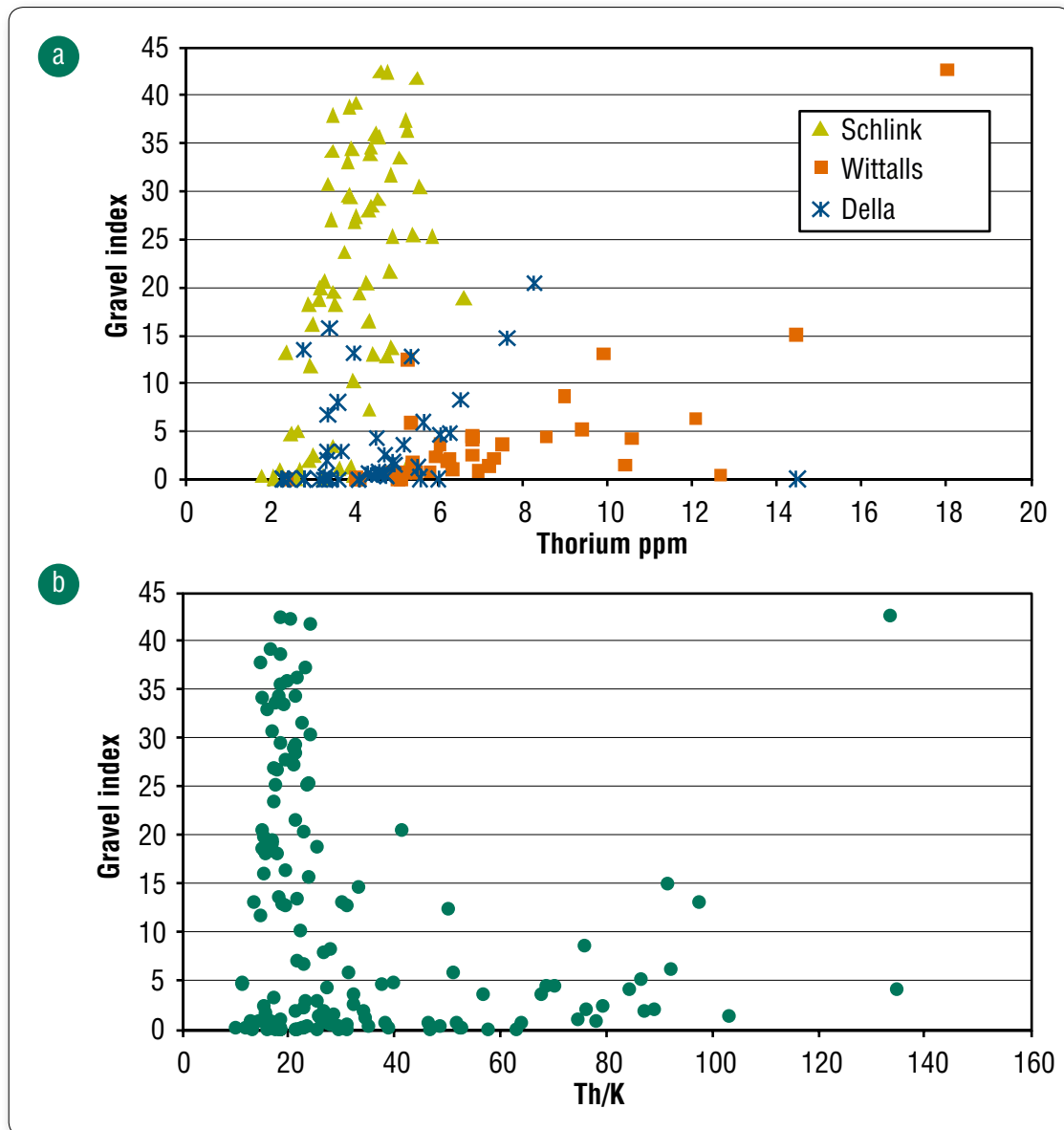


Figure 6.9 Relationship between (a) thorium and gravel index and (b) Th/K ratio and gravel index for three paddocks on the Esperance sandplain. Gravel index is depth weighted average based on gamma emissions halving with 10cm depth increments. Gravel Index = gravel % (0–10cm)*0.5 + gravel % (10–20cm)*0.25 + gravel % (20–30cm)*0.125.

Combinations of EM and gamma radiometrics

Combinations of EM and gamma can give clues to soil properties or the type of soil present. The diagnostic will have similar features to that presented in Table 6.3.

Classifying soils according to their EM and gamma readings has been achieved near Buntine using EM (<15 and >20mS/m) and gamma K (<40, >80 counts/sec) as diagnostics for good sands, poor sands, gravel and clay soil types (Wong and Pilmer 2008, Wong et al. 2010).

Table 6.3 Prediction of soil properties based on EM and gamma values

EM	Total count	Soil property
Low	Low	Deep sand
Low	High	Gravel, Bedrock
Low	Medium	Sandy loam
High	Low	Saline sand, Seep
High	High	Clay

In many respects, the combination of EM and gamma is a more powerful tool for defining and mapping soil variation. Much work still needs to be done to determine how useful this is in defining VRT production zones. Part of any further work would be to define at a paddock and regional level what constitutes high, medium and low values in terms of total count and EM.

Identifying production zones using gamma on sandplain soils

In theory, the lack of mineralogical difference among sandplain soils will limit the usefulness of gamma radiometrics. To test this, datasets (yield, EM and gamma) from three paddocks were interpolated to the same grid. The yield data was normalised and divided into two groups, consistently low yielding (20% or more below the mean) and consistently high yielding (more than 20% above the mean) over several seasons. Corresponding EM and gamma values were extracted for the low and high yielding groups. Normal distributions of EM, TC, K, U and Th for the whole paddock, high and low yielding zones were calculated.

Site 1 Gibson: deep sand and gravel

The paddock at Gibson is on sloping country with predominantly deep sands and sporadic gravel layers. The gravel soils at this site are generally associated with higher production. Frequency distributions for EM and gamma radiometrics for the Gibson site are given in Figure 6.10. EM was unable to discriminate between the high and low production areas in this paddock with the frequency distributions for the high- and low-production areas being almost identical. Given that EM cannot discriminate between sands and gravels, this finding is to be expected.

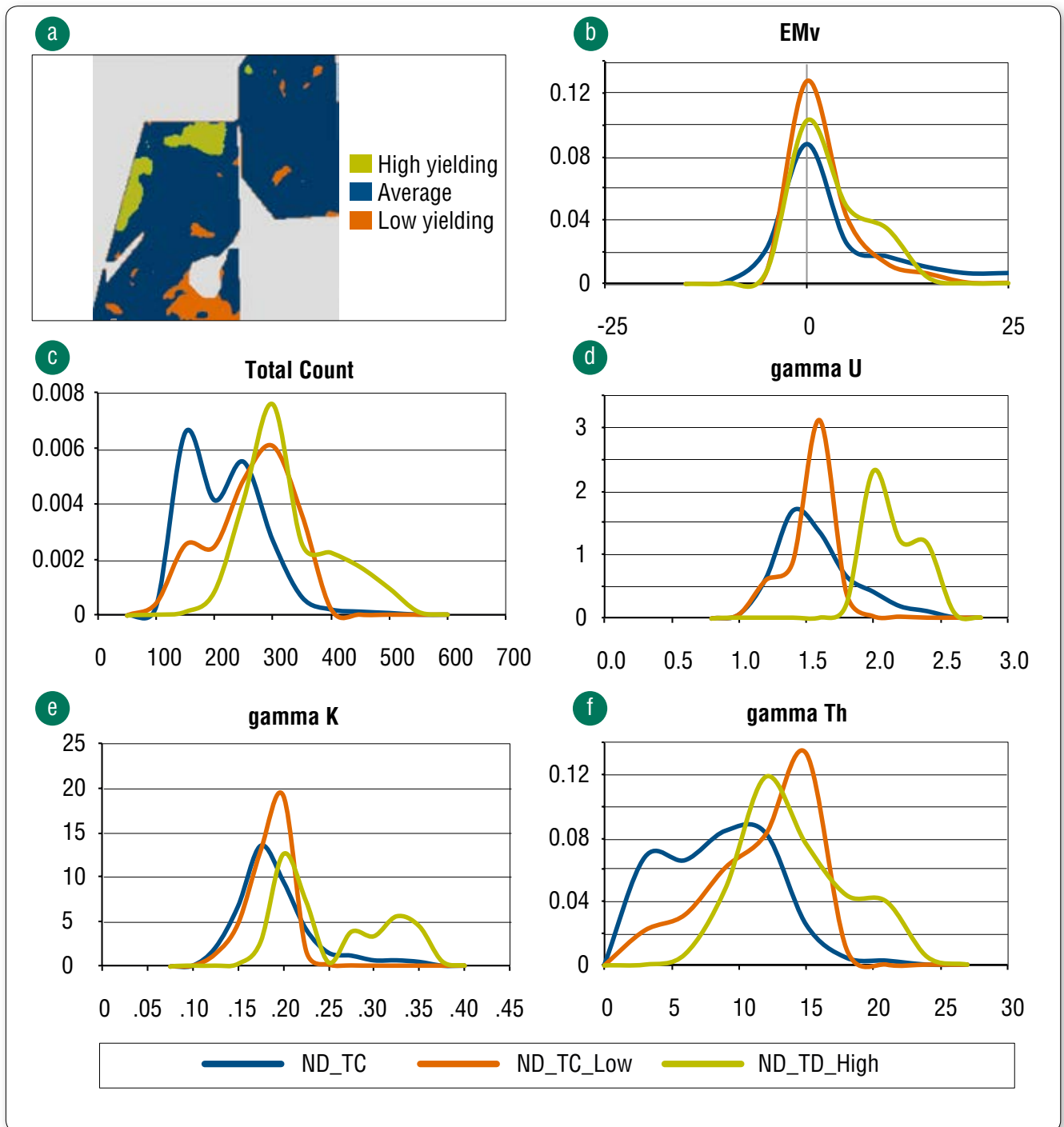


Figure 6.10 Paddock location (a) and areas of high and low production. EM (b) and gamma [TC (c), U (d), K (e), Th (f)] frequency distributions for consistently high- and low-production sites. The greater the lateral separation between normal distribution lines, the greater the potential for geophysics to discriminate between production zones. Paddock located at Gibson.

Total count and gamma thorium had very similar frequency distributions showing that higher TC and Th were generally associated with higher production sites. However, there is considerable overlap between the TC and Th frequency distributions for high- and low-production sites. This suggests that using TC or Th alone will not be enough to define production zones. Gamma U (Figure 6.9d) and to a lesser extent gamma K (Figure 6.9e) were better at discriminating between high- and low-production sites. Overall, the higher the gamma K, U, and Th value, the higher the incidence of increased yields. It is interesting to note that thorium, which is usually associated with gravels, was no better than TC in discriminating between the production zones at this site.

Site 2 Neridup: deep sand, gravel and clay

The paddock at Neridup is about 5km from the Gibson site. The paddock is mainly deep sand with areas of gravels and clays. The paddock has been clayed to ameliorate water repellence. Of the geophysical measurements, EM (Figure 6.11b) and gamma K (Figure 6.11e) were the only measurements that provided useful means for discriminating between the high- and low-production sites. All other measurements (TC, U, Th) had considerable overlap in their frequency distributions.

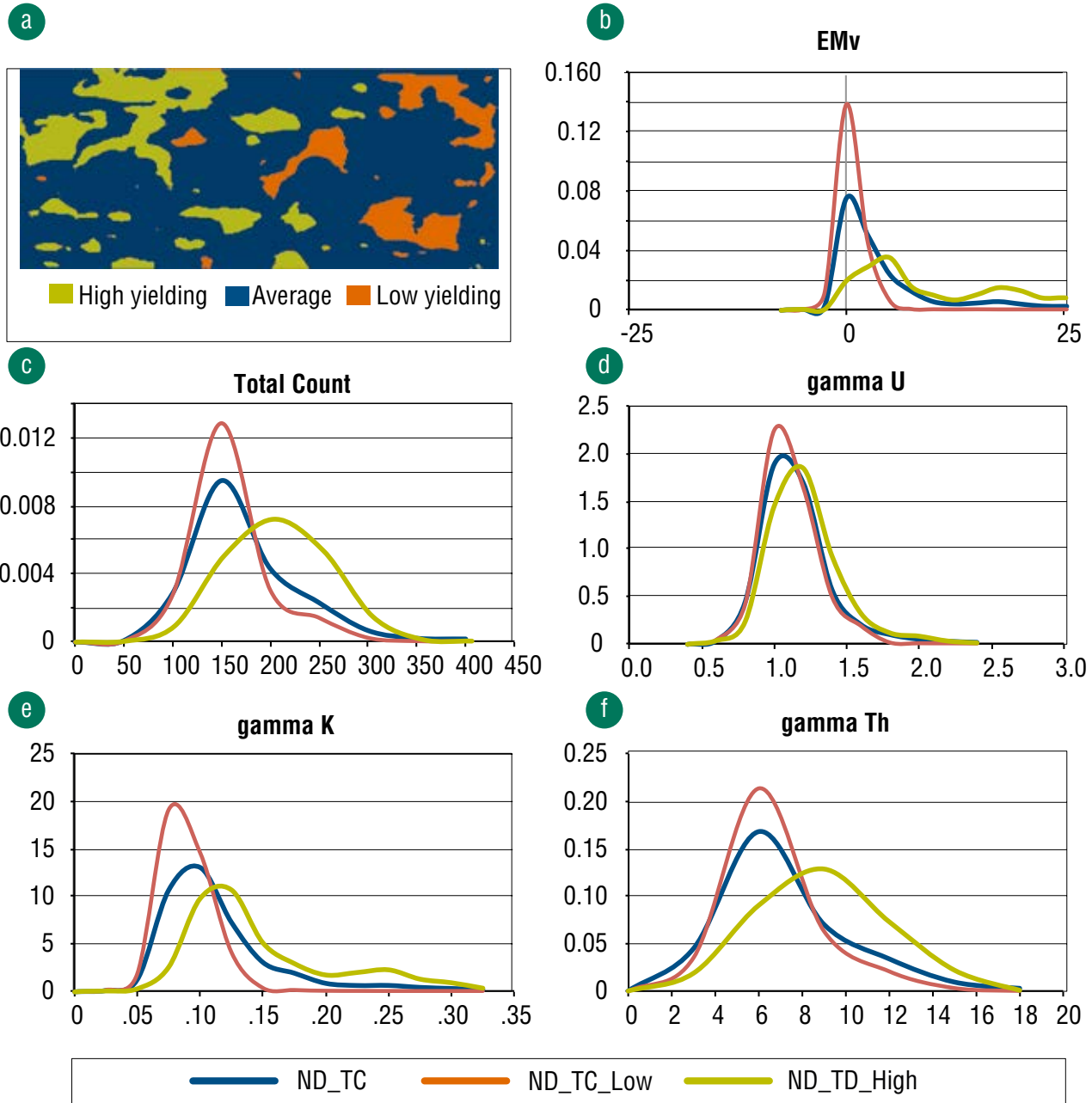


Figure 6.11 Paddock location (a) and areas of high and low production. EM (b) and gamma [(TC) (c), U (d), K (e), Th (f)] frequency distributions for consistently high (green) and low (red) yielding sites. The greater the lateral separation between normal distribution lines, the greater the potential for geophysics to discriminate between production zones. Paddock located at Neridup.

While the results from both sites show that geophysics can discriminate between high- and low-yielding sites, the utility of the system for zoning is compromised by the lack of consistency between the geophysical measurements as surrogates for productivity.

The results from the two sites highlight the variability in soil properties that affect yield. When averaged over all the sites, it is clear that soils with higher emissions of gamma radiation and EM generally have higher yields (Table 6.4). The values presented in Table 6.4 are at best a guide to interpreting the likely productivity of a site based on EM and gamma radiometrics collected on sandplain sites.

Table 6.4 A guide to interpreting sandplain site productivity based on EM and gamma radiometrics

	Crop yields		
	High	Low	Mean
EMv	24.08	12.49	19.4
EMh	9.68	4.65	9.58
TC cps	218.59	173.91	185.20
K%	0.27	0.22	0.24
U ppm	1.61	1.37	1.48
Th ppm	9.27	7.51	7.58
N_Yld1	1.32	0.60	1.00
N_Yld2	1.34	0.63	0.99

Note: Average EMv (Electromagnetic induction vertical mode), EMh (Electromagnetic induction horizontal mode) and gamma (Total Count, K, U, Th) values for high- and low-production sites on the Esperance sandplain. Yield data (N_Yld) has been normalised. Data collected from Gibson, Neridup, Condingup and Jerdacuttup.

Utility of yield maps, NDVI and geophysics

At the beginning of this section, the criteria for assessing the utility of geophysics were proposed for VRT. Based on the information presented above, an attempt has been made to define and assess each component (Table 6.5). In summary, yield maps have the advantage that they are data rich, are related to grain yield and can be readily accessed and transformed into VRT fertiliser prescription maps by growers. Their weakness is that there can be season-to-season variability, which makes yield maps unstable over time. This problem can be overcome by converting yield maps into fertiliser “replacement” prescription maps when using a nutrient replacement approach. Yield maps are best used for VRT fertiliser applications. NDVI and greenness indices are relatively unstable over time; however, they do give a “snapshot” of how a crop is performing. This can be useful when determining if and how much mid-season nitrogen needs to be applied. NDVI images are generally supplied and converted into VRT application maps by consultants. However, new generation “on the go” “cell density” sensors give the grower control over data collection and VRT application rates. This technology is still in its infancy and needs to be tested thoroughly.

EM is stable over time and tends to be highly correlated with soil properties that affect yield in landscapes where there is clay within 50cm of the surface (i.e. shallow duplex, sandplain, and most mallee soils). Conversely, EM is poorly correlated with yield where sands and gravels dominate within the root zone. EM mapping

is provided by consultants and is mainly used for VRT gypsum applications and delving operations. Gamma radiometrics is stable over time and readily differentiates between soils that have different mineralogy. Gamma is effectively limited to near surface (0–30cm) soil properties. Gamma is best used in landscapes with diverse mineralogy. The uses of gamma have not been explored fully.

On sandplain soils, the role of gamma radiometrics in differentiating between soil types and zones remains unclear. The two sites presented (Figure 6.10 and 6.11) showed that different measurements were required to discriminate between high- and low-production zones for each site. This makes the task of interpreting gamma radiometrics and EM on sandplain soils difficult, as it appears that any interpretation needs to be done paddock by paddock as opposed to universal thresholds applying to all sandplain soils. Perhaps these results are to be expected given that sandplain soils on the south coast have similar parent material and mineralogy, and have undergone the same soil-forming processes. This, combined with deep sands and the inherently low levels of gamma radiation, suggests that there may be insufficient gamma emissions to differentiate between production zones. What is clear is that further work needs to be done to assess the level of mineralogical diversity required for differentiation between soil types and production zones using gamma radiometrics.

Table 6.5 Criteria for assessing the utility of yield maps, NDVI and geophysics

	Yield map	NDVI/Greenness	EM	Radiometrics
Accessibility	Grower	Consultant/ Grower	Consultant	Consultant
Quality (data richness correlated with yield)	Excellent	Variable	Good – Shallow duplex Poor – deep sand or gravel	Good – dissected landscapes with differing soil-forming processes Poor – uniform landscapes with similar soil-forming processes
Implementation	Grower/ Consultant	Grower/ Consultant	Consultant	Consultant
Stability	Unstable to stable	Unstable	Very stable	Very stable
VRT uses	P,K,S replacement	“On the go” N	Gypsum, delving, fertiliser, lime?	K?, gravel, soil mapping

Finally, in order to adopt VRT, a grower must decide whether the variation in production within a paddock is large enough to warrant different input rates or whether such variation is beyond their control. Once this decision is made, the argument for VRT is that redirecting inputs from low to higher yielding zones will improve input efficiencies and reduce risk. The argument against this is that it is a “self fulfilling prophecy” and that we need to understand the limitations affecting yields more thoroughly before implementing VRT fertiliser programs — or the low yielding areas will always produce less. Both arguments have merit. It is for this reason that growers who adopt VRT need to embed test strips into their VRT prescription maps to confirm that the fertiliser prescription for a given zone is meeting crop requirements.

Potential uses for elevation models to understand WUE and how this could be used with other remotely sensed data

Nigel Metz, SEPWA

Digital elevation models (DEMs) have been used in agriculture for property planning and hydrology management for some time. The advent of higher accuracy GPS guidance signals means that there are now many implements passing over the paddock logging GPS elevation data. In the past, data of this sort was collected by specialist survey at a cost to the farmer. Now it has become a by-product of logged data from a seeding, spraying or harvest program often covering the whole farm.

Due to the cost of surveying, previous DEM data was often collected at wider swath widths during surveying. Creating a continuous surface of DEM from this point dataset warranted significant mathematic interpolation, which is common in DEM. Bishop and McBratney (2002) examined various methods of interpolation and concluded the TOPOGRID tool produced the most representative DEM of paddocks in a precision agriculture application. It is likely, however, that data collected from a seeding tractor at 18m swaths spacing significantly improves datasets and reduces the reliance on mathematical interpolation.

Previous DEMs for farm planning were based on landscape scale datasets with accuracy of $\pm 1\text{m}$, which also emphasised the mathematical aspects of DEM. It is now accepted that meaningful DEM at a paddock level requires datasets of less than $\pm 20\text{cm}$ accuracy (Bishop and McBratney 2002). With this in mind, only Real Time Kinematic GPS (RTK) signal is of sufficient accuracy for paddock-scale DEM. Typical accuracy for RTK signal is quoted by manufacturers as $\pm 2\text{cm}$; however, experimental experience has shown elevation accuracy to be more realistic at $\pm 5\text{cm}$ (Schmidt and Persson 2003).

The most obvious application of DEM is that of modelling lateral water flow across a paddock. The fact that DEM is constant (rarely alters unless there is significant earth works to a paddock) means that reliable prediction of water accumulation points in a paddock can help explain crop behaviour. In GIS platforms, this is modelled and is referred to as Topographic Wetness Index (TWI). Areas with low TWI values tend to be sloped whereas low-lying flat areas have higher TWI values. This modelling has been found to work well in areas with good relief and even soil types (Schmidt and Persson 2003).

Unfortunately, TWI assumes uniform horizontal and vertical water movement across the paddock. The usefulness of TWI needs to be tempered with understanding of the spatial variation of soil type as well as an individual season's rainfall conditions (Schmidt and Persson 2003). The use of EM surveying or other means to predict soil variations is suggested as a means to further refine TWI. Aspects such as water infiltration and soil water storage are closely related to soil texture and hence would affect the in-field reality compared to that of TWI modelling alone (Qin et al. 2009). From this work it appears an integration of soil mapping and DEM may have more meaningful outcomes than DEM alone.

An alternative to TWI modelling is MrVBF methodology (Gallant and Dowling 2003), in which relatively flat areas are identified in the landscape from DEMs. An advantage of this methodology is that it operates at a range of scales yet will display the overall results in a single multi-resolution image. For example, mid-slope flat areas are identified as well as the creek lines and valley floors. This has potential advantages over TWI as it will show where cold air may drain to in frost situations, or

where slow water flow rates can cause seasonal waterlogging. Being developed in a geomorphology context, the ability to potentially map sedimentary accumulation in the landscape may also be useful in interpretation of paddock soil types and hence crop variation.

There have also been various applications of DEMs in attempts to classify land management units. MacMillan et al. (2007) automated an interpretive concept to predict forest cover in Canada that was then later applied by Kryzanowski and Kutcher in 2010 to crops of the Great Plains of North America. This methodology outlined that soil moisture is a key variant in crop performance and its response to fertiliser. Topography (characterised from DEM) was a useful means to model water accumulation and crop performance; however, these relationships were noted as being inconsistent between seasons due to a host of interacting agronomic and seasonal factors. For example, the response to N was not significantly different when rainfall was optimal for crop growth; however, in dry situations, down-slope areas had a higher economic response than up-slope ridges.

Work in Germany (Reuter et al. 2005) also aimed to classify landform units based on DEM. Reuter noted that generally there were differences in crop yields of up to 0.7t/ha in relation to the localised topography. However, like the Canadian experience, there needed to be consideration of seasonal agronomic factors in determining the topographical impact on crop yield. This experience also correlates with Australian observations where yield maps have been noted to flip-flop depending on the seasonal conditions.

The background work on the topic can be summarised as:

- Topography is a key determinant of water accumulation and will affect crop yields and WUE; hence, DEM is useful information.
- DEM alone does not take into account variation in soil texture, cover and management and therefore simple water accumulation modelling (TWI) alone is unlikely to have widespread application.
- MrVBF may offer an opportunity to map frost risk and transient waterlogging at a paddock level as well as mapping sedimentary soils.
- Annual variation of rainfall and agronomic factors mean that the relationship of crop performance to topography varies between seasons. Management based on DEM will need to be seasonally specific and adaptable.
- High accuracy elevation data will more than likely be integrated with other spatial survey data (e.g. EM, gamma and yield) as a means to diagnose soil landscape zones and potential drivers of yield variability.

Areas of interest that have been highlighted

- Crop yields on the south coast: could the seasonal topographic interaction help understand the flip-flopping of yield?
- Interaction between soil mapping and DEM: Can we map waterlogging?
- Seasonal management: Is it possible to model different approaches?
- Frost risk and DEM: Can we access frost yield maps and see if we can correlate spatial datasets?
- Water accumulation modelling compared with MrVBF: What are the differences and how could we use each of these?
- Frost risk on mallee soils: what impact does the interaction of soil type and elevation have on frost risk?
- Sandy soils: Can we use EM values and elevation to find and map sandy soils that are at risk of frost?

Gypsum application theory and trial demonstrations

David Hall and Jeremy Lemon, DAFWA

Role of gypsum

Gypsum is a soil conditioner and fertiliser. In Australia, gypsum is predominantly used as a soil conditioner to improve water infiltration and drainage in dispersive sodic clay soils. A secondary role of gypsum in Australian agriculture is as a calcium (Ca) and sulphur (S) fertiliser. Both Ca and S are essential nutrients; however, most S fertilisers (elemental sulphur, ammonium sulphate) acidify soils. Gypsum is non-acidifying, making it highly suitable for amending sulphur deficiencies in acidic soils. It is frequently used as an S fertiliser for canola on the south coast of Western Australia (WA). Historically, gypsum has been applied regularly as a constituent of single superphosphate (10.5% S as gypsum) but high analysis fertilisers commonly used for cropping contain little or no S. Elsewhere, gypsum has been used to amend aluminium toxicity associated with acidic subsoils (Sumner 1993, McLay et al. 1994a,b). These multiple uses of gypsum are highly relevant to the south coast of WA where sodicity, subsoil acidity and nutrient limitations have the potential to restrict crop production.

This chapter documents the properties and uses of gypsum in agriculture. The focus will be on the south coast of WA. In particular, we will concentrate on the use of gypsum to overcome key limitations to crop production including sodicity, transient salinity and boron toxicity that occur mainly in the lower rainfall mallee region as well as nutrient limitations and subsoil aluminium toxicity that are found across the higher rainfall sandplain.

Nature, source and properties of gypsum

Gypsum is the hydrated form of the salt calcium sulphate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). It occurs naturally in arid areas often in association with past or present marine activity. Gypsum is also a by-product of phosphoric acid manufacture (phospho-gypsum). Both natural and by-product gypsum are widely used in agriculture.

In southern WA, agricultural gypsum is mainly derived from marine aerosols, Aeolian sediments and, to a lesser extent, marine sediments and bedrock. The shallow saline lake systems across the south coast often contain gypsum either in the lakebed floor or as windblown deposits adjacent to the lakes (McArthur et al. 1989).

Natural gypsum deposits can contain a number of impurities i.e. salt (NaCl) that adversely affect crop production. Gypsum should have a chloride content less than one per cent. Analyses of gypsum deposits in the Esperance region are given in Appendix 8A. Purity of the gypsum ranges from 84–88%. This compares with most phospho-gypsum sources, which range from 80–100% gypsum (Abbott and McKenzie 1986).

Apart from purity, the quality of gypsum is assessed on its fineness, which is a surrogate for solubility. Pure gypsum has a solubility in water of 2.1g/litre which is almost 200 times more soluble than pure lime, but 150 times less soluble than NaCl (Alward and Findlay 1977). The solubility of gypsum can be variable and is related to the surface area. Mined gypsums can differ in their crystalline structure and

hence their surface area and particle size. Most mined gypsum will have 50–80% of particles <2 mm compared to phospho-gypsum with 80–100% (Abbott and McKenzie 1986). No data on particle size is available for local gypsum sources.

Uses of gypsum

Amelioration of sodic clay soils (topsoil and subsoils)

On the south coast of WA, gypsum is most commonly used to improve the structure and stability of dispersive clay soils. When dispersive aggregates are inundated, they separate into their sand, silt and clay fractions. Dispersed clay fills and blocks soil pores resulting in impervious layers. Dispersion is diagnosed by the cloudy appearance of suspended clay particles when aggregates are immersed in rainwater. The degree of cloudiness and separation of primary particles from natural and remoulded aggregates is used to rate dispersion and gypsum responsiveness of a soil (Emerson 2000).

Dispersion is related to the types of cations (positively charged counter ions) present and salinity. Clay particles are bound by electrostatic forces. Clay surfaces are negatively charged and are balanced with cations that form loose electrostatic bonds at the soil–water interface. This interface, consisting of negatively charged clay surfaces and adsorbed cations, is also known as the diffuse double layer (DDL) illustrated in Figure 8.1. Within the double layer, cations are not only attracted by the clay surface but also repel one another. The net attraction–repulsion forces determine how tightly cations are bound to the clay surface. The order of electrostatic bonding strength within the DDL is $H^+ > Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ > Na^+$ (Brady 1974, Rengasamy 1984).

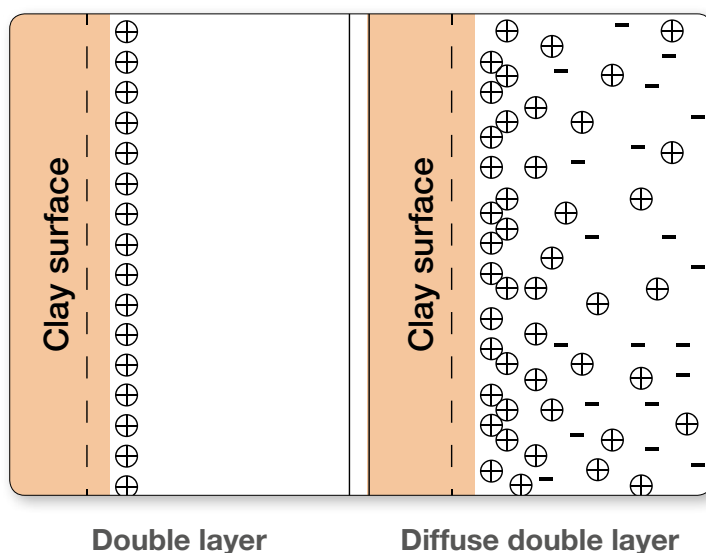


Figure 8.1 Representation of diffuse double layer at the clay surface to soil water interface. Source: http://www.landfood.ubc.ca/soil200/images/14images/14_DL&DDL.jpg (19/1/12).

Soils dominated by the cations with strong bonds have a narrow DDL. The wider the DDL, the weaker the electrostatic bonds between the clay particles. Furthermore, when two clay plates come in contact there will be two layers of cations. Where the ions are concentrated midway between the two plates within the DDL, the resulting ionic concentration is sufficient to create a higher osmotic pressure which draws surrounding water between the clay plates resulting in dispersion (Aust. Academy of Science 1999). Consequently:

- Strongly bound cations (i.e. Al^{3+} , Ca^{2+}) reduce dispersion whereas the weakly bound cations (i.e. Mg^{2+} , Na^+) increase dispersion.
- Weakly bound cations (i.e. Na^+) will be replaced by strongly bound cations (i.e. Ca^{2+}) — the cation replacement effect.
- If the surrounding soil water has a high concentration of salts (i.e. electrolytes), the osmotic forces will compress the DDL thus reducing dispersion — the electrolyte effect.

From this discussion, it is evident that increasing exchangeable calcium in sodic soils will reduce dispersion by displacing sodium ions. If the source of exchangeable calcium also increases the electrolyte concentration, then dispersion will be further reduced. It is for these reasons, along with availability and price, that gypsum is the product of choice for controlling dispersion in sodic clay soils. In separating the electrolyte effect from the cation replacement effects of gypsum, Loveday (1976) showed that in the absence of changes in exchangeable cations, the hydraulic conductivity of dispersive clay soils increased from 0.005cm/hr to 0.4cm/hr immediately after the application of 7.5t/ha gypsum. This demonstrated the importance of the electrolyte effect. Subsequent irrigated field studies showed that 12t/ha of gypsum had totally dissolved within three years of application and that within the 0–40cm layer the residual cation exchange had a 10% increase in exchangeable calcium and a 20% and 5% reduction in exchangeable sodium and magnesium respectively. It was also shown that displaced sodium cations increased below 120cm within the soil profile. The residual cation replacement effect resulted in a two-fold increase in hydraulic conductivity within the 0–40cm layer. Hence, the electrolyte effect is immediate and highly effective in reducing dispersion but is transient, lasting only a few seasons following application. The cation exchange effect is moderately effective but longer lasting.

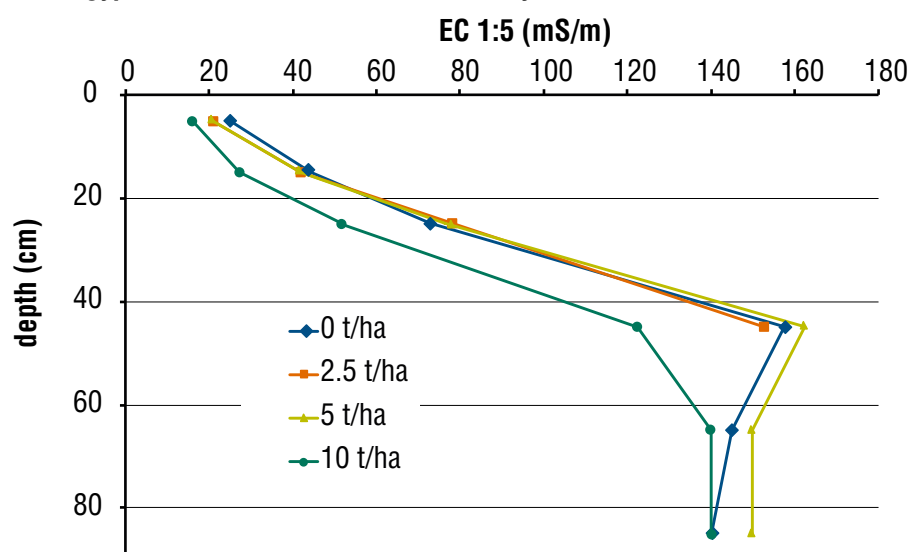
Generally, dispersive soils have more than 15% clay and an exchangeable sodium exceeding 5% of the total base cations. The degree of dispersion is increased by the presence of exchangeable magnesium where the ratio of Ca:Mg is less than 2:1 (Emerson and Bakker 1973) and the concentration of soluble salts is low (<0.5dS/m, McKenzie et al. 1993). All non-saline clay subsoils on the south coast are potentially dispersive.

Amelioration of transient salinity in subsoils

The above review has shown that gypsum increases water movement and leaching within sodic clays. Throughout the drier agricultural areas of Australia, sodic subsoil clays can restrict drainage, resulting in an accumulation of salts within the root zone. Transient salinity occurs because of cyclic salt accumulation, perched watertables and high evaporation but is not associated with regional groundwater processes (Rengasamy 2002). Transient salinity is generally associated with the mallee on the south coast of WA along with the York and Eyre peninsulas in mallee areas of South Australia (SA) and Victoria. The effect of gypsum on increasing leaching and reducing salinity within the root zone has been demonstrated at numerous sites in SA (Rengasamy and Kelly 2003). A summary of these results is presented

in Appendix 8B. Similarly, reductions in transient salinity have also been measured 20 years after gypsum application at Cascade. High rates of gypsum (10t/ha) were found to reduce electrical conductivity from 1.6dS/m to 1.2dS/m at 50cm depth on a clay loam over clay soil. A reduction in exchangeable sodium was also measured at this site to a depth of 30cm (Figure 8.2). Significant increases in crop yields were found at the Cascade site when measured 20 years after gypsum was applied. Much of the increase in crop yields was obtained at gypsum rates of 2.5–5t/ha and is attributed to reduced salt and boron concentrations and associated improvements in plant available water capacity PAWC, root penetration and water uptake (Lemon, pers. comm.).

1984 gypsum effect on subsoil conductivity



1984 gypsum effect on subsoil ESP

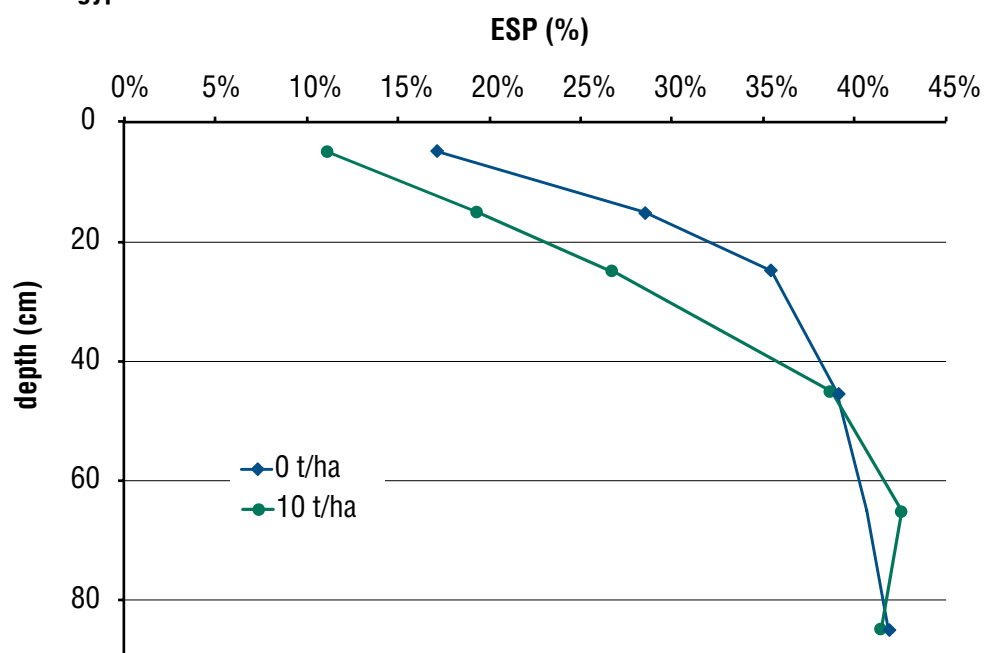


Figure 8.2 Changes in profile salinity and exchangeable sodium percentage (ESP) resulting from gypsum applied 20 years prior to measurement at Cascade. Source: J Lemon.

The quantity of gypsum required to reduce sodicity can be calculated using a mass balance approach. Using this approach, the amount required to reduce exchangeable sodium percentage (ESP) to less than 5% often results in impractically high application rates of gypsum in terms of cost and potential for crop damage (Table 8.1). Consequently, surface-applied gypsum is rarely spread at more than 15t/ha. Often 2–5t/ha is used to ameliorate surface soils while higher rates would need to be applied where subsoils are to be ameliorated. Multiple applications of gypsum would appear to be warranted in highly sodic soils in order to change cation balances and leach toxic salts deeper into the profile. However, further work is needed to confirm this as current field observations suggest that 2.5–5t/ha may be sufficient to ameliorate transient salinity in the longer term (Lemon pers. comm.).

Hence, it is possible to postulate that there are two long-term effects of gypsum from a plant growth and WUE point of view.

- Gypsum allows leaching of salts and so increasing PAWC by reducing osmotic pressure in the subsoil leading to drier crop lower limits (CLL). Adjusting the PAWC in subsoil layers increased modelled yields by about 200kg/ha, which is similar to what has been observed.
- Better subsoil structure allows better root exploration and water extraction, and hence likely lower CLL and higher PAWC. This may be more important on low transient salinity sites if we measure better crop yields on these.

Table 8.1 Soil chemical properties that affect dispersion and calculated gypsum requirement to reduce ESP <5 to 1m depth for various soil types in the Esperance Region

Soil type	ESP	EC 1:5 dS/m	Ca:Mg ratio	Clay %	Calculated gypsum* t/ha
Fleming	8–20	0.2	1:2	34–60	4
Boyatup	10–27	1.0	1:4	30–40	10
Scaddan	24–44	1.4	1:5	35–45	30
Kumarl	34–50	2.4		23–50	45

* Calculated using data from Esperance Land and Resource (survey data and www.bcg.org.au/public_resource_details.php?resource_id=597)

Why should gypsum have an effect on subsoils that have high electrolyte values (i.e. saline) and which may also have natural gypsum at depth? The answer may be that the soils above these saline layers are less saline, more dispersive and more gypsum responsive. Allowing water to drain more freely from layers above may allow salts and boron to be leached deeper into the profile.

A further question is how effective gypsum applications are where the dispersive clay layer may be tens of centimetres below non-dispersive sandy topsoils? At present, we have little information to answer this, except for some anecdotal evidence that waterlogging is reduced in wet seasons when gypsum is applied to shallow duplex soils where there is a poorly structured sodic B horizon at 0–15cm depth.

Amelioration of subsoil aluminium toxicity

While gypsum is most commonly used to improve microaggregate stability in sodic clay soils, it has also been used to ameliorate subsoil acidity in some situations. McLay et al. (1994a) demonstrated increased wheat yields in deep acid sands in the central wheatbelt of WA as a result of differing combinations of gypsum and lime.

They found that gypsum is more soluble than lime and can be leached to greater depth than lime over a shorter period. The sulphate ions bind with aluminium and reduce the activity and hence toxicity of aluminium ions. The chemical reaction of gypsum in soils is complex and beyond the scope of this review. However, Sumner (1993) and McLay et al. (1994b) have summarised the chemistry of gypsum in acid soils as follows:

- There is some evidence of an increase in pH as a result of gypsum application; however, this has not been a universal finding. Changes in pH due to gypsum are generally small (i.e. <0.2 units). Much of the effect is due to sulphate replacing hydroxide ions on the mineral surfaces (i.e. “self liming”).
- There is an increase in AlSO_4^{4+} ions and a reduction in Al^{3+} activity as a result of gypsum. AlSO_4^{4+} ions are less toxic to plants than Al^{3+} . Precipitation of some complex aluminium sulphates occurs.
- The concentration and activity of calcium increases due to gypsum application.

Where other forms of calcium (i.e. CaCl_2) have been applied to acid soils, there has not been a reduction in Al^{3+} activity. This suggests that the sulphate ions are the key to reducing aluminium toxicity. It appears that not all acid subsoils will respond to gypsum addition. Much of the research has been conducted on soils with high clay contents, in particular kaolinite, in a range of environments (tropical, temperate). Defining which soils will or will not respond is at present vague. Sumner (1993) suggests a test for gypsum responsiveness in acid soils based on changed pH in solutions of CaCl_2 and CaSO_4 plotted against gypsum sorption. The rationale for this has not been stated clearly. On a more cautionary note, on very sandy soils the application of gypsum (5t/ha) has been found to leach magnesium and potassium beyond the root zone, resulting in nutrient deficiencies in plants (Sumner 1993, Shainberg et al. 1989).

An important conclusion from Shainberg et al. (1989) was that gypsum is not seen as an alternative to lime in the control of topsoil acidification. The benefits from gypsum application will occur after liming has rectified topsoil acidity. The effects of surface applied gypsum (3t/ha) on crop growth on a deep sandplain soil at Neridup were investigated in 2007 and 2008. Soil properties of the site are given in Table 8.2.

Table 8.2 Soil properties at the liming and gypsum experiment Neridup

	EC mS/cm	pH (CaCl_2)	Al ppm (CaCl_2)	ECEC ^a cmol(+)/100g	% base saturation
0–10	5	4.6		2.13	0.94
10–20	2	4.4	2	0.59	0.71
20–30	2	4.2	3	0.43	0.47
30–40	3	4.1	9	0.79	0.39
40–60	3	4.2	11	0.79	0.43
60–80	2	4.6		0.26	0.65
80–100	1	5.0		0.37	0.84

^a ECEC is estimated cation exchange capacity in units of centimoles of positive charge (per 100 g of soil).

No significant differences in lupin (2007) or canola (2008) growth or grain production were found between the gypsum applied or control. Hence, while there is a certain amount of theory to support the use of gypsum to control aluminium toxicity, there is as yet no conclusive evidence to support the use of gypsum as an ameliorant for subsoil acidity on sandplain soils. More detailed research needs to be done to define the role of gypsum in acid sandplain soils.

More information is required to identify Al toxic soils that will respond to gypsum. From the work of Sumner (1993), there is a test but the chemistry behind this test needs to be explored further in a WA context. Relationships between gypsum, pH, Al ion species, mineralogy and toxicity could be developed further for WA subsoils.

Ameliorating calcium and sulphur nutrient deficiencies with gypsum

Both calcium and sulphur are essential elements required for crop growth and production. Calcium deficiencies affect the development of terminal buds and apical root tips resulting in reduced and deformed bud and root formation. Sulphur is used in the production of amino acids that are essential building blocks for enzymes. Deficiencies are displayed as stunted chlorotic yellowing growth particularly in younger leaves (Tisdale and Nelson 1975, Mason 2004). Calcium and sulphur are removed from the soil at rates of 0.5–4kg/tonne of grain and 1.5–10kg/tonne of grain (i.e. cereals, canola and lupin) respectively (Hazelton and Murphy 2007). Canola has the highest requirements for both nutrients. Sulphur is taken up by plants in the sulphate (SO_4^{2-}) form and is mainly found within the organic fraction of soils. Sulphate is readily leached in high rainfall areas.

Ca and S in the form of gypsum salts are added to south coast soils via cyclic rainfall and the historical use of single superphosphate containing 10–12% S. At Gibson, about 3.4kg/ha of Ca and 2.9kg/ha of S are added annually to the soil via marine salts in the rainfall (Hingston and Gailitis 1976). Due to leaching, the sulphur content of sandplain topsoils commonly ranges from 4 (potentially deficient) to 12mg/kg (KCl 40 test). Much of the sulphur is leached and held within the subsoil clays resulting in high (>40 ppm) S values. This suggests that where clays occur within the root zone S deficiencies are unlikely to occur. Coarse deep sands in high rainfall environments with low organic matter — and that have not had a long (or recent) history of single superphosphate applications — are most vulnerable to S deficiencies (Mason 2004).

Gypsum is relatively soluble at 2.1g/litre. Assuming that gypsum is applied at a rate of 5t/ha (= 0.5kg/m²), then much of the gypsum will dissolve in about 300mm of rainfall resulting in 2800kg/ha of SO_4 and 1150kg/ha of Ca washing into the soil profile. A single application of gypsum can therefore meet plant requirements for calcium and sulphate for many years, if not leached below the root zone. Gypsum is also one of the few commercially available sulphur compounds that does not acidify soils (Moore et al. 2001). This is important for acid-prone sandplain soils that have pH values ranging from 4–5 with little buffering capacity.

Appendix 8A

Gypsum analysis from pits near Esperance. Values are concentrations expressed as per cent of material analysed

Sample Concentration %	Wandhill	Lake Tay	Grass Patch
Al ₂ O ₃	1.24		0.28
SiO ₂	7.99		0.61
TiO ₂	0.05		0.03
Fe ₂ O ₃	0.37		0.10
MnO	0.01		
CaO	28.50		
K ₂ O	0.22		0.06
MgO	0.08		
P ₂ O ₅	0.02		
SO ₃	41.10		45.40
Na ₂ O	0.26		
Loss on ignition	20.26		20.40
SO ₃ as CaSO ₄ ·2H ₂ O	88.00	96.0	82.00
Chloride	0.58		
Ca%	20.35	23.4	
S %	16.44	17.9	

Appendix 8B

Effect of gypsum on salinity (EC 1:5dS/m) within the root zone of soils with “transient salinity”. Summary of results from gypsum trials in SA (Rengasamy and Kelly 2003).

Site	Depth cm	Gypsum 0t/ha	Gypsum 2.5t/ha	Gypsum 5t/ha	Gypsum 10t/ha	Gypsum 15t/ha
Minnipa in year of application after 1000 mm irrigation	0–30	0.12	0.1		0.1	
	30–50	0.29	0.12		0.12	
	50–70	0.60	0.13		0.13	
	70–120	0.83	0.38		0.2	
Cleve 9 years since application	0–20	0.19	0.14		0.14	0.13
	20–30	0.24	0.13		0.12	0.12
	30–60	0.76	0.16		0.14	0.12
Lock after second application	0–10	0.19	0.08			
	10–20	0.16	0.07			
	20–40	0.25	0.07			
	40+	0.28	0.11			
Murdinga after 6 applications over 13 years	0–20	0.08		0.11		
	20–40	0.64		0.31		
	40–60	0.70		0.36		
Tuckey 3 years after application	0–20	0.28	0.17			
	20–30	0.23	0.12			
	30–40	0.63	0.38			
	40+	0.58	0.39			

Lime requirements: predicting where and how much to apply

Jeremy Lemon, DAFWA

Soil acidification is a natural process but is more rapid under agricultural land. The main causes of acidification are inefficient use of nitrogen and product export (Davies et al. 2009). Leaching of nitrate is related to plant available water capacity PAWC, fertiliser practices and root depth in relation to rainfall patterns. In general, low PAWC (high nitrate leaching potential) of any soil layer is strongly related to clay content and organic carbon (OC) content and at the same time buffering capacity. Additionally, ammonium fertilisers contribute acidity to the soil (Baldock 1999, Gazey and Davies 2009).

The amount of lime required to amend soil to target pH is determined by the current pH level together with the pH buffering capacity (pHBC). pH buffering capacity is measured as $\text{cmol H}^+/\text{kg/pH unit}$, which is then converted to $\text{kg lime/ha/pH unit}$. Soil pH buffering is widely regarded as being influenced by clay content but OC content has more influence in Western Australian (WA) soils (Moore et al. 2001, Wong and Wittwer 2010).

Commercial practice in WA takes little account of the buffering capacity of soils. Recommended lime rates are usually determined by soil pH alone. Lime rates and area treated per season are influenced by farm profitability and further refinement of lime rates by estimates of buffering capacity is not warranted. Monitoring of soil pH, both surface and deeper layers, is used to measure effectiveness of amelioration and the need for further treatment.

If too much lime is applied, any in excess of current requirements will remain in the soil, creating higher pH ready to neutralise future acidity so it is not wasted in the end. Problems may arise when some zones of a paddock regularly receive excess lime for the rate of acidification. It is usually uneconomic to spend money before you need to (unless there are tax considerations), so applying excessive lime is not recommended.

Potential for zoning lime requirements

Several studies have used geophysical sensing to develop variable rate (VR) lime application maps. Wong et al. (2008) report on using a combination of EM and radiometric survey together with yield maps and grower knowledge of paddocks to develop such maps. Some yield maps reflect the zones related to lime requirement but not in every season nor in every paddock. Intense sampling of profile pH measurement allows small zones to be described accurately but at a cost. D'Emden et al. (2010) report a case where EM survey describes lime requirement accurately in a landscape where flat neutral to alkaline valley floor is adjacent to acidic sandy gravel. These soil types have very different apparent electrical conductivity (EC_a) values and at the same time lime requirement, meaning the EM contrast lends itself to defining zones for liming.

Some commercial precision agriculture (PA) consultancies use a combination of EM and gamma to define zones suitable for VR lime. EM has limitations at lower conductivity where sands and gravels show little difference. But gamma can identify zones within the low EM range that can be sampled for pH, correlated with remote-sensed data, and converted to VR maps to adjust lime rates to requirement.

Adamchuk et al. (2007) describe “on the go” pH measurement in the US where soil pH (and inferred lime requirement) can be measured at an intensive scale with appropriate equipment. They discuss in detail the economics of varying lime amendment compared to uniform application but the economics reported is short term, one or two seasons. Liming in WA has long-term benefits that can still have rigorous economic analysis.

For example, a simple soil map derived from aerial photo interpretation and grower knowledge to target limited sampling is presented by Davies et al. (2009). The study reported commercial testing by Joel Andrew, of Precision SoilTech. In this study, measuring soil pH profiles allows targeted application to address both topsoil and subsoil pH. The study shows six profile sites being used for a 90ha paddock and shows the benefit of profile sampling to address both topsoil and subsoil acidity on a zone basis. The zones were apparent from aerial images and grower knowledge of soil types in the paddock.

Predicting lime requirement from measuring soil acidification processes

Acidification rates and associated lime requirements can be calculated from crop yields and fertiliser type and quantity. Yield maps provide a platform for VR lime based on the quantity of product (i.e. grain, biomass) and consequently base cation exported. While high production levels increase the rate of acidification from base cation export, high production is usually (but not always) associated with higher pHBC. This means a given amount of acid will have less influence on the pH but still require the same amount of lime for neutralisation whether in high or low buffering soil. Lower producing areas will not have the higher base removal with product export but will likely have lower PAWC and hence be more prone to acidification from nitrate leaching. Adding the acidification from product export and nitrate leaching will tend to make acidification more even across a range of production zones in a paddock.

One question is whether to apply frequent lower amounts of lime on high-production zones in response to calculated lime requirements or larger amounts less frequently in response to a measured decline of pH. Low-producing zones may well need frequent lime from measured pH decline.

Soil properties that predispose soils to nitrate leaching are closely related to PAWC and associated seasonal rainfall. Sand and gravel content of soil can be mapped from a combination of EM and gamma radiometrics defining areas that are likely to leach nitrate in conducive seasons. This could be calculated for each zone. The decision support program Optlime (Bowden et al. 2008) can be used to estimate rate of acidification from the contributing factors of production level, N fertiliser types and rates as well as estimates of nitrate leaching. Optlime is also useful to evaluate the economics of alternative liming strategies. Soil properties used to estimate natural lime content can be mapped with EM in some landscapes (D’Emden et al. 2010) and hence describe areas with differing current lime requirement.

Direct measurement of pH for certainty

Indirect methods of estimating lime requirement could be used for five to seven seasons but profile pH sampling and measurement is needed to verify the effectiveness of any strategy before there is any serious acidification on areas that have received insufficient lime.

In all cases, soil sampling and actual soil pH measurement is needed to determine lime requirement. After varying lime rates across any paddock, continued sampling is recommended to monitor pH of the soil and the success of the liming strategy. Given that lime is applied every three to five years in a maintenance-liming program and liming cost is \$30–\$60/ha, moderate intensity sampling is a relatively small cost.

The main use of PA techniques is to define zones that are likely to have different lime requirements in order to sample them separately and to vary lime rates according to zones if there are sufficient differences.

10 Strip trial design and analysis

Nigel Metz, SEPWA; Andrew van Burgel and Kelly Kong, DAFWA

Introduction: Strip trials

This chapter captures the findings of the Agronomy Jigsaw project in relation to strip trial analysis from yield mapping. The project team has analysed many working examples of grower strip trials provided by Precision Agronomics Australia (PAA) and their clients. Some significant findings need to be considered when using precision agriculture (PA) to conduct trials.

Generally, the project has drawn on previous work from the CSIRO's PA projects on strip trials. Essentially, our approach sets out two aims of a strip trial:

- Is there a difference in yield between treatments? (treatment effect)
- Do the yield responses to treatments differ between zones? (zone by treatment effect).

The project team set about to extract data from growers' yield maps across a number of trial sites to answer these questions as well as to develop the analysis methodology outlined in this Bulletin.

By doing this, we found there was a significant gap in skills for both growers and agronomists, resulting in limited yield data collection and display. Consequently, many issues in strip trial analysis have yet to be encountered at an industry level because many growers have not loaded their yield data. As industry skills improve, the guidelines set out in this Bulletin will become more relevant for people conducting strip trials.

History of strip trials

In the early 2000s, the adoption of guidance technology in broadacre agriculture in Western Australia (WA) enabled variable rates (VR) of inputs to be applied to different parts of a paddock. Silverfox, a business specialising in making VR fertiliser maps and their paddock implementation, was the first to offer the commercial package to growers. As part of this new VR approach, Silverfox placed trial strips of different rates of fertiliser within their prescription maps with the intention of using the grower's GPS-equipped harvester to measure yield variation. The aim of these strip trials was not only to measure the effect of different application rates on crop performance but also to determine whether there was a variation of the response to the application between the different production zones (or soil types) within the paddock.



Figure 10.1 Classic VR fertiliser map with strip trial embedded.

This simple trial design has since been the blueprint for the PA industry and now the concept of strip trials is common. Although the trial design appears simple enough, numerous approaches have been tried on how best to analyse the harvester yield data to determine any treatment effects.

Initial consultations with PAA identified that one of the key topic areas for the Agronomy Jigsaw project was to “define a protocol for strip trial analysis”.

Sourcing historic trials and corresponding yield data

The yield data from strip trials are used to evaluate the yield effects of rate treatments in different production zones of a paddock. Through collaboration with PAA, the project was able to access a number of paddocks that had VR gypsum applications with strip trials embedded in the application maps. More than a dozen paddocks of PAA clients have been assessed during the project, and six of these have been selected for detailed analyses to “define a protocol for strip trial analysis”.

The key advantage of using PAA’s client data is the real grower examples of VR applications and corresponding yield data collection at harvest. This use of working examples allows insights into trial design that would otherwise not have been possible. The following descriptions are based on the project’s findings on the variations of the strip trial concept due to both accidental and deliberate trial outcomes.

One of the most striking aspects of following up strip trials is the lack of yield data capture and display capabilities by the host grower. Although some growers showed well-developed yield mapping and downloading skills, most were not able to load yield data from their data cards nor display data from the trial paddock. As a result, analyses of trials are rarely conducted unless a skilled agronomist or a project such as the Agronomy Jigsaw project specifically monitors the site.

Seven clients of PAA were approached for yield data on trials that had been implemented on their farms, following paddock surveys and VR applications. From these host growers, a possible 12 crop years’ worth of observation since the trials had been implemented were available. Unfortunately, only seven of these 12 crop

years had sufficient yield data available to analyse trial results. Of this proportion of available data, few growers had actually loaded yield data from their harvester data card.

It may seem obvious to assume that growers who are investing in precision farming practices would have well-developed skills in archiving and manipulating yield maps to determine benefits and make adjustments for the future. This is not necessarily the case. Few growers have well-organised yield datasets, which remains a problem for industry adoption and documentation of PA benefits.

Trial analysis methodology

Growers have used trial strips in grain production to answer the simple question: “Did the treatment have an effect (and, if so, for how many years)?” We also recognised that different parts of the paddock may have quite different production characteristics. Correspondingly, the relative effect of a management treatment is likely to also vary. In response to this, trial analysis needs to accommodate the range of treatment effects between different production zones. Measuring such response variability is fundamental when WUE factors are considered spatially as well as topically.

In assessing several trial datasets from PAA, the project team developed the following guidelines:

- Define the management zones of the paddock, in particular within the trial strips.
- Define run lines of appropriate raw data that are wholly within treatments and zones from which data strings can be extracted.
- Extract raw data strings.
- Conduct the statistical analysis relevant to the trial design.

Each of these points is explained in more detail below.

Raw data: why use it

Traditionally, yield monitor data on a grower scale have been displayed as continuous surface maps. The raw point data collected from the header’s GPS is interpolated (by Kriging or inverse distance weighting) to produce a continuous, visually pleasing map surface. For trial analysis, the aim is to produce blocked data units that can be compared for variation between treatments for statistical difference. After trial analysis from the data provided by PAA, the Agronomy Jigsaw project elected to work entirely with raw point form yield data for the following reasons:

- The interpolation of point data to grid or raster format can dilute or smudge treatment effects by incorporating adjacent data which may be from different treatment strips, or give disproportionate weight to sections of the data.
- Interpolating data results in a lack of balance across harvester runs as well as including runs that are outside or partly outside the treatment area. Considerable differences between harvester runs have been observed and this is best taken into account in the analysis by using the raw data.

- Using the raw data is simpler in that it avoids the need for selecting and implementing a method for how each interpolated point is based on a weighted average of nearby raw data.
- While working with raw data, the project has highlighted some significant anomalies in data collected from harvesters. While some of these are unavoidable, having the data in raw format allows these anomalies to be identified and put into context in the analysis of the trial results. Left unchecked, these data anomalies could in some cases significantly distort trial results.

Raw data: how we extract it

Point yield data is relatively simple to extract from the yield file, display in Microsoft Excel and compile into a data table similar to any other traditional set of trial results. Examples of such data layout are shown in Table 10.1.

Table 10.1 Example of layout required for identifying and analysing raw yield mapping data from paddock strip trials (a) comparing overall treatment effect (b) comparing treatment effects across zones

(a)

Run ID	Treatment	Average yield for whole run
2	0t/ha	2.32
3	0t/ha	2.16
5	5t/ha	2.52
6	5t/ha	2.76
8	2.5t/ha	2.45
9	2.5t/ha	2.66
11	0t/ha	1.84
12	0t/ha	1.98

(b)

Run ID	Treatment	Zone	Average yield
2, 3	0t/ha	A	2.4
5, 6	5t/ha	A	2.8
8, 9	2.5t/ha	A	2.8
11, 12	0t/ha	A	2.1
2, 3	0t/ha	B	2.6
5, 6	5t/ha	B	3.0
8, 9	2.5t/ha	B	2.9
11, 12	0t/ha	B	2.4

Point data, once extracted, can easily be shared in Excel format. This open format removes any exclusivity of data analysis synonymous with PA trials in the past. This provides opportunities for those in the industry who don't possess specialist PA or GIS software or skills, yet who have considerable agronomic experience, to contribute to trial analysis.

A summary of the data extraction process is described below.

Defining zones

To account for within-field yield variation across the trial area, management zones separating areas of differing yield potential need to be defined first. These zones

could be based on EM or gamma data, a previous year's yield map, soil data or a paddock "mud map".

The precise boundary between zones is arbitrary; we are drawing lines across a gradient. The primary role of comparison between zones is that the zones are of different soil types or production potential and will be likely to respond differently to trial treatments. In some cases, a transition zone or middle ground can be established to create a buffer between the soil types to increase confidence that zones are different.

Two zones (i.e. high and low) are sufficient. More zones can be used as long as each zone has sufficient yield data across the treatments.

Selecting run lines

Before extracting data, you need to identify the run lines in the raw yield data that will be used for analysis. Select runs that are completely (or almost) within the treatment boundary. Consider including run lines outside of the strip trial on either side to act as controls.

In the Run column, record the header run line that was extracted. The run lines should be numbered from left to right, north to south, starting from the first run line of the first control and finishing at the last run line of the final control. The run lines that are not selected for extraction should also be included in the numbering sequence so that the ones that are discarded can also be identified.

Eliminate unwanted data points

Eliminate unwanted data points such as:

- points within 30m of a turnaround
- points within 10m of the end of a treatment
- points too close together (indicates a speed change)
- data outside of biological limits (i.e. wheat yields >8t/ha).

Extract yield data

Extract data for each zone in each treatment and copy into Microsoft Excel. As much as possible, extract yield data from similar adjacent lengths of each treatment strip. If extracting within the zone, do this for each zone, treating zones at different ends of the treatment strip separately.

If extracting data for a zone by treatment analysis (Table 10.1b), aggregate raw data points into approximately 20m x 20m cells. It may seem obvious, but data points from the harvester yield monitor that are 2–3m apart will have relatively similar values and will not be independent as required for statistical analysis. In the data extraction process, we looked at what number of yield data points should be combined for comparison of yield that might be realistically different. From a statistical approach termed "variogram analysis", data points 5m apart are believed to be considerably less independent than those 20m apart. Therefore, by aggregating data strings into 20m sections and calculating the cell mean yield, we have more confidence that each cell value will be independent.

Findings on trial designs from trial analysis

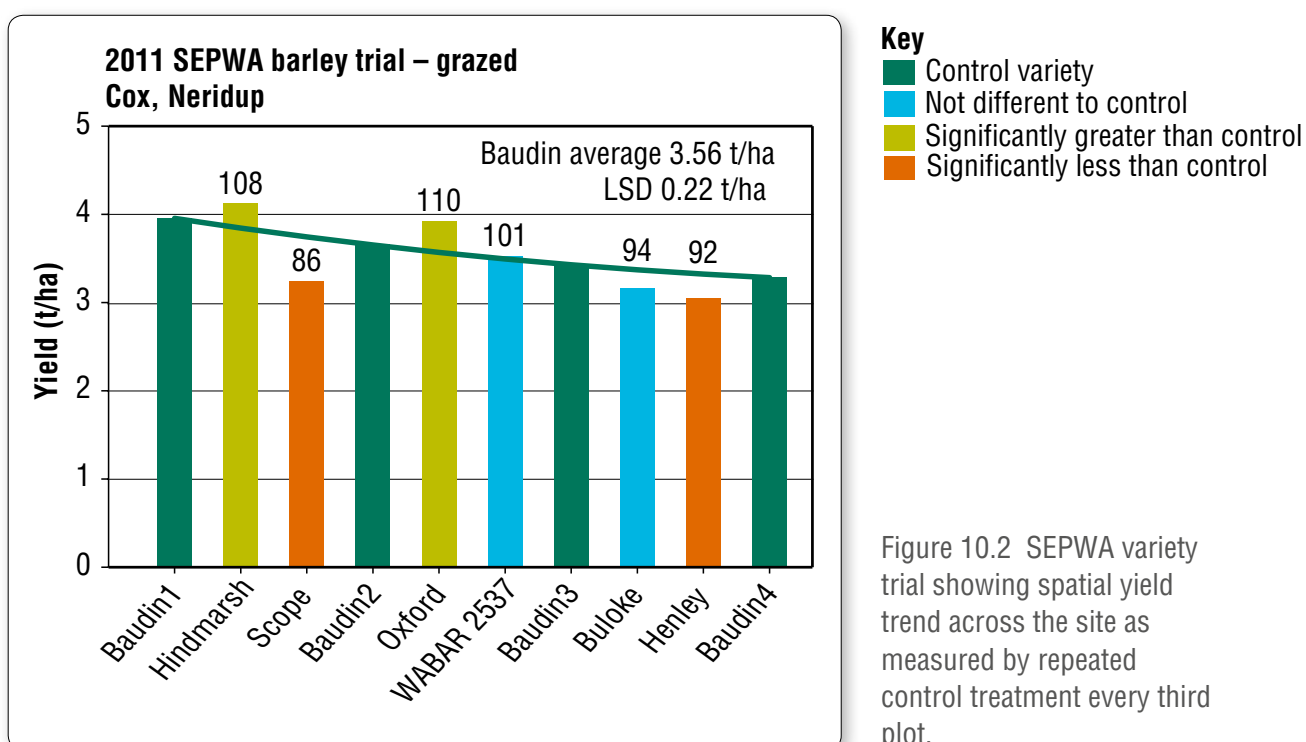
After analysing many grower strip trials, several issues must be considered for optimum results.

Trial treatment strips need to be wide enough for at least two, though ideally three, header runs. Seeder and harvester run lines will not always align; hence, you will need at least two header widths to ensure that the entire header front is within the treatment area for at least one header run, and not harvesting part of the adjacent treatment. By ensuring three or more harvester widths for each treatment, at least two run lines will always fall completely within a treatment strip.

Repeat or replicate the trial. By conducting the trial treatments twice or more within the trial or by simply repeating the trial in another part of the paddock, you can have greater confidence in your results. Replication is an essential component of a good trial design (van Burgel 2012).

Keep it simple. Similar to the CSIRO findings of PA trial designs (Lawes 2010), fewer treatments are generally better. From an analysis approach, one or two treatments present a relatively simple analysis. Combined with this, the farm-scale treatments of three header widths soon add up, making the trial wider and more prone to variation across the paddock. Make your treatments very different, so that the effect on crop yield can be easily detected — for example, double or nothing treatments against the standard paddock rate.

Include control strips. Having a control treatment among the trial strips every second or third plot — as well as making the extreme outside treatments into controls — allows for site trends to be easily recognised and factored into the analysis. Yield trending up or down across the site can be measured in the control strips, and plot yields adjusted for the effect. One drawback to this approach is that it starts to make the trial wider. This further reinforces the need to keep the trial design simple and limit the number of treatments. A working example of this concept is the SEPWA variety trial layout (Figure 10.2), although repeating all treatments (not just the control) is still preferable.



Collection of yield data: pointers for operating headers

Analysis of several grower trials and harvesting has highlighted some interesting anomalies that, left unchecked, could distort the trial result. During harvest, the growers' priority is not trial data collection. The recommendations in this chapter are not intended to impede harvest logistics, but to limit errors in data capture to ensure robust data for analysis. Below is a summary of these findings.

Use a single header to harvest a trial. Variation in yield monitor calibration between harvesters is an obvious source of error in trial yield assessments. Despite the most diligent efforts of machine calibration, side-by-side runs of different harvesters are rarely comparable to the accuracy required for trial analysis. For harvest logistics, other harvesters can work away from the trial area while the trial is being harvested.

If practical, harvest the entire trial in the same direction. Figure 10.3 shows an example of variation in the yield recorded on side-by-side harvester runs depending on the harvester travel direction. In some cases, there is 20% yield difference between adjacent runs harvesting in opposite directions. This variation is neither consistent nor predictable and varies in different parts of the paddock and at different times of day. As a result, there is no obvious means to correct yield data for this variation. If the machine is harvesting up the paddock within the trial, to maintain data integrity the machine should jump several run lines to be outside the trial area on the return runs down the paddock.

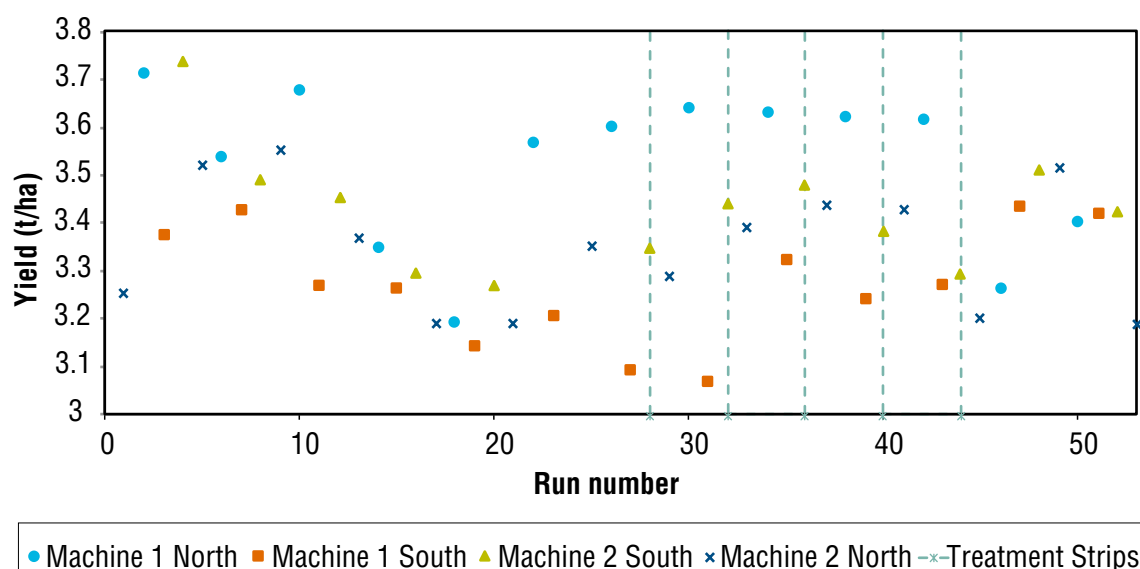


Figure 10.3 Average yield of consecutive parallel run lines about 10m apart and about 500m long (Curnow paddock 14, wheat 2008). Large machine and direction effects are evident between runs 22 and 44. Some consecutive runs differ in yield by about 0.5t/ha.

Keep the harvester moving at a constant speed. Harvest stoppages cause significant irregularities in the harvester yield data that have the potential to distort trial results. Simple stoppages for 10–30 seconds while waiting for a chaser bin cause a surge, drop and surge in the recorded yield data that has the potential to distort segments of data once extracted for analysis. Keeping the harvester at a constant speed (for example 80% machine capacity) also limits blockages, and

hence stoppages, limiting data irregularities. Machine blockages and stoppages, however, can be easily filtered from datasets via the “Distance” attribute (i.e. ground-speed recording) removing data from short runs.

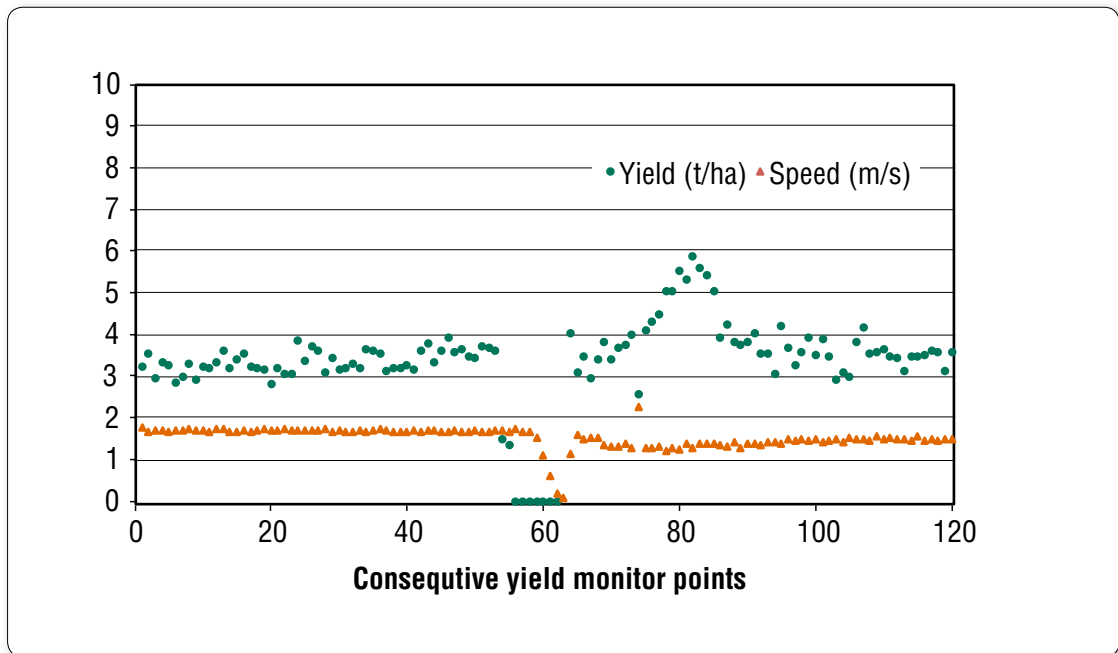


Figure 10.4 Yield and speed sequence of about 200m of a harvest run including a slow-down and stoppage by the harvester (Curnow paddock 14, wheat 2008).

Analysis

The approach to analysis will depend on whether you are comparing overall treatment effects or comparing treatment effects between zones (van Burgel 2011).

Comparing treatments

Once the average yield for the relevant run lines has been extracted (Table 10.1a), a formal analysis approach would be analysis of variance (ANOVA), which may require assistance from a biometrician. Alternatively, consider the natural variation you have in your data by calculating the difference in yield between run lines within each of the treatment strips. In the example data of Table 10.1a, side-by-side runs within a treatment vary by up to 0.23t/ha. As a rough guide, there is little confidence that differences between treatments that are less than this amount (0.23t/ha in this example) reflect real treatment effects.

Zone by treatments effects

Treatment means can be calculated and compared within each zone; however, it is important to bear in mind that differences need to be large enough to be confident they are not simply the result of variation in the data. Analysis of variance can be used to determine whether we can be confident that the treatment effects are significantly different between zones. Analysis of variance may require assistance from a biometrician and can be done with adjacent 20m cells as “blocks”.

The simple strip trial design: harvesting along the trial strips

Concept

The original concept of the strip trial approach was that the trial treatment boundaries would correspond (i.e. run parallel) to the seeding and harvester run lines. The treatment strips would run the entire length of the paddock and ideally pass over two or more production zones. At least one of the strips should be designated as a control or standard treatment.

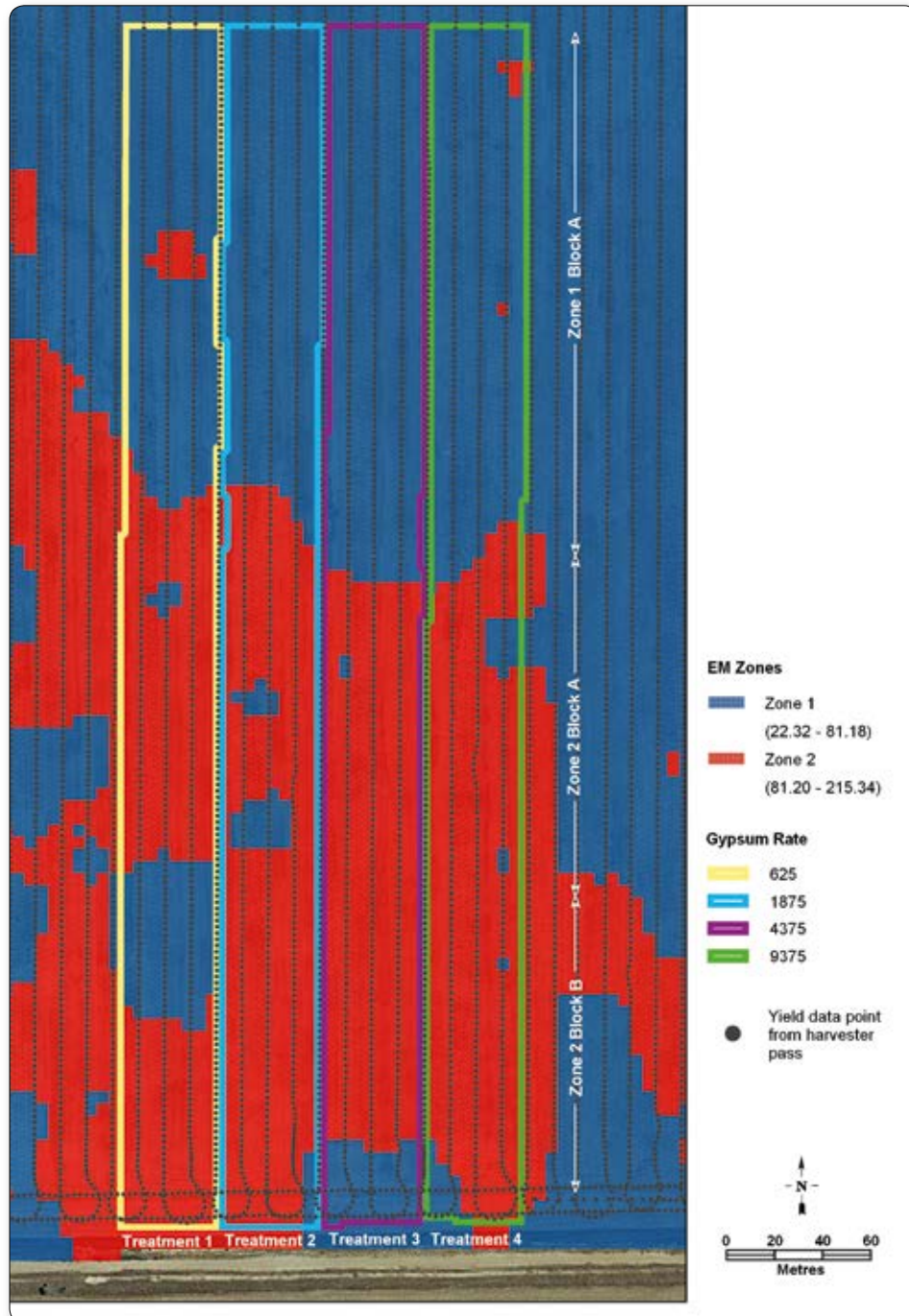


Figure 10.5 Typical strip trial design laid out over EM zones. The trial strips run parallel to the harvest run lines, showing the position of subsequent header runs in the treatment strips.

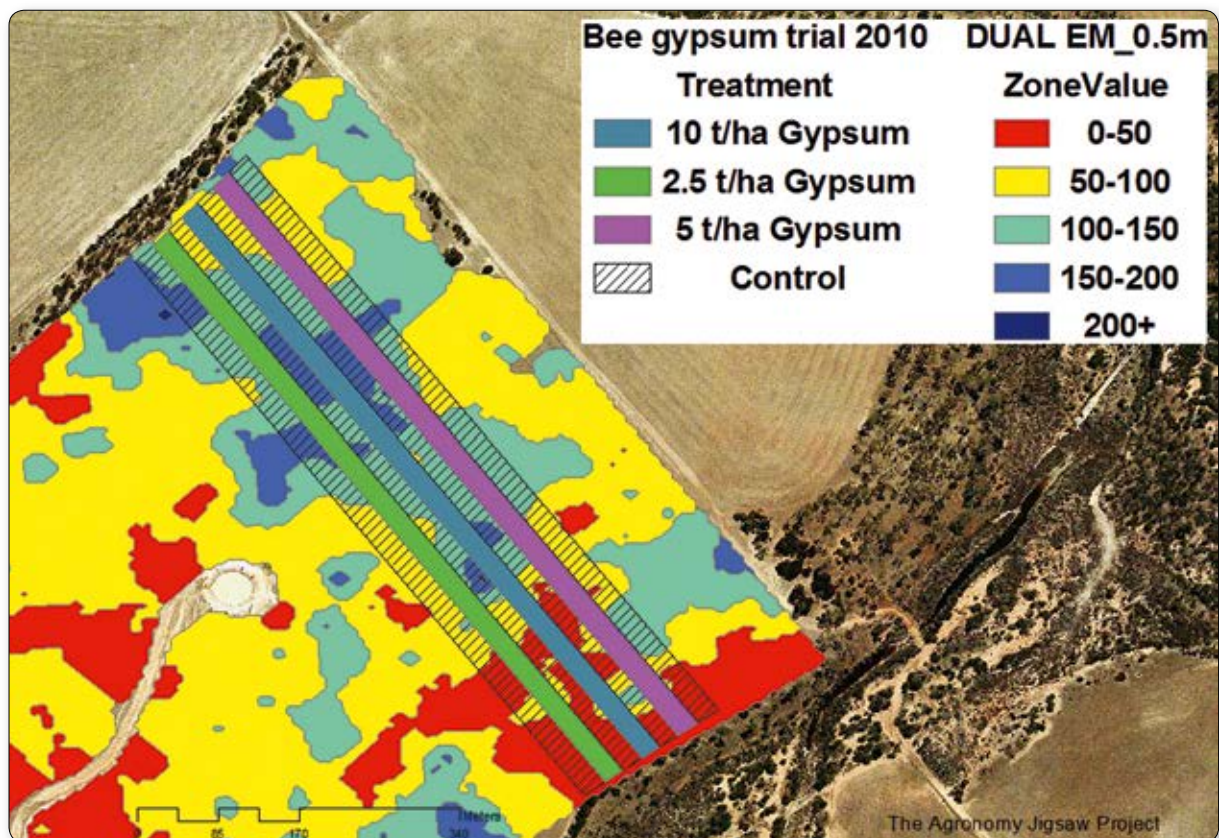


Figure 10.6 Gypsum trial in Jerramungup laid out over EM zones with alternate control strips running parallel to the AB guidance run line.

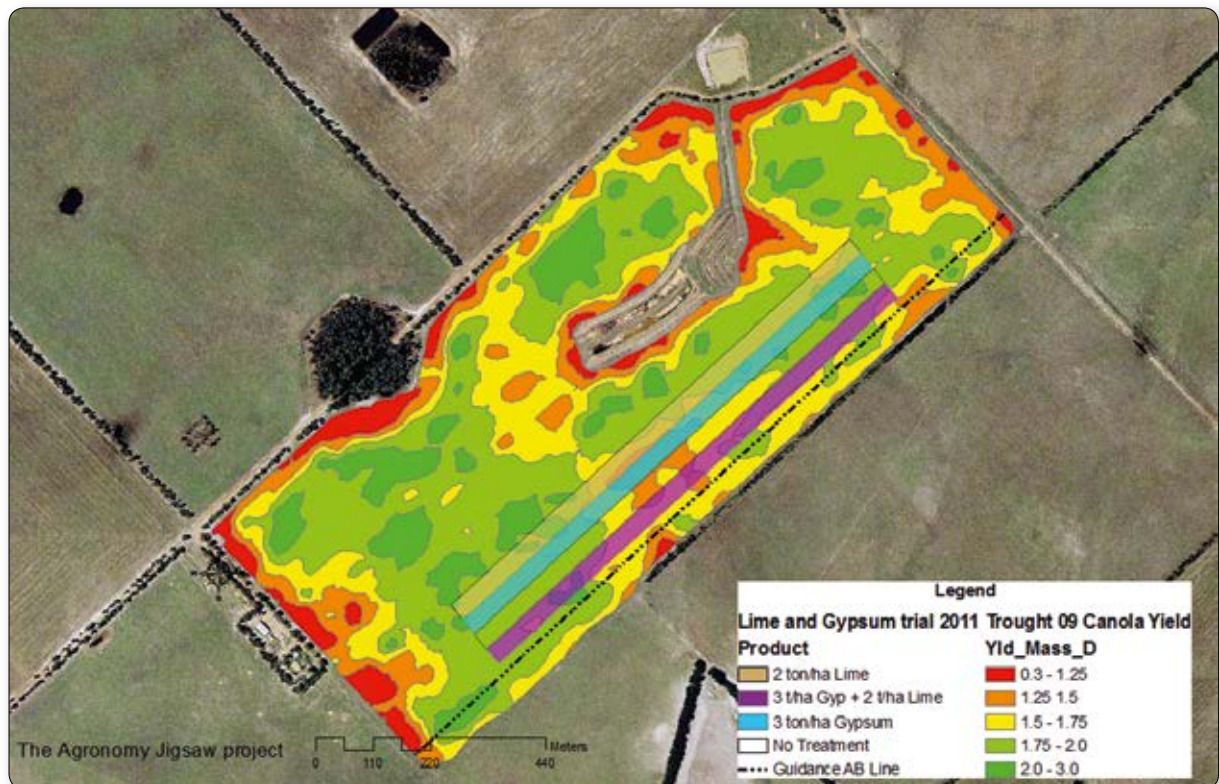


Figure 10.7 Lime and gypsum strip trial laid out over a yield map with the AB guidance line shown as the dashed black line. Trial in Jerradcuttup in 2011.

Benefits

This design is well recognised in industry, and is relatively simple to implement. The treatment rate is simply set for several runs up the paddock, and then different rates are set out alongside. The run lines can then be recorded with GPS, and the trial layout then transferred into the PA or GIS software ready for the header data overlay.

Limitations

Often the placement of these trials can be tricky. Placing a trial that may be 120m wide (4 treatments of 30m widths) in a solid strip which runs up a paddock in parallel with the tram lines and passes over the required soil zones can be challenging.

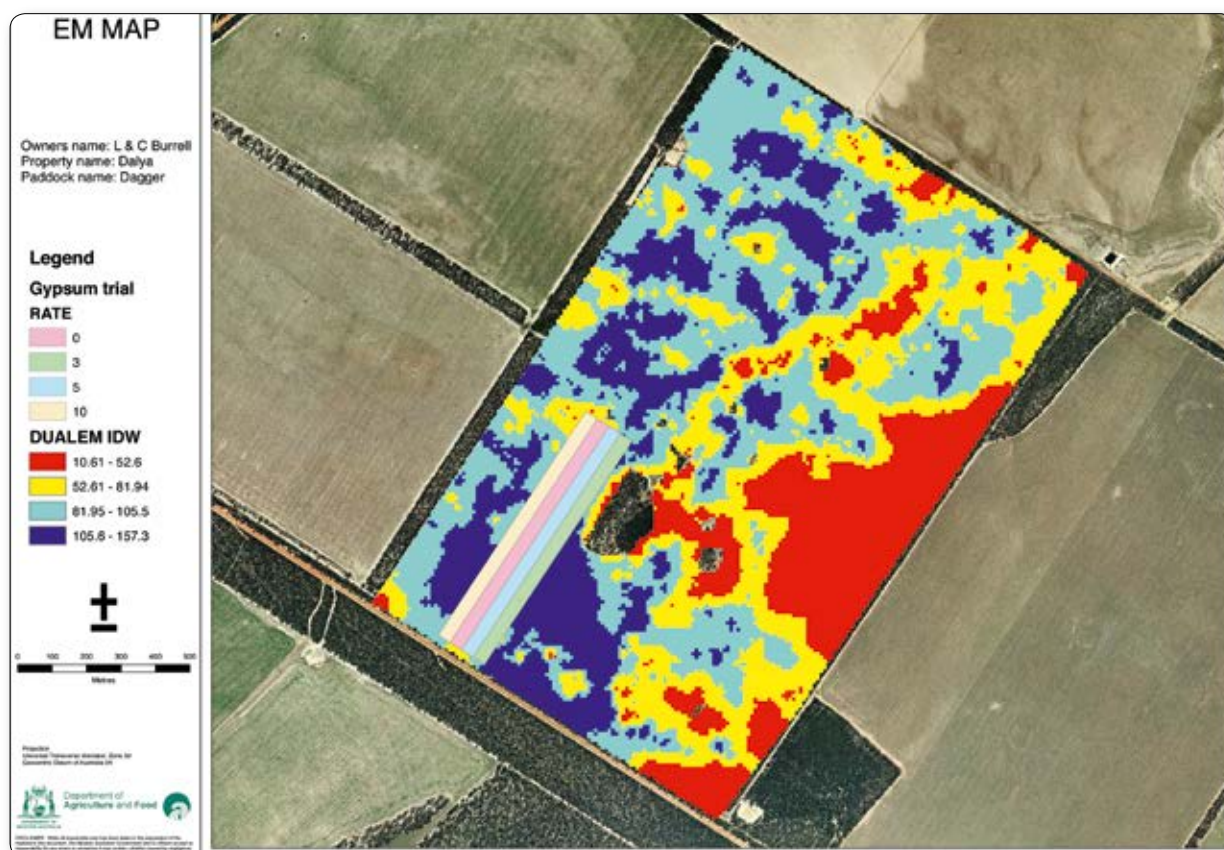


Figure 10.8 Example of a trial that covers only a single zone (100–150 EM value region). Covering the second soil type in the 0–50 EM zone would require a second trial area.

Variation between consecutive harvester runs (even within a treatment) due to multiple harvesters, harvest direction or other reasons makes the analysis less powerful for detecting overall treatment effects because the analysis should be done using the average yield of each harvester run. This problem does not apply to the analysis of differences in treatment effects between zones because the run effects cancel out for this comparison.

Solutions

Simplify the trial and run several strip locations up the paddock. For example, instead of trying to run three treatments, reduce the number of treatments to two and repeat the layout in another location. Essentially, you now have two trials; however, you will be confident that you have located treatments squarely in a target zone/soil type.

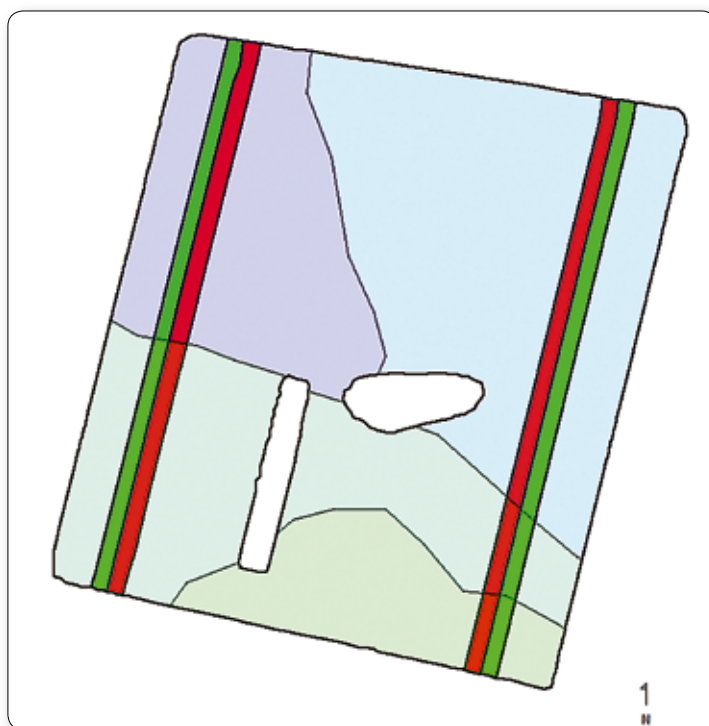


Figure 10.9 Example of trial layout repeated to cover all zones in the paddock identified by the grower's "mud map". Red strip is 0 treatment, green strip is 120kg/ha, and remainder of paddock is the control with 60kg/ha.

Simple strip trial design: harvesting across the trial strips

Concept

The project encountered two examples of strip trials that had been laid out in an east–west direction; however, following fence removal or redesign, the harvesting occurred in a north–south direction. This posed both limitations and opportunities for the trial analysis.

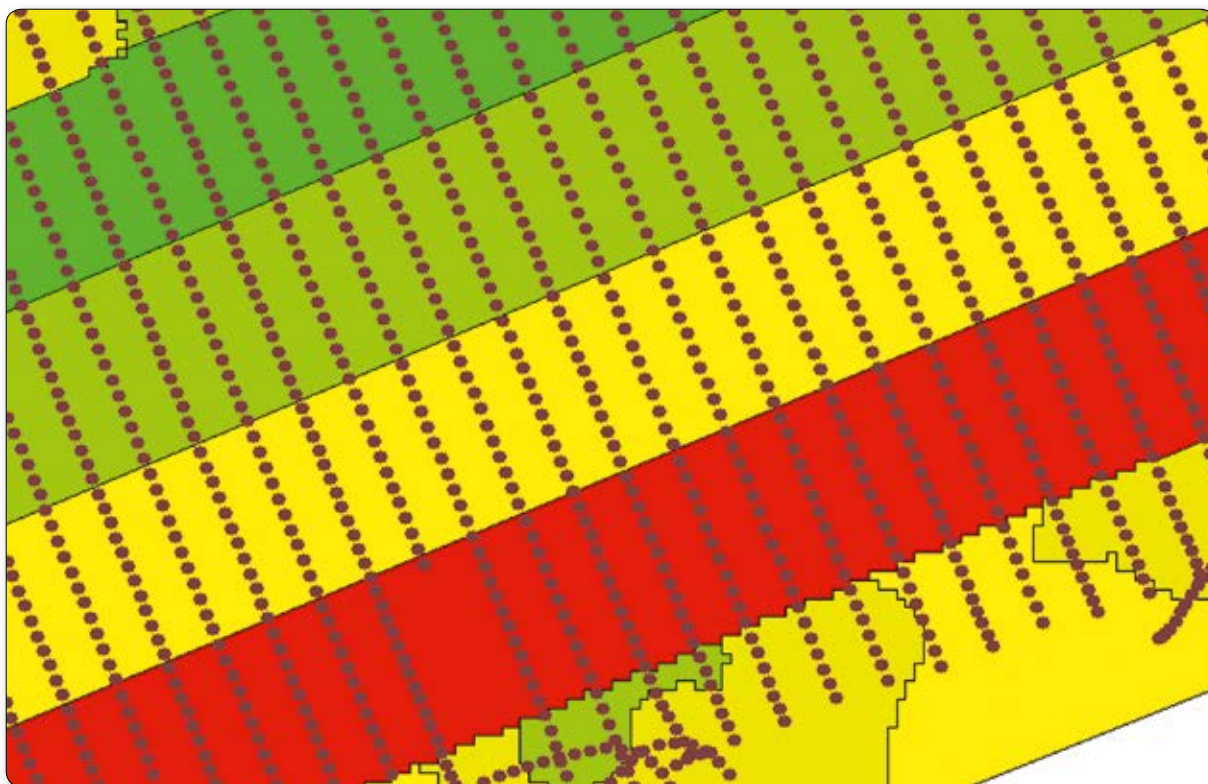


Figure 10.10 Example of strip trial laid out in an east–west direction while the harvest runs are north–south.

Benefits

The immediate benefit of this design variation is that the run variation effect encountered with the direction of travel of the harvester does not impact upon treatment analysis. This is because each harvest run passes across the full set of treatments.

Limitations

Data selection in this design needs to be much more precise. Consider the harvester passing over a 30m wide treatment. The first 10m bordering the adjacent treatment needs to be discarded to allow for data collection smudge as the harvester passes from one treatment to another. This can be further complicated by incorrect settings in the header's GPS monitor, which can result in the mapped data point not being correctly geographically located. This is known as "look ahead time". Although this problem can be corrected in the PA or GIS software, its extent must first be identified. Trials that are harvested across treatments need to be closely checked for this. A dataset that has an incorrect "look ahead" setting is shown below.

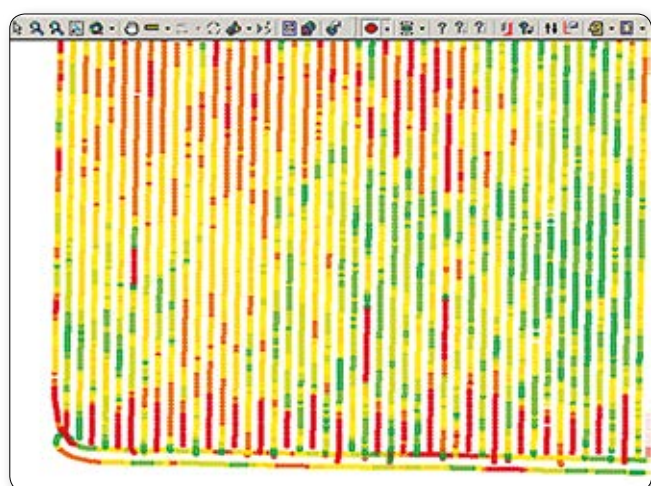


Figure 10.11a Raw data straight from the header (NH CX8000 model) with IntelliView™ Plus II steering and yield mapping. A series of red dots near the headland on alternating rows indicate an incorrect 'look ahead' setting with the GPS. This can be clearly seen in the video replay mode of SMS Advanced. Source: Derk Bakker, DAFWA.

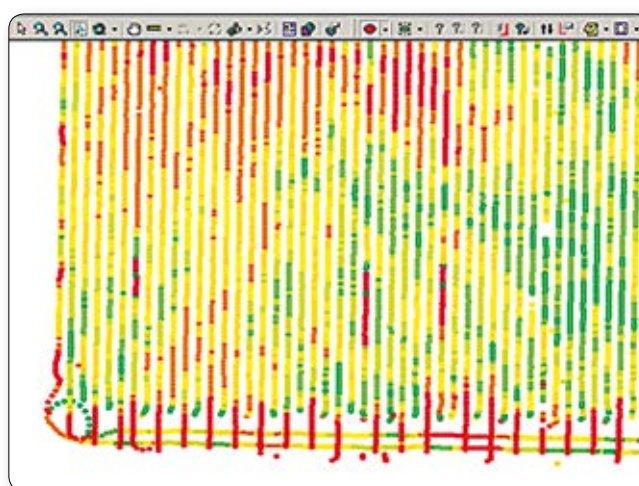


Figure 10.11b Corrected data (GPS positioned 20m in front of the harvester). Source: Derk Bakker, DAFWA.

Solutions

Carefully check point data is in the correct location before data extraction.

Trial window design

Concept

Laying out a trial within a set number of run lines that passes over two distinctly different zones/soil types in a paddock can sometimes be challenging. Often your chosen run lines of the treatments can clearly pass through one zone but only just capture the edge of another. In this case, direct comparison of the treatment effect in different zones can be difficult as the run lines are not wholly located in the target zones. Confronted with this problem in several paddocks, the Agronomy Jigsaw project varied the PA trial design so that treatments could be confidently located centrally in soil or production zones. Termed “trial window design”, the idea is that several treatment windows are placed in parts of the paddock of sufficient size that yield data may be extracted and compared. In the example below, the treatment windows were about 40m x 100m.

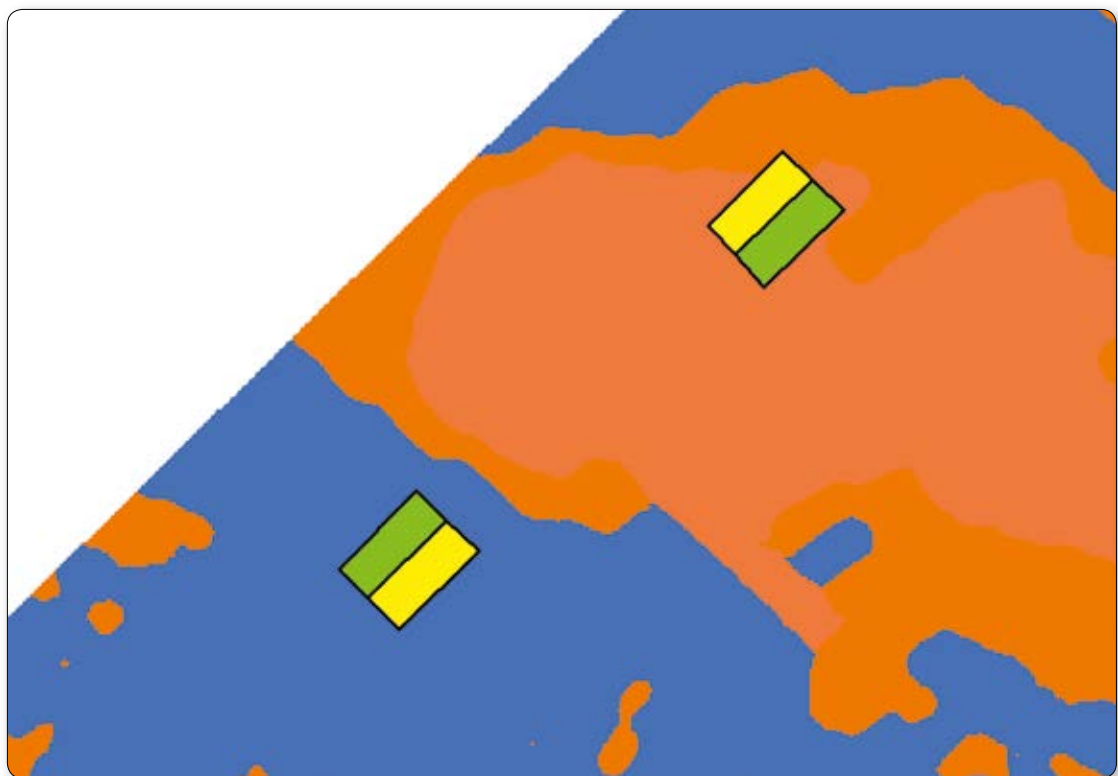


Figure 10.12 Trial window design on separate single soil types. Replicate treatments are then implemented independently in another part of the paddock in a different zone. Untreated control areas surround the treatments.

Benefits

Treatments can be clearly located within a zone. The treatment areas could actually be cut out and harvested with a weigh trailer if closer scientific analysis was desired.

Treatments that may be highly intensive (and expensive) can be implemented at a farm scale with this design yet not need whole run-line lengths.

Limitations

Treatments are not a simple variation of several adjacent run lines. They are now designated areas that need to be GPS-located then treated as per the trial layout. This will not be as simple as, say, double rate for a couple of runs with the seeder.

Solutions

Growers planning to use a trial window design will need either the window layout embedded into a prescription map or have access to a handheld GPS to peg out the treatment boundary and apply the treatment.

Table 10.2 Summary of benefits, limitations and their solutions of trial designs examined in this study

	Strips – harvesting along	Strips – harvesting across	Trial window design
Benefits	Well known Simple to implement Easy to locate	Header direction effects cancelled	Treatments placed accurately in zones Smaller areas treated
Limitations	Hard to cover all zones Take care with header direction	Precise data positioning needed More data points discarded	More difficult to implement Harder to locate and mark
Solutions	Simplify the trial Replicate the strips in other parts of the paddock	Take extra care with yield recording positions	Embed treatments in VR prescription map Locate treatments with GPS – separate task

Agronomy Jigsaw project: YouTube videos

Home page

<http://www.youtube.com/user/agronomyjigsaw>

This site contains agronomy information helping grain growers of south coast WA to find the pieces to maximise water use efficiency. You can access all Agronomy Jigsaw videos outlined below from this site.

The Agronomy Jigsaw project introduction

<http://www.youtube.com/watch?v=uSXSJG3agyw>

DAFWA project leader Ben Curtis introduces the project and explains how the project aims to find pieces of agronomy information to maximise WUE in south coast WA.

Precision Agronomics Australia: project partners

<http://www.youtube.com/watch?v=1mul408HTv8>

Precision Agronomics Australia (PAA) offer a specialist soil survey and agronomy service across WA. They are project partners in the Agronomy Jigsaw project, providing guidance and data to help understand how gains in WUE can be made in the cropping region of the south coast.

Lime: where and how much to apply

<http://www.youtube.com/watch?v=0L5sKB12WS8>

Soil acidification is a natural process in productive agriculture. Jeremy Lemon, of DAFWA, talks about the causes of acidification and determining factors to be considered in applying variable rates of lime.

Variable rate Lime part 2

<http://www.youtube.com/watch?v=zPu4ewxr5b4>

Jeremy Lemon, of DAFWA, reviews the work to date on approaches to varying lime rates across a paddock to ameliorate soil acidification.

What is GIS

<http://www.youtube.com/watch?v=rtAiVTw7R2s>

Kelly Kong, of DAFWA, outlines GIS and how it is used in precision agriculture.

Google Earth and Project Grower Group Introduction

<http://www.youtube.com/watch?v=8UbRsrf1jEY>

The Agronomy Jigsaw project will be using Google Earth to communicate with the region's grain growers. This video introduces the region's grower groups while demonstrating how to use Google Earth.

What is Gamma Radiometric survey?

<http://www.youtube.com/watch?v=tjp4llcJyUU>

Paul Galloway, of DAFWA, explains how gamma radiometric surveys indicate different soil types in the south coast region of WA.

Gypsum and its uses

<http://www.youtube.com/watch?v=wGzJkay-am0>

David Hall, of DAFWA, explains the uses of gypsum in the cropping region of the south coast of WA.

What is EM survey

http://www.youtube.com/watch?v=Eu_aRyzgdTo

Paul Galloway, of DAFWA, explains the workings of an EM machine and how it generates paddock survey maps.

DIY year to date rainfall graph for grain growers in WA

<http://www.youtube.com/watch?v=iBYint7cq1w>

Brendan Nicholas, of DAFWA, shows how easy it is to generate a year-to-date rainfall graph for local areas in the WA agricultural region with a few clicks on the DAFWA website.

Mapping soils with EM for variable rate

<http://www.youtube.com/watch?v=QuVqhl8qCow>

EM mapping of paddocks measures soil conductivity, which can closely correlate with subsoil sodicity. This video covers the concept of using an EM map to create a variable rate application map.

Mapping soils with Gamma radiometric surveys

<http://www.youtube.com/watch?v=4L0MTpD-nho>

Paul Galloway, of DAFWA, shows an example of a gamma radiometric map of the Lake Warden catchment, north of Esperance, WA. Paul highlights different landscapes, their soils and associated gamma radiometric readings.

Deep placement of Gypsum - Trenching

<http://www.youtube.com/watch?v=TKQYO-PW0lw>

David Hall, of DAFWA, explains the theory behind trenching gypsum into sodic subsoils as well as trial treatments in a paddock north-east of Esperance, WA.

Other uses for Gypsum

<http://www.youtube.com/watch?v=qPdwViBq0CU>

David Hall, of DAFWA, covers the theory behind the use of gypsum as a fertiliser and its potential to limit aluminium toxicity in acidic subsoils.

Design of on Farm Trials using Precision Agriculture Equipment

<http://www.youtube.com/watch?v=buZ1wkAdADs>

This video gives detailed instructions on trial design for on-farm trials. It is aimed at using farm-scale PA machinery to implement the trial, collect yield data and interpret results. It gives tips on trial design and layout so that you can be confident of your trial results. This is a “must watch” if you are planning any on-farm experiments or PA variable rate applications.

On Farm trial designs from the Agronomy Jigsaw project

<http://www.youtube.com/watch?v=8YWRAXcbG6o>

This video details the design of farm-scale PA trials in the Agronomy Jigsaw project on the south coast of WA.

Marking out your trial with a GPS

<http://www.youtube.com/watch?v=GYf8yzCyJzg>

By marking your trial with a GPS, you will be able to locate your trial points at harvest time. This video gives basic instructions on recording your trial points in the paddock in the correct format with a handheld GPS, plugging them into Google Earth and sharing them with others via email. This outline then becomes the “cookie cutter” for your harvester’s yield data and hence the trial analysis in your PA GIS software.

Tips for harvesting farm scale trials with your harvesters PA yield monitor

<http://www.youtube.com/watch?v=Ubf2yz22Yp0>

This video gives tips to improve the accuracy of the yield data collected by the PA monitor. The information will increase your confidence in your yield map data and in using them to interpret your farm-scale trials.

Precision Agriculture trials - Guidelines for data extraction from Yield maps

http://www.youtube.com/watch?v=zYfK-pF_zK8

This video provides guidelines for extracting yield data from crop yield maps collected with PA crop harvesters. It gives basic tips to ensure that the data extracted can accurately represent trial treatments and hence determine results from farm-scale PA trials.

Precision Agriculture Trial Analysis - Part 1

<http://www.youtube.com/watch?v=extGjA3Kc9M>

This video builds on previous trial design and data extraction videos to assist growers, agronomists and researchers in the methodology of trial analysis where trial treatment strips run **parallel** with the harvester direction.

Precision agriculture trial analysis - part 2

<http://www.youtube.com/watch?v=ZxnHz5ntCc0>

This video builds on previous trial design and data extraction videos to assist growers, agronomists and researchers in the methodology of trial analysis where the trial treatment strips run **perpendicular** to the harvester direction of travel.

Precision agriculture trial analysis - part 3

http://www.youtube.com/watch?v=h4DBN_8DdHE

This video builds on previous trial design and data extraction videos to assist growers, agronomists and researchers in the methodology of trial analysis where the trial window design is used to implement treatments in a paddock or crop.

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